

FIBER-ICE COMPOSITES

DuraTherm

Structure-Property Relationships, Thermal Regulation, Long-Fiber Refrigerant
Architecture, a Controlled Infrared Comparison, and Deployment Engineering

Technical White Paper and Literature Synthesis

Revised and expanded edition, October 2026

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Evidence and prototype record current through October 2026. Supersedes the edition of September 2026.

DuraTherm is patent pending. Evidence classes (I, II, III) are defined in Section 1.

Abstract

Fiber reinforcement changes ice from a brittle, flaw-sensitive crystalline solid into a multiphase composite capable of crack bridging, pull-out, crack deflection, distributed damage, post-fracture cohesion, altered water mobility, and modified heat-transfer behavior. DuraTherm applies this established foundation to a long-fiber refrigerant architecture in which cotton distributes water throughout a sealed pack and controls the geometry of the frozen and thawing mass. The working embodiment is designed for thermal regulation rather than structural strength: the pack must store useful thermal energy, keep its water and ice spatially distributed, limit bulging, present a comparatively uniform surface temperature, survive handling, and support practical manufacture and deployment.

This revision adds the first large controlled comparison of DuraTherm against commercial gel packs. In a 14-hour test (October 3–4, 2026; ambient 73.6 °F), 23 medium DuraTherm units and 27 medium FreezPAK gel controls, together with small (4 vs. 6) and large (1 vs. 1) units, were removed from the same freezer and imaged by infrared thermography on the rear face at 40 processed reads. A total of 2,463 images were analyzed with investigator-drawn outlines, a colour-to-temperature conversion calibrated against the camera's own spot readout, five-zone face mapping, and a camera-orientation-based assignment of the neck end. The whole-face mean temperature of the medium DuraTherm group was below that of the medium control group at every read (mean difference 2.7 °F; Welch $p < 0.05$ at 30 of 40 reads). DuraTherm faces were less dispersed at every read (mean within-face standard deviation 3.8 vs. 5.2 °F; $p < 10^{-9}$ across packs), although the share of the face within ± 2.5 °F of its coldest part did not differ while faces were below 51 °F. Median time below 40 °F, counted from freezer removal to the last scan below the limit, was 4.8 h for DuraTherm versus 3.5 h for controls and below 45 °F 6.3 vs. 5.5 h (both significant); below 51 °F it was 8.3 vs. 8.0 h (not significant). By 5:00 a.m., 14 of 27 controls had reached the 70 °F end criterion and no DuraTherm unit had. The coldest part of the face was nearly identical in both groups, so the advantage arose from suppression of warm regions, consistent with the mass-distribution mechanism proposed for the architecture. The small format did not show the same advantage: small DuraTherm units ran warmer than small controls after about 3.5 h while remaining more uniform. The neck end was the warmest zone in both groups.

The paper separates four layers of evidence: foundational published science; DuraTherm prototype observations and the October 2026 test; engineering interpretation connecting the two; and proposed extensions that still require validation. It also corrects earlier statements that the new measurements do not support, and incorporates approved sections on dermal and open-wound safety, borate chemistry, fluid retention, final-mile hydration, cold-injury handling, end of life, and add-on extensions.

Keywords: fiber-reinforced ice; pykrete; cotton sliver; cellulose–water interaction; cold pack; phase-change refrigerant; infrared thermography; surface-temperature uniformity; cold chain; freeze expansion.

Key Scientific Findings

- Ice behavior depends strongly on temperature, strain rate, grain structure, flaws, and specimen geometry; single strength values are incomplete without test conditions.
- Fiber reinforcement primarily addresses fracture and post-crack integrity through bridging, pull-out, debonding, crack deflection, and distributed load transfer. Published cotton-ice research supports cotton as a legitimate ice reinforcement from quasi-static to impact strain rates.
- Long-fiber sliver is a distinct architecture from sawdust or pulp: overlapping centimeter-scale staple-fiber networks can create pack-scale continuity and hydraulic pathways. Cellulose holds free, freezing-bound, and nonfreezing-bound water, so thermal storage depends on both water quantity and its interaction with the fiber network.
- Freeze expansion (about 9% by volume for unconstrained water) is a packaging constraint. Measured conventional controls carry substantial headspace (about 25% of internal volume in the medium FreezPAK and 19% in the small); the cotton and water of a DuraTherm unit fit within that headspace.
- In the October 2026 infrared comparison, medium DuraTherm units were colder on average than medium gel controls at all 40 reads, had lower within-face dispersion at all 40 reads, and stayed below 40 and 45 °F significantly longer (median 4.8 vs. 3.5 h and 6.3 vs. 5.5 h); none reached 70 °F within the 14-hour test, versus 14 of 27 controls. By the stricter cold-anchored criterion, uniformity did not differ while faces were below 51 °F.
- The DuraTherm advantage came from warm regions being less warm, not from a colder coldest point: the coldest 10% of the face averaged 42.7 °F (DuraTherm) and 42.9 °F (control), while the 99th-percentile temperature was 3.1 °F lower in DuraTherm.
- The small format (4 DuraTherm vs. 6 controls) did not reproduce the medium result: small DuraTherm units became warmer than small controls after about 3.5 h, while remaining more uniform. The large format (n = 1 per type) favored DuraTherm at every read but is descriptive only.
- The neck end of the shell was the warmest zone in both groups (DuraTherm +8.9 °F and controls +8.1 °F above the center zone on average), identifying the shell's neck and shoulder cavities as a common thermal weak point.
- Measured surface temperature depended strongly on handling history: a face just turned up from the insulation read about 5 °F colder than the same face a few minutes later, in both pack types, so imaging intervals must be standardized.
- Repeated localized-hole and inversion testing has shown no coolant discharge under the conditions tested; expressing liquid from a thawed unit through its open port required sustained compression of about 22–44 N and released only a few grams.
- Dry shipment and final-mile hydration remove most of the eventual water mass from long-haul freight; the planning model places about 110,000 dry DuraTherm units in a 40-ft container versus 47,880 conventional 0.9-lb gel packs.

Revision Notes

This edition supersedes the September 2026 edition. The principal changes are:

- Part III is new. It reports the October 3–4, 2026 comparative infrared test: test articles and conditioning, procedure, image-analysis method and margin of error, bulge measurements (pending), temperature analysis, special comments, and limitations. Per-read statistics are in Appendix E.
- The earlier statement that DuraTherm reduces condensation because it operates at a warmer surface temperature is withdrawn; the new measurements show DuraTherm faces were colder on average (Section 15).
- The bulging claim is qualified for the current batch to a difference in the form of bulging; numerical bulge results are pending (Sections 10.3 and 24).
- The small format did not show the medium-format temperature advantage (Section 25.8), and the neck end of the shell is the warmest zone in both pack types (Section 25.5). The surface-uniformity result is reported under both dispersion-based and cold-anchored criteria (Section 25.4).
- Composition, masses, and volumetric accounting are updated to the 115-ball medium standard (Table 1; Sections 10.2, 13.4, and 18.1).
- New sections cover fiber mobility during manufacture (Section 19), dermal and open-wound safety (Section 31), cold injury (Section 32), closure and fill port (Section 34), extensions to the base pack (Section 39), and end of life (Section 40). The final-mile hydration process (Section 18.2), fill-port retention (Section 14), freeze time (Section 13.5), borate antimicrobial (Section 30), and borate-compatible restraints (Section 37) are expanded.
- Parts and sections are renumbered: Part III of the previous edition is now Part IV, and Part IV is now Part V.
- The FDA establishment registration fee is updated to fiscal year 2027 (Section 46).

Contents

Part I — Scientific Foundation.....	7
1. Scope, Terminology, and Evidence Hierarchy.....	7
2. Water and Ice as the Matrix Phase.....	7
3. Cellulose and Cotton as the Reinforcement Phase.....	8
4. Composite Formation During Freezing.....	10
5. Mechanical Behavior of Fiber-Ice Composites.....	11
6. Thermal and Phase-Change Behavior.....	14
7. Porous-Media Transport and Long-Fiber Water Distribution.....	17
8. Enclosure and Pack Geometry.....	18
Part II — DuraTherm: Architecture and Prototype Findings.....	20
9. DuraTherm Long-Fiber Refrigerant Architecture.....	20
10. Reduced Bulging and Geometric Stability.....	21
11. Surface-Temperature Uniformity.....	23
12. Useful Cooling Duration and Temperature-Time Behavior.....	23
13. Pack-Level Thermal Capacity and Useful Cooling Performance.....	24
14. Localized Damage, Penetration, and Coolant Retention.....	26
15. Condensation and Surface Sweating.....	27
16. Large-Format Scaling.....	27
17. Internal Thermal-Conduit Architecture — Harrington Thesis.....	27
18. Dry Shipping and Final-Mile Hydration.....	28
19. Fiber Mobility During Manufacture and Hydration.....	29
Part III — The October 2026 Comparative Infrared Test.....	31
20. Objectives, Hypotheses, and Design.....	31
21. Test Articles and Pre-Test Conditioning.....	31
22. Test Environment and Procedure.....	33
23. Infrared Thermography and Image Analysis.....	34
24. Bulge Measurements.....	37
25. Temperature Analysis.....	37
26. Special Comments.....	44
27. Limitations and Threats to Validity.....	47
28. Summary of the October 2026 Test.....	47
Part IV — Extended Science, Engineering, and Research.....	49
29. Freeze-Thaw Durability and Aging.....	49
30. Microbiology, Water Quality, and Antimicrobial Considerations.....	50
31. Regulatory and Safety Considerations: Potential Dermal or Open-Wound Contact.....	50
32. Cold Injury and Conditioning Before Use.....	52
33. Shell Materials and Thermal Resistance.....	53
34. Closure and Fill Port.....	53
35. Material Substitution and Supply Resilience.....	54
36. Manufacturing the Long-Fiber Architecture.....	54
37. Temporary Water-Soluble Fiber Restraint.....	54
38. Composition Variability, Product Grading, and Material-Yield Efficiency.....	55
39. Extensions and Modifications to the Base Pack.....	55
40. End of Life.....	56

41. Experimental Methods, Standardized Testing, and Cold-Chain Qualification.....57

42. Remaining Research Questions and Validation Priorities.....58

Part V — Deployment and Business-Relevant Engineering..... 60

43. Material Purchasing and Production Inputs.....60

44. Emergency, Strategic, and Military Stockpiling.....60

45. Application and Deployment Classes.....61

46. FDA Classification and Regulatory Pathway.....61

47. Translation from Research to Commercial Qualification.....62

Appendices..... 63

Appendix A. Evidence Matrix: Fiber–Ice and Related Material Systems.....63

Appendix B. DuraTherm Prototype Data.....63

Appendix C. Comparative Geometry and Scaling.....65

Appendix D. Proposed Test Protocols.....65

Appendix E. October 2026 Test: Per-Read Statistics and Data Record.....67

References.....72

PART I

SCIENTIFIC FOUNDATION

1. Scope, Terminology, and Evidence Hierarchy

The term fiber–ice composite is used here broadly for a frozen water matrix containing discrete or connected fibers, fibrils, fibrous particles, or porous cellulose architectures. “Pykrete” historically refers to ice reinforced with wood pulp or sawdust, but the scientific design space now includes cotton, paper fiber, nanocellulose, long natural fibers, synthetic fibers, hybrid polymer–fiber systems, and water-rich gels. The physical mechanisms overlap but are not interchangeable.

Three evidence classes are kept separate throughout this paper. Class I comprises measurements reported in peer-reviewed or authoritative primary sources. Class II comprises cross-study synthesis grounded in well-established thermodynamics, heat transfer, porous-media transport, and composite mechanics. Class III comprises DuraTherm-specific hypotheses and prototype observations. Class III statements identify what is scientifically plausible or what has been observed in prototypes; they do not imply that standardized validation has already been completed. The controlled comparison of October 2026 (Part III) is DuraTherm-specific and has not yet been replicated or peer reviewed; it is reported as Class III evidence, distinguished from informal prototype observation by its stated protocol, sample sizes, statistical treatment, and uncertainty analysis.

A central methodological caution is that fiber–ice studies use different specimen sizes, freeze histories, fiber contents, fiber measures (mass fraction, volume fraction, or mass per volume), temperatures, loading directions, and strain rates. Direct numerical ranking across papers can therefore be misleading. Multipliers relative to each study’s own plain-ice control are often more transferable than absolute strength values.

2. Water and Ice as the Matrix Phase

2.1 Phase change and energy storage

The refrigerant value of water comes primarily from its large latent heat of fusion. At atmospheric pressure near the melting point, the latent heat of fusion is approximately 333.5 J/g. During warming from a freezer set point to 0 °C, the frozen pack first absorbs sensible heat; during melting it then absorbs latent heat at nearly constant phase-change temperature; after complete melting, the liquid absorbs additional sensible heat.

$$Q_{\text{useful}} \approx m_{\text{ice}} c_{p,\text{ice}} \Delta T_{\text{ice}} + m_{\text{freezable water}} L_f + m_{\text{liquid}} c_{p,\text{water}} \Delta T_{\text{water}} \quad (1)$$

For a fiber–ice composite without an additional phase-change material, the latent term scales primarily with the mass of freezable water. Dry cellulose contributes sensible heat but does not contribute water’s fusion enthalpy. Bound or strongly confined water may freeze differently or remain nonfreezable, particularly in nanocellulose and hydrogel systems; native cotton sliver is expected to retain a much larger fraction of bulk-like free water than densely crosslinked gels, but that expectation must be confirmed by DSC.

2.2 Density change and freeze expansion

Water is unusual because its stable ordinary ice phase is less dense than the liquid. Near the melting point, representative densities of approximately 0.9998 g/mL for liquid water and 0.9167 g/mL for ice imply an unconstrained liquid-to-solid volume increase of about 9.07%. The approximately 9% value refers to water-phase volumetric expansion; the external dimensional response of a fiber-ice composite or finished pack can be much smaller because internal redistribution, compressible void volume, fiber compaction, and enclosure compliance accommodate part of that change.

$$\Delta V/V_{\text{liquid}} = \rho_{\text{liquid}}/\rho_{\text{ice}} - 1 \approx 0.091 \quad (2)$$

This is the thermodynamic volume requirement for unconstrained bulk water. It is not identical to the visible thickness increase of a cold pack. A pack can accommodate some expansion by consuming headspace or pores, compressing a porous fiber skeleton, redistributing still-liquid water ahead of the freeze front, flexing the shell, or compressing trapped gas. Conversely, a locally sealed water pocket can generate high hydrostatic stress as freezing progresses.

2.3 Mechanical baseline of unreinforced ice

Petrovic's review places freshwater-ice tensile strength at approximately 0.7–3.1 MPa and compressive strength at roughly 5–25 MPa over –10 to –20 °C, with fracture toughness only about 50–150 kPa√m. The elastic modulus is of order 10 GPa. These figures immediately explain why unreinforced frozen water is vulnerable to cracks and impact even when its compressive strength appears respectable: fracture toughness and tensile capacity are comparatively poor.

Compression is strongly temperature and strain-rate dependent. Lower temperatures and faster loading generally increase apparent compressive strength, while the ductile-to-brittle transition itself shifts with temperature. Tensile behavior is less rate-sensitive but strongly influenced by grain size, flaws, porosity, and specimen volume. Ice is therefore not a single-property material; it is a time-temperature-microstructure-dependent matrix.

3. Cellulose and Cotton as the Reinforcement Phase

3.1 Molecular water affinity

Cellulose is a linear β(1–4)-linked glucan rich in hydroxyl groups. It interacts strongly with water while remaining insoluble. Water penetrates less ordered regions, changes hydrogen-bonding relationships, causes swelling, plasticizes interfaces, and strongly affects fiber-fiber and fiber-matrix interactions. These behaviors are central to a water-filled composite because the reinforcement is not simply an inert inclusion: it is a hydrophilic porous phase coupled to the water matrix.

Cotton is unusually cellulose-rich and retains a hierarchical structure from macrofiber to fibrils. Cotton Incorporated describes a longitudinal lumen and a fibrillar wall structure in which capillary action pulls liquid inward and holds liquid in pores between fibrils. At the pack scale, additional capillary pathways exist between adjacent fibers. The result is two nested porous systems: intrafiber/fibrillar sorption and interfiber capillary transport.

3.2 Staple length, aspect ratio, and sliver continuity

A crucial distinction for DuraTherm is between individual fiber length and network continuity. CottonWorks defines sliver as a rope-like strand of loose fibers with very little twist formed from a carded web. Current U.S. upland cotton averages approximately 1.1–1.2 inches in upper-half mean length, while

Cotton Incorporated classifies 1.11–1.26 inches as “long.” Individual fibers therefore do not normally span an entire cold pack. Instead, thousands of overlapping, entangled staple fibers create a macroscopically continuous assembly.

A typical cotton fiber diameter of a few tens of micrometers combined with a ~28–30 mm staple length gives an individual aspect ratio on the order of 10^3 . High aspect ratio increases the probability of mechanical entanglement, interfacial contact, crack interception, and formation of long hydraulic pathways. Sliver additionally preserves fiber-to-fiber cohesion through convolutions, friction, hooks, and overlapping geometry even with minimal twist.

This architecture differs from sawdust and rice-husk Pykrete, where reinforcing units are shorter, thicker, more particulate, and more prone to gravity-driven segregation. It also differs from CNF gels, where fibrils are nanoscale and the percolated network derives from colloidal interactions. DuraTherm occupies an intermediate and comparatively under-studied regime: a centimeter-scale or larger staple-fiber network creating pack-scale connectivity without chemical crosslinking.

3.3 Cotton mechanical properties and low-temperature suitability

Cotton bundle strength in current U.S. classing data is commonly around 30 g/tex, and cotton’s dry/wet behavior differs from many regenerated cellulose: cotton generally becomes stronger when wet. Cotton is not thermoplastic and does not undergo the low-temperature glass transition that embrittles many synthetic polymers. For frozen aqueous use, this means the reinforcement can remain flexible and pull-out-capable even when the surrounding ice matrix is brittle.

The useful reinforcement variable is not simply intrinsic cotton tensile strength. Composite performance depends on whether fibers are wetted, frozen into the matrix, mechanically anchored, oriented across likely crack planes, sufficiently long to develop pull-out resistance, and sufficiently dispersed to avoid dry fiber bundles or large voids. An entangled sliver may therefore outperform the same mass of poorly distributed cotton even if the individual fibers are identical.

3.4 States of water in cellulose: free, freezing-bound, and nonfreezing-bound

A fiber/ice refrigerant cannot be treated thermodynamically as dry cellulose plus perfectly bulk-like water. Differential scanning calorimetry has shown for decades that water associated with cellulose separates into at least three populations. Nakamura, Hatakeyama, and Hatakeyama (1981) observed bulk-like free water, freezing-bound water with depressed crystallization/melting behavior, and nonfreezing-bound water in cotton, linen, jute, rayon, kapok, and wood cellulose.

The molecular origin is straightforward. Hydroxyl-rich cellulose surfaces hydrogen-bond to adjacent water, while nanometer-scale confinement in fibrils and pores restricts molecular rearrangement needed to form ordinary hexagonal ice. The first few hydration layers can therefore remain nonfreezing, while water in somewhat larger pores freezes at temperatures below the bulk melting point. Water in larger interfiber voids behaves increasingly like ordinary water.

For natural cotton, published thermal-analysis work has reported maximum bound-water quantities of approximately 0.16 g water per gram of dry cotton under the studied conditions. This value should not be imported as a universal DuraTherm constant: cotton finishing, packing density, temperature history, fiber accessibility, and saturation state all matter. It nevertheless establishes that a measurable fraction of nominal pack water can have phase behavior different from bulk water.

This distinction sharpens the DuraTherm design tradeoff. Increasing fiber loading does more than replace water mass with solid cellulose. It also increases cellulose surface area and the amount of interfacially

constrained water. Consequently, the decrease in effective latent heat can be slightly steeper than the simple water-mass dilution line. Differential scanning calorimetry on the actual DuraTherm cotton and hemp formulations is therefore essential.

3.5 Fiber-length hierarchy and why long fiber is a separate design regime

The literature frequently uses the single word “fiber” for reinforcement scales that differ by orders of magnitude. Cellulose nanofibers are nanoscale in diameter; defibered wood pulp is typically millimeter-scale; ordinary upland cotton staples are centimeter-scale; and a cotton sliver is a pack-scale assembly whose continuity comes from overlap and entanglement rather than from one fiber spanning the entire device.

These scales change both mechanics and transport. Shorter, finer fibers maximize surface area per unit mass and can increase heterogeneous nucleation and interfacial friction. Longer fibers increase bridging length, topological entanglement, and resistance to gross redistribution. A sliver can therefore remain macroscopically connected after individual ice domains crack or after portions of the composite thaw.

Long fiber is not automatically superior. Excessive alignment can produce anisotropy; dense bundles can trap air or resist complete hydration; very high fiber fractions reduce latent heat; and insufficient transverse connectivity can create preferential channels. The scientific advantage is not simply “longer is better,” but that long-fiber topology provides a different control variable unavailable to particulate Pykrete.

4. Composite Formation During Freezing

4.1 Freeze-front interaction with insoluble fibers

As water freezes, the advancing ice front interacts with insoluble fibers, dissolved impurities, bubbles, and pre-existing interfaces. Depending on particle size, interface energy, front velocity, and thermal gradient, inclusions can be engulfed, rejected, or concentrated between grains. Fiber networks can simultaneously nucleate ice, constrain crystal growth, and become incorporated within grain interiors or grain boundaries.

The 2026 Materialia study of cellulose nanofibers provides unusually direct microscopy evidence: CNFs distributed through grain interiors, bridged grain boundaries, and formed a percolated network that remained intact as ice formed around it. CNFs also modified crystallographic fabric and inhibited grain growth. Although native cotton staples are orders of magnitude larger, the study establishes the key principle that a cellulose network can survive the liquid-to-solid transition as a continuous second phase rather than being destroyed by freezing.

4.2 Grain refinement, interfacial area, and crack path complexity

A fiber network creates a high density of ice–cellulose interfaces. These interfaces can act as heterogeneous nucleation sites and alter grain size, but they also introduce potential debonding planes. Whether an interface strengthens or weakens the composite depends on interfacial adhesion, local porosity, fiber orientation, and the energy required for a propagating crack to cross, deflect around, debond from, or pull a fiber out of the matrix.

Smaller fibers provide greater interfacial area per unit mass. Nixon and Smith’s wood–ice fracture study found the highest toughness at a given reinforcement mass for the smallest-diameter fibers, consistent

with energy dissipation through pull-out and debonding. For DuraTherm, long cotton combines small diameter with large length, potentially producing both large interfacial area and long pull-out lengths.

4.3 Air and porosity

Entrained gas is mechanically harmful but can be dimensionally useful. The CNF microstructure work notes that even ~1–2% entrapped air can materially reduce ice strength depending on loading mode. Air pores serve as stress concentrators and reduce effective load-bearing area. In a refrigerant pack, however, deliberately retained compressible void volume can absorb part of the ~9% freezing expansion. The design optimum therefore differs from structural ice, where void minimization is normally desirable. Measured conventional controls confirm that retained void volume is substantial in commercial packs: the medium FreezPAK contains about 122.5 ml of air (about 25% of internal volume) against a calculated freeze expansion of about 34 ml for its gel charge, and the small about 46.0 ml (19%) against about 18 ml, assuming approximately water-like expansion.

For long-fiber packs, porosity exists on multiple scales: lumen/fibrillar pores within cotton, capillary pores among fibers, larger inter-bundle voids, trapped gas, and any intentional headspace. The freezing behavior and bulge response depend on the distribution of those volumes, not merely on total porosity. Micro-CT or destructive sectioning should be used to quantify them.

5. Mechanical Behavior of Fiber-Ice Composites

5.1 Fracture toughness and the fundamental toughening mechanisms

Fracture toughness is arguably more important than peak strength for a handled refrigerant pack. A pack can survive with internally cracked ice if the frozen mass remains coherent and does not create concentrated shell loads. The foundational Nixon–Smith results show why fibers are powerful: adding only 5–20 wt% wood-based reinforcement increased measured K_{IC} by approximately 500–2000%, reaching 0.69–1.92 MPa√m versus roughly 0.05–0.15 MPa√m for ordinary ice.

The proposed energy-dissipation mechanisms—fiber pull-out and interfacial debonding—remain central to modern studies. A crack approaching a fiber must either fracture the fiber, debond its interface, pull it out, or deflect around it. Each process consumes energy and reduces the crack-tip driving force. Long fibers increase the available embedded length and therefore the potential pull-out work, provided the bond is neither so weak that the fiber slips freely nor so strong that brittle fiber rupture dominates.

$$G_{\text{composite}} \approx G_{\text{ice}} + G_{\text{debond}} + G_{\text{pull-out}} + G_{\text{crack deflection}} + G_{\text{friction}} + G_{\text{distributed damage}} \quad (3)$$

This framework explains why a “cracked but intact” fiber–ice mass can be functionally superior to stronger but brittle plain ice. For a cold pack, post-crack integrity reduces fragment mobility, local point loading, and abrupt redistribution of water/ice during thaw.

5.2 Compression

Compression is the most extensively studied loading mode. Pulp-fiber studies report compressive strength several times that of plain ice under comparable conditions, with greatly increased peak strain and post-peak ductility. The 2026 CNF study increased compression from 2.6 to 7.2 MPa with only 1 wt% CNF. The 2026 PVA/flax hybrid reached 8.1 MPa, 3.5× the study’s pure-ice control. Sisal/pulp hybrids increased compression by 76.2% and broadened the stable plastic deformation window.

The common stress–strain transformation is from a steep rise followed by abrupt loss of capacity to a response with yielding, plateau behavior, and gradual softening. Mechanistically, fibers bridge shear

bands and cracks, carry load after matrix fracture, redistribute stress, and dissipate energy through pull-out and friction.

5.3 Cotton-specific compression from quasi-static to impact rates

Cotton-specific evidence spans more than seven orders of magnitude in strain rate. Huang's 2016 study tested 0, 3, 6, 9, and 12 wt% cotton between 10^{-3} and 10^{-1} s^{-1} . Cotton increased compressive strength and toughness, but at 10^{-3} s^{-1} strength began to decline once cotton exceeded 6 wt%; at 10^{-1} s^{-1} strength increased with cotton content. The optimum therefore shifted with rate.

Nie, Ma, and Li (2023) tested 0, 3, 6, and 12 wt% medical absorbent cotton at 10^{-4} , 10^{-3} , and 10^{-2} s^{-1} . Plain transparent ice transitioned from ductile to brittle behavior around 10^{-3} s^{-1} . Cotton increased compressive yield strength and produced the visually important “cracking but not breaking” failure mode. The study further analyzed critical strain-energy density and showed that cotton alters how input work is partitioned into fracture and plastic deformation.

Huang and Kang's dynamic hail-simulation study extended cotton reinforcement to $300\text{--}4000 \text{ s}^{-1}$ using a split-Hopkinson pressure bar. With 0–12 wt% cotton, compressive strength rose with both strain rate and cotton content. Reinforced specimens displayed linear-elastic, yield-softening, and plateau regimes instead of simple catastrophic collapse, with increased toughness and ductility. This is the closest available literature analogue to high-rate impact resistance in a cotton-ice composite.

These dynamic tests should not be translated directly into a “drop rating” for a refrigerant pack. A falling pack experiences shell bending, contact stress, fluid–solid interaction, geometry-dependent acceleration, and often repeated lower-energy impacts. Nevertheless, the cotton studies establish a strong material-level basis for expecting improved fragmentation resistance and post-crack cohesion.

5.4 Tension

Ice is weakest in tension, so tensile crack suppression is central to durability. Lou and Wu tested pulp-fiber-reinforced ice by splitting tension across 0–6% fiber, -20 to -5°C , and loading rates from 0.33 to 10 mm/min. Fiber reinforcement changed brittle failure to ductile failure and produced tensile strength approximately $2\text{--}3.5\times$ that of plain ice. Strength increased as temperature fell, loading rate increased, and fiber content increased within the tested range.

For long cotton sliver, the most relevant mechanism is fiber bridging across a crack plane. The efficiency depends strongly on orientation: fibers nearly perpendicular to the crack plane provide stronger bridges; fibers parallel to it contribute less direct opening resistance. A sliver with preferential axial alignment can therefore be mechanically anisotropic even if the pack appears macroscopically homogeneous.

5.5 Shear

Direct-shear tests on bleached sulfate softwood pulp FRI show one of the largest reinforcement effects in the literature. At 6% fiber, shear strength was reported approximately $3.8\text{--}5.9\times$ plain ice and peak deformation roughly $2\text{--}3\times$, depending on temperature. Lowering temperature from -5 to -20°C increased shear strength by about $2\text{--}2.5\times$. Fibers also increased post-peak bearing and energy absorption.

Shear behavior matters to packs because frozen slabs experience internal shear during bending, handling, twisting, and differential shell deformation. A long-fiber network that resists sliding between cracked ice domains should reduce internal fragmentation even when the pack is not designed to bear structural loads.

5.6 Flexure and post-crack behavior

Three-point bending tests with long pine-needle reinforcement demonstrate deflection hardening and multiple cracking—behavior qualitatively similar to fiber-reinforced cementitious composites. Ultimate flexural strength reached roughly twice plain ice at an optimum fiber content of 56 g/dm³, but performance fell at 78 g/dm³. The authors attributed the decline to insufficient ice matrix surrounding the excessive fiber content and degraded bond/load transfer.

The CNF study similarly showed strong flexural gains: 1 wt% CNF increased 3-point flexural strength from 3.1 to 5.8 MPa and 4-point flexural strength from 1.7 to 3.8 MPa, while apparent toughness rose 2–10×. The different absolute values between test geometries illustrate why method must accompany every reported strength number.

5.7 Fiber fraction is a multi-objective optimization variable

No universal optimum fiber percentage exists. Structural pine-fiber ice peaked at 56 kg/m³ in one bending/compression program. Cotton compression at low strain rate showed declining strength above about 6 wt%, while dynamic cotton performance continued improving through 12 wt%. Sisal/pulp hybrids identified 3 vol% as an optimum balancing strength, energy, and material use. Delgado's cold-chain study selected 14 wt% cellulose because thermal/cooling behavior and physical integrity—not structural peak strength—were the objective.

This is one of the most important conclusions for DuraTherm. Its optimum must be established against a weighted objective function containing at least latent heat, surface-temperature uniformity, dimensional stability, hydration behavior, freeze time, impact survivability, flexural handling, manufacturing repeatability, and cost. The fiber fraction that maximizes compressive strength may be inferior as a refrigerant formulation.

5.8 Direct tension, hybrid fibers, and rate-dependent optimization

The 2023 direct-tension study of plain ice and pulp-fiber-reinforced ice filled an important gap left by splitting tests. Across 0–6% pulp and –20 to –5 °C, increasing fiber content increased peak tensile strength and peak strain while decreasing elastic modulus. Lower temperature increased peak strength, peak strain, and modulus. This combination—greater ultimate resistance but lower stiffness with added fiber—is characteristic of a matrix becoming less brittle and more damage-tolerant.

Polypropylene and basalt fibers provide an instructive control because they are not cellulose. In approximately 200 specimens tested at –10 °C with 0–8% fiber, both fiber types improved tensile/compressive behavior and transformed brittle failure toward ductile behavior. This demonstrates that some mechanical benefits arise from generic fiber bridging and pull-out rather than from cellulose chemistry alone.

Conversely, natural-fiber hybrid studies show that fiber chemistry and surface morphology still matter. The 2026 sisal/pulp study reported a 76.2% compressive-strength gain relative to plain ice in the highlighted hybrid system and microscopy evidence of thorn-like interlocking, crack bridging, and pull-out dissipation. A 3% volume fraction was judged an optimum considering strength, energy, and material consumption.

The engineering implication is that DuraTherm should not inherit an optimum fiber percentage from any structural paper. Mechanical optimum varies with strain rate, temperature, fiber geometry, and test mode; thermal optimum additionally depends on water fraction and heat-transfer requirements. The product must be optimized in the multidimensional space relevant to its actual use.

6. Thermal and Phase-Change Behavior

6.1 Latent heat and the water-fraction ceiling

For a water-dominant refrigerant, latent heat is constrained by the mass of water that actually freezes. Under a fixed-total-composite-mass assumption, an idealized upper bound can be written by treating all non-fiber internal mass as pure freezable water and neglecting the shell. This is a conditional thermodynamic comparison, not a direct model of the standard DuraTherm pack, whose fiber mass, water loading, enclosure volume, and final pack mass are selected together.

$$L_{\text{composite,max}} \approx (1 - w_{\text{fiber}}) \times 333.55 \text{ J/g} \quad (4)$$

Under that fixed-mass assumption, 14 wt% dry fiber gives a theoretical ceiling of about 286.9 J/g composite before accounting for bound or nonfreezable water. The calculation remains useful for constrained-volume or high-fiber regimes in which added fiber actually displaces freezable water. It should not be interpreted to mean that standard DuraTherm necessarily loses pack-level water capacity in direct proportion to fiber mass.

6.2 Thermal conductivity and diffusivity

Pulp- and CNF-reinforced ice generally exhibits lower thermal conductivity than pure ice. Asenath-Smith et al. measured up to ~10% conductivity reduction with 0.1–1 wt% CNF. Zhang et al. found pulp-fiber composite ice had lower conductivity and heat-storage coefficient than pure ice, with conductivity decreasing as fiber content rose, while specific heat remained close to that of pure ice.

Lower conductivity is not unconditionally beneficial. It slows heat penetration into a frozen body, which can prolong the persistence of an icy core under some boundary conditions, but it can also slow freezing and reduce the rate at which internal latent capacity is accessed. Refrigerant performance therefore depends on geometry and external convection as well as intrinsic material properties. A thin flat pack may remain conduction-efficient even with modest k reduction; a thick pack may develop larger internal gradients.

The characteristic diffusion time is

$$t_{\text{diff}} \sim L^2/\alpha, \text{ where } \alpha = k/(\rho c_p) \quad (5)$$

The square dependence on characteristic thickness L is especially important. Doubling pack thickness roughly quadruples internal diffusion time if material diffusivity is unchanged. Consequently, DuraTherm's low-bulge/controlled-thickness behavior could have thermal significance independent of fiber chemistry: predictable thickness produces predictable diffusion distance.

6.3 Melt resistance

The 2025 CNF study demonstrated a striking ~10× reduction in melt rate at only 1 wt% CNF under the study's radiative/thermal conditions. Two mechanisms were identified: reflectance at 640 nm increased from about 20% to 70%, reducing absorbed radiation, and thermal conductivity fell by up to ~10%. CNFs also facilitated freezing without statistically changing specific heat.

Only the conductivity/microstructure part transfers directly to an opaque packaged refrigerant. If the composite is enclosed inside pigmented HDPE or another opaque shell, the shell largely controls optical absorption, so the CNF reflectance mechanism cannot be credited to the internal fiber phase. This illustrates why exposed-ice melt experiments must be decomposed mechanistically before applying them to a pack.

6.4 Surface-temperature uniformity versus energy capacity

A cold pack can have high total latent heat yet poor local temperature uniformity if water, ice, and internal air space are unevenly distributed. Conventional gels and underfilled water packs can develop thick frozen regions adjacent to thin or air-filled regions; as thaw progresses, mobile liquid can pool under gravity while remaining ice migrates or floats. In DuraTherm comparative testing, conventional control packs exhibited warmer regions associated with underfilled areas and internal air pockets, consistent with the view that total thermal capacity alone does not ensure uniform surface temperature. Local shell temperature reflects both the amount and distribution of phase-change material beneath that location and the local thermal resistance.

A distributed fiber network can plausibly improve uniformity through mass stabilization: capillary and mechanical retention resist centimeter-scale water migration, while the network subdivides the internal volume and supports a more persistent spatial distribution of ice and meltwater. This mechanism does not require the network to have high conductivity. Indeed, uniformity can improve even if effective k decreases, because spatial variation in phase fraction and thickness is reduced. This is a central hypothesis for DuraTherm. The October 2026 infrared comparison supports its surface-temperature consequence for the medium format: within-face dispersion was lower in DuraTherm units at every read, and the advantage came from smaller warm regions rather than from a colder core (Sections 25.3 and 25.4). By a stricter cold-anchored criterion the groups did not differ within the useful range, and the small format did not show the temperature advantage (Section 25.8). The internal mechanism itself still requires confirmation by internal imaging or frozen cross-section.

6.5 Cold-chain evidence

Delgado et al. provides one of the closest classical Pykrete studies directed toward cold-chain use. The work evaluated uncased, exposed fiber-ice composites made from water and cellulosic organic waste, including sawdust, whole rice husk, and ground rice husk, at 5, 14, and 20 wt% cellulosic material. The authors identified 14 wt% as the most useful concentration among the tested mixtures: the 20% formulations were excessively dry, while 5% behaved more like plain water. The exposed specimens were evaluated during ambient thermal exposure for melt behavior, structural degradation, and retention of the water matrix. Ground rice husk at 14 wt% provided the strongest balance for retarding melt and maintaining composite cohesion. This work is an important baseline for cellulose-ice refrigeration, but it differs materially from DuraTherm because the Delgado specimens were uncased and used short particulate or fragmented cellulose rather than a sealed enclosure containing a pack-spanning long-staple network.

Firdaus et al. similarly found Pykrete provided longer cooling duration than ordinary ice but with poorer cooling stability when tested as an exposed bulk sample. These results confirm that cellulose-ice composites can function as refrigerants but do not resolve the pack-level questions of sealed geometry, flatness, local surface uniformity, controlled hydration, or long-fiber architecture.

6.6 Fiber loading as a thermal-regulation variable

Under a fixed-total-composite-mass constraint, the simplest thermal effect of increasing fiber fraction is dilution: a larger dry-fiber fraction leaves a smaller fraction available as water. If every remaining gram of water were bulk-like and fully freezable, the upper-bound latent heat per gram of composite would be $L_{\max} \approx (1 - w_f)L_{\text{water}}$, where w_f is the dry-fiber mass fraction. This relationship applies to the stated constraint; it is not an assumption that every gram of cotton in a standard DuraTherm pack must replace one gram of intended water loading.

Cellulose-water physics adds a second-order correction because some water is freezing-bound or nonfreezing-bound. Using 0.16 g bound water per gram of dry cotton only as an illustrative literature-based sensitivity — not as a DuraTherm measurement — produces an estimated 14 wt% fixed-mass composite latent-heat ceiling near 279.4 J/g rather than the simple-dilution value of about 286.9 J/g. DSC on the actual formulation is required to replace this estimate.

A lower latent heat per gram does not necessarily mean shorter useful time within a selected temperature band. Fiber can also reduce effective thermal conductivity, broaden or redistribute the phase-change zone, inhibit large-scale liquid convection, and alter how heat reaches the melt front. Useful dwell time is therefore governed by both stored energy and heat-transfer rate.

This distinction supports two design regimes. In the standard DuraTherm regime, fiber structures and distributes the water while pack geometry and fill are selected to maintain the intended pack-level water and thermal capacity. In a constrained-volume or high-fiber regime, fiber eventually occupies enough volume that less water fits, and the theoretical latent-energy penalty becomes directly relevant. The resulting temperature band and duration must be measured at the finished-pack level.

6.7 Enclosure effects: why a sealed pack is thermally different from an exposed fiber-ice block

An exposed Pykrete block and a sealed DuraTherm pack are not the same heat-transfer experiment. An exposed block receives heat by external convection, radiation, and direct contact at the composite surface. A packaged system inserts one or more shell layers between environment and composite, so heat must cross external convection/contact resistance, shell conduction resistance, the internal shell-composite interface, and finally the phase-changing porous composite.

The shell can be a weak insulator and still matter because the relevant thermal resistance is cumulative. More importantly, it prevents external air from sweeping directly across newly exposed melting surfaces. Meltwater cannot simply drain away, and large internal liquid movements are constrained by the enclosure and further suppressed by a dense fiber network. These effects change the apparent melt curve and can smooth the temperature response.

Pack geometry introduces scales absent from calorimeter specimens: face area-to-volume ratio, wall thickness, corner radii, seam geometry, contact pressure, orientation, headspace, and whether one or two broad faces dominate heat transfer. Consequently, thermal performance should be reported at pack level using surface-temperature maps, internal phase fraction, heat flux where possible, and payload temperature rather than extrapolated from bulk Pykrete alone.

6.8 Medical, health, biologic, and food temperature windows

DuraTherm's applications span fundamentally different thermal targets. Pharmaceutical and vaccine logistics commonly use validated 2–8 °C cold-chain conditions, while FDA food cold-holding guidance commonly uses 5 °C (41 °F) or below for time/temperature-controlled foods. These are payload requirements, not necessarily refrigerant-surface temperatures.

Clinical cryotherapy introduces an additional distinction between device temperature and tissue temperature. Recent controlled cryocompression research treats approximately 10–15 °C skin temperature as a therapeutic target for knee cooling, and demonstrates that skin can stabilize several degrees warmer than the circulating coolant setting. A pack surface at a given temperature therefore cannot be equated automatically with skin temperature.

For DuraTherm, approximately 34–50 °F (about 1–10 °C) should be treated as a current reference pack-surface/design window, not as an intrinsic or exclusive operating range of the platform. DuraTherm can be engineered for higher temperatures and other target thermal profiles by adjusting formulation, water loading, geometry, enclosure, and heat-transfer design. Clinical interface measurements must establish the temperature actually delivered to skin or deeper tissue, and medical protocols must specify barriers, contact pressure, exposure time, body site, and patient factors. Units used directly from a low-temperature freezer also present a cold-injury hazard; conditioning before skin application is addressed in Section 32.

Health applications such as personal overheating control introduce yet another regime: the objective may be sustained heat extraction without the very low interface temperature used in acute cryotherapy. This is precisely where tunable fiber loading is scientifically attractive: a formulation family can be optimized for distinct thermal power and duration rather than forcing every use case into one PCM.

7. Porous-Media Transport and Long-Fiber Water Distribution

7.1 Capillary infiltration

Hydration of a dry sliver is a porous-media imbibition problem. For an ideal cylindrical capillary, Lucas–Washburn scaling gives penetration distance squared proportional to surface tension, effective pore radius, contact-angle wetting, and time, and inversely proportional to viscosity:

$$x^2 \approx (\gamma r \cos \theta / 2\mu) t \quad (6)$$

Real cotton sliver has a broad, evolving pore-size distribution, tortuosity, fiber swelling, trapped air, and gravity. The equation is therefore not a direct design calculator, but it identifies the variables governing hydration: fiber finish/cleanliness and contact angle; sliver compression and pore radius; water viscosity and temperature; path length; and availability of vent paths for displaced air.

7.2 Saturated redistribution and permeability

Once wet, redistribution can be approximated conceptually by Darcy-type flow: hydraulic flux scales with network permeability and pressure gradient and inversely with liquid viscosity. Freezing changes both permeability and pressure dramatically as ice occludes pores. The liquid fraction becomes confined to progressively narrower channels and regions ahead of the freezing front.

$$q = -(k_{\text{perm}}/\mu) \nabla P \quad (7)$$

For DuraTherm, this implies a potentially useful sequence: before freezing, the network distributes water by capillarity and permeability; during freezing, shrinking liquid pathways may transmit displaced water toward remaining compliant pore/headspace regions; after partial thaw, the network again restrains gravity-driven pooling. The mechanism is physically plausible but has not been directly measured in a sealed long-cotton refrigerant pack.

7.3 Orientation and anisotropy

Textile research confirms that cotton sliver has measurable fiber orientation and that processing changes parallelization, hooks, bulk, and cohesion. A highly parallel sliver is likely to wick and carry tensile load preferentially along its axis. For a flat refrigerant pack, an engineered architecture could exploit or suppress this anisotropy by folding, cross-lapping, serpentine placement, needling, or using multiple sliver directions.

Anisotropy should be treated as a design variable, not a defect. Axial fiber alignment may promote rapid lengthwise water distribution and crack bridging, while transverse connectivity is needed for through-thickness uniformity and resistance to layer separation. The ideal topology for a cold pack may therefore be quasi-three-dimensional rather than perfectly parallel.

Fiber architecture is hypothesized to govern the direction of expansion forces within the pack (Class III). On hydration, cotton fibers swell substantially in diameter but only marginally in length. In a sliver, where fibers are predominantly parallel, hydration-driven expansion is therefore expected to act predominantly radially from the sliver axis, with only a minimal axial component arising from fiber deconvolution and interfiber slippage. Cotton balls, formed by coiling sliver, present continuously varying local fiber orientation; an assembly of randomly oriented balls is therefore expected to exert approximately isotropic expansion pressure. A distinct mechanism applies under mechanical loading: a sliver oriented upright and compressed along its axis stores elastic energy in buckled fibers and may exert an axial restoring force, attempting to recover lost height under high confining pressure. Hydration swelling and compressive elastic recovery should thus be treated as separate contributions to internal pressure. These hypotheses are untested; orientation-controlled placement may provide a means of directing internal expansion forces.

7.4 Capillary retention, Darcy flow, and suppression of internal liquid convection

Wicking and water retention are related but distinct. Capillary pressure scales approximately as $\Delta P = 2\gamma\cos\theta/r$ for a simplified pore, so smaller wettable pores generate stronger capillary suction. The classic Washburn relation predicts penetration distance proportional to the square root of time when gravity and inertia are negligible. Cotton's hierarchical pores therefore promote redistribution into initially dry regions.

Once the network is saturated, bulk liquid movement is better viewed through porous-media permeability. Darcy flow scales with permeability divided by viscosity. Increasing fiber density generally reduces pore size and permeability, so thawed water becomes less able to convect or pool over pack-scale distances. This can matter thermally because free liquid convection can move sensible heat faster than pure conduction.

A long-fiber network may therefore perform two different hydraulic functions over a cycle: capillary forces help distribute water during filling or rehydration, while reduced permeability and entanglement oppose gross redistribution after saturation and during thaw. The balance depends on compression, orientation, wetting history, fiber treatment, and void fraction. It should be measured directly rather than described simply as absorbency.

8. Enclosure and Pack Geometry

A finished refrigerant pack is not thermally equivalent to an exposed laboratory block. The shell adds thermal resistance, controls contact area, constrains expansion, and determines how internal redistribution becomes external thickness variation. Geometry therefore belongs in the scientific model rather than being treated as packaging decoration.

8.1 Surface area, volume, and thickness

For geometrically similar objects, volume grows with the cube of characteristic length while surface area grows with its square; surface-area-to-volume ratio therefore decreases as size increases. Thermal diffusion time through a homogeneous layer scales approximately with the square of characteristic

thickness. This makes thickness a particularly expensive way to add capacity when the design objective is rapid and spatially uniform access to stored thermal energy.

8.2 Headspace, shell compliance, and freeze expansion

Near 0 °C, unconstrained water occupies roughly 9% more volume after freezing. The water phase undergoes this expansion regardless of what else is present; the external response of a pack can be smaller because headspace, shell compliance, trapped gas, redistribution through the fiber network, fiber compaction, freeze-front progression, and seam geometry accommodate much of that change internally. DuraTherm prototype observations likewise indicate a finished-pack size increase much smaller than the 9% water expansion would imply if applied directly to external package dimensions. In the October 2026 batch, DuraTherm bulging was distributed across the face rather than localized; its overall magnitude awaits analysis of the caliper series (Sections 10.3 and 24).

Measured capacities show that conventional controls carry headspace of about 2.6–3.6 times their coolant's freeze expansion (small: 46.0 ml air versus ~17.7 ml calculated expansion; medium: 122.5 ml versus ~33.9 ml, assuming approximately water-like volumetric expansion of the gel), yet still bulge visibly. Total headspace alone therefore does not prevent bulging; its location relative to the freezing coolant is decisive.

8.3 Design implication

DuraTherm pack geometry should be scaled according to the required thermal profile rather than by simple geometric enlargement. Increasing broad-face area remains the most direct way to add capacity while preserving short thermal paths and large contact area, but greater thickness is not inherently excluded. Thicker DuraTherm configurations can be used where additional stored thermal energy is required, provided that water distribution, freeze expansion, internal geometry, and heat-transfer distance are deliberately managed. In larger or deeper designs, internal thermal-transfer pathways may be introduced to shorten effective conduction distances and improve access to the stored thermal mass. Accordingly, DuraTherm should be treated as a scalable thermal architecture rather than a pack format constrained to one preferred thickness.

8.4 Shell-specific internal features

The current reference shell has a central neck flanked by two triangular shoulder cavities intended for storage fit. These cavities are part of the measured internal volume but drain poorly and can trap water or air depending on orientation. Whether the fiber network extends into these cavities, or whether they remain as fiber-free water or air pockets, should be confirmed by frozen cross-section, as they are candidate locations for local surface-temperature deviation. The October 2026 infrared comparison confirmed the neck end, which includes these cavities, as the warmest zone of the face in both DuraTherm units and controls, by about 8–9 °F relative to the center zone (Section 25.5). The cavities are therefore a thermal weak point of the current shell regardless of the internal phase.

PART II

DURATHERM: ARCHITECTURE AND PROTOTYPE FINDINGS

9. DuraTherm Long-Fiber Refrigerant Architecture

DuraTherm is a family of refrigerants in which water is intentionally frozen in the presence of a fibrous phase, and the formulation and enclosure are selected to deliver a desired thermal response. The working embodiment uses cotton in the form of cotton balls, which are rolled cotton sliver, or continuous sliver; hemp and other qualified fibrous systems remain possible variants. The reference medium pack uses the FreezPAK medium shell (Altor Solutions designation "Small"), approximately 7 in × 3.6 in × 1.6 in measured outside (label 6.8 × 3.4 × 1.4 in), with an internal water capacity of 495.7 ml.

The defining architecture is not merely cotton mixed with water. It is a distributed long-fiber network intended to keep water throughout the available internal volume, reduce large-scale liquid migration, stabilize frozen geometry, and provide a controlled thermal interface.

Current reference formulation (October 2026 test batch). Since September 27, 2026 the medium standard has been 115 cotton balls per unit (previously 100), adopted because the shell had room for the additional fiber and earlier units with the larger charge showed better temperature regulation and fit. Measured ball masses (about 0.72–1.0 g each) are heavier than the 0.62 g planning figure. The internal aqueous phase contains disodium tetraborate decahydrate (borax) as an antimicrobial at a specification of 1–2% w/w (Section 30). The dry unit (shell, cotton, borax, and a 0.4 g label) was brought to a target of 117.8 g, and water was added by tare to a target of 380 g. Table 1 summarizes the measured batch values; the cotton charge, obtained by difference, is about 71–76 g depending on the borax dose, about 14–15% of finished pack mass.

Table 1. Composition of the October 2026 medium DuraTherm batch (units 1–20) and the medium control

Quantity	DuraTherm units 1–20	Medium FreezPAK control
Empty shell mass	36.8 g (lightest of 20 cleaned shells)	36.8 g (same shell)
Fiber phase	115 cotton balls; ≈71–76 g by difference	none
Dry unit mass (shell + cotton + borax + label)	116.9–122.4 g (mean 118.2 g; target 117.8 g)	—
Water (filled minus dry)	379.1–381.3 g (mean 380.2 g)	—
Coolant charge	≈380 g water + borax	373.2 g gel in the reference unit; ≈385 g mean estimated from post-test masses
Filled mass before sealing	496.5–502.0 g (mean 498.3 g)	410.0 g (reference unit)
Post-test mass, sealed	485.0–516.5 g (all 23 units; mean 506.2 g)	408.0–436.0 g (27 units; mean 421.4 g)

The DuraTherm water charge is therefore comparable to the control's gel charge (about 1% lower). The DuraTherm unit is about 77–85 g heavier, and the difference is cotton, borax, and sealant rather than additional coolant. Units 21–23 are legacy units built earlier to a different standard (units 21 and 22 at 100 balls, unit 23 at 115 balls), contain no borax, and were tested as-is.

10. Reduced Bulging and Geometric Stability

Bulging is not merely a packaging or appearance issue. It changes the spatial distribution of coolant, pack thickness, contact geometry, thermal mass, and heat-transfer distance across the working surface. In conventional flexible gel and water-based packs, the liquid phase can move freely before freezing. Gravity, handling orientation, headspace, trapped air, shell flexibility, and the progression of the freeze front can therefore produce a frozen pack with thick coolant-rich regions next to thin, underfilled, or air-containing regions.

This behavior has been directly apparent in the conventional controls used in DuraTherm testing. Frozen controls developed marked differences in thickness and coolant distribution across their faces: some regions held concentrated frozen material and pronounced bulging, while others were comparatively thin or contained substantial internal air space. In thermal mapping, underfilled and air-pocket regions produced some of the warmest surface measurements.

DuraTherm addresses the problem through its internal fiber architecture. Rather than allowing water to move freely through an otherwise open enclosure, the cotton network distributes water through the available internal volume and restricts large-scale redistribution, so that the developing ice remains associated with a spatially distributed network instead of concentrating into isolated masses. Water still undergoes its normal phase-change expansion; how much of that expansion appears as external deformation depends on internal redistribution, fiber compaction, available gas and headspace, shell compliance, and composite structure.

10.1 Internal-volume utilization

A conventional flexible pack can contain the required total mass of refrigerant while using its internal volume poorly. A thick frozen bulge is a local concentration of thermal mass, while an adjacent air pocket or thin region is internal volume holding comparatively little. Nominal fill mass alone therefore does not describe the spatial distribution of refrigerant. In the medium reference control, approximately one quarter of the internal volume is air.

The physical chain proposed for DuraTherm is: fiber-distributed water → fuller and more uniform use of internal volume → reduced localized bulging and fewer large air gaps → more consistent frozen thickness and thermal mass → smaller surface-temperature deviations.

10.2 Freeze expansion and external dimensional change

Liquid water expands by about 9% on freezing regardless of what else is present in the pack. In DuraTherm, cotton is added to the coolant charge rather than substituted for part of it: the water charge (≈ 380 g) is comparable to the control's gel charge (373.2 g in the reference unit). A naive volumetric accounting therefore predicts more, not less, need for expansion accommodation: the 115-ball cotton charge (≈ 71 – 76 g, about 14–15% of finished mass, occupying roughly 46–49 ml or 9–10% of the internal volume as solid fiber at a cellulose density of about 1.54 g/cm^3) occupies space in addition to a comparable coolant volume, and the water still undergoes its full freezing expansion.

Measured shell capacity quantifies the accounting. The medium control's 373.2 g gel charge occupies about 75% of the 495.7 ml internal volume, leaving 122.5 ml (25%) of air. A current DuraTherm unit contains about 380 ml of water, about 46–49 ml of solid cotton, and a few millilitres of borax, occupying roughly 87% of the internal volume before freezing. After the ~ 34 ml freeze expansion of the water, about 6% of the internal volume (≈ 28 – 33 ml) remains free, compared with about 89 ml in the control (assuming approximately water-like expansion of the gel). The factory headspace therefore explains why the added

material fits; it does not by itself explain a difference in bulging, because the control retains roughly three times more free volume after freezing. Where DuraTherm shows less localized bulging, the leading hypothesis is that the fiber network distributes void volume (fiber lumens, inter-fiber channels, and interstitial gaps) close to where ice forms, rather than leaving one concentrated air pocket. This is a Class III hypothesis. It can be distinguished from a simple headspace explanation by frozen cross-sections of both unit types, by direct thickness mapping before and after freezing, and by matched-fill tests in which control and DuraTherm units are filled to identical, controlled headspace.

10.3 Comparative observations, including the October 2026 batch

Earlier prototype comparisons repeatedly showed less localized bulging in DuraTherm than in conventional controls: controls had visibly concentrated frozen regions with corresponding thin or air-containing regions, while DuraTherm units kept a more evenly occupied internal volume and external profile.

The October 2026 batch qualifies that result. Caliper measurements were taken on camera before imaging (tape-measure and contour-gauge methods were abandoned after a few attempts). Qualitatively, control bulges were sharper and more localized ("spiky"), whereas DuraTherm bulges were usually spread across the whole face. The investigator judges that the current batch carries a heavier cotton fill than preferred (about 4–5% of pack mass above the intended level) and attributes a larger overall bulge to that fill. The caliper series has not yet been reduced to numbers and is reported in Section 24 as pending. A lower-fill offset batch is planned to test whether reduced cotton loading lowers overall bulge while preserving thermal performance (Section 42).

Accordingly, the supported statement for the current batch is a difference in the form of bulging (distributed rather than localized), not a demonstrated reduction in overall thickness growth. Standardized characterization should report nominal and frozen thickness on a defined grid, maximum and minimum thickness, maximum bulge height above the nominal plane, the thickness range and coefficient of variation, pre- versus post-freeze change, internal air or underfilled regions where measurable, orientation dependence, and change across repeated freeze–thaw cycles, for small, medium, and large formats.

10.4 Scaling and engineering significance

Bulging becomes more important as pack size increases: a larger pack holds more coolant, undergoes larger absolute phase-change displacement, and offers longer distances over which unfrozen coolant can redistribute before freezing fixes it. Simply enlarging a flexible pack can therefore magnify sagging, pooling, localized thickness, seam loading, and uneven contact. DuraTherm introduces an internal structural network into this otherwise unconstrained volume. This does not establish that DuraTherm has no practical size or thickness limit; it establishes a different scaling architecture in which the coolant is spatially organized rather than free to redistribute.

Reduced localized bulging gives a flatter and more predictable geometry, distributes thermal mass more consistently across the working surface, reduces coolant-poor regions, and narrows the range of local thermal path lengths. Geometric stability is therefore directly relevant to thermal performance (Section 11).

11. Surface-Temperature Uniformity

11.1 Internal-space utilization as the proposed mechanism

The proposed mechanism for closer surface temperatures is spatial: the cotton–water architecture uses the internal pack space more completely and evenly. Conventional gel or water packs can develop thick frozen bulges next to underfilled or air-rich regions. Those regions hold different amounts of thermal mass and have different thermal path lengths, so their external surfaces do not warm at the same rate.

11.2 Evidence from the October 2026 test

The October 2026 test provides a quantitative check (Part III). For the medium packs, the within-face standard deviation of DuraTherm units was lower than that of controls at every one of 40 reads (mean 3.8 vs. 5.2 °F; per-pack means compared by Welch's test, $p \approx 4 \times 10^{-10}$), and the spread between the 1st and 99th percentile of face temperature was smaller at every read (17.0 vs. 19.7 °F). Using the cold-anchored criterion defined in Section 23.6, 25% of DuraTherm scans were cold-uniform and 45% warm-uniform, against 19% and 29% for controls; 52% of control scans and 30% of DuraTherm scans were non-uniform. Within the useful range (whole-face mean below 51 °F), however, the share of the face within ± 2.5 °F of its coldest part did not differ between groups (28% vs. 27%); the DuraTherm advantage there lay in a tighter main body of temperature, with 59% of the face inside one 5 °F window against 46% for controls (Section 25.4).

The pattern of the difference is informative. The temperature of the coldest 10% of the face was essentially the same in both groups (42.7 vs. 42.9 °F, averaged over all scans), while the 99th-percentile temperature was 3.1 °F lower in DuraTherm (58.5 vs. 61.6 °F). The colder DuraTherm average therefore came from warm regions being less warm, which is what the mass-distribution mechanism predicts, rather than from a colder frozen core.

11.3 What the mechanism is not

The uniformity mechanism should not be described as cotton conducting heat better than water or ice; fiber can lower effective thermal conductivity in some composite systems (Section 6.2). The observed uniformity is attributed to spatial control of water, ice, thickness, and thermal mass. Confirming the mechanism directly requires internal imaging or frozen cross-sections (Section 42).

12. Useful Cooling Duration and Temperature-Time Behavior

The product objective is not maximum coldness but an application-appropriate temperature–time curve. Current work uses approximately 34–50 °F as a reference pack-surface window; this is not an exclusive DuraTherm range, and other target profiles can be engineered. Medical interface temperature and protected-payload temperature must be treated separately and validated for each intended application (Section 6.8).

The October 2026 test measured useful duration directly at the pack surface (Section 25). Counting from removal from the freezer to the last scan below each limit, the median medium DuraTherm unit stayed below 40 °F for 4.8 h (control 3.5 h), below 45 °F for 6.3 h (control 5.5 h), and below 51 °F for 8.3 h (control 8.0 h). Below 60 °F the medians were 9.8 and 10.3 h. Counting instead to the first scan at or above each limit, which is more sensitive to short excursions, the medians were 3.1 vs. 1.8 h (40 °F), 6.3 vs. 5.2 h (45 °F), and 8.3 vs. 6.8 h (51 °F), excluding units already at or above the limit at their first scan (14 controls and 1 DuraTherm unit at 40 °F). The final-exit differences were significant at 40 and 45 °F but not at 51 or 60 °F

(Section 25.6). No DuraTherm unit reached 70 °F within the 14-hour test; 14 of 27 controls did. These results replace the earlier qualitative statement that 480–485 g, 100-ball prototypes "remained competitive" with controls.

The duration advantage is concentrated in the priority bands. Above about 55 °F the two groups warmed at similar rates for much of the night, and the late-phase difference (DuraTherm 2.1 vs. control 2.6 °F/h between 1:15 and 5:00 a.m.; $p = 0.012$) is partly a consequence of controls approaching ambient temperature.

13. Pack-Level Thermal Capacity and Useful Cooling Performance

The thermal performance of a refrigerant pack cannot be described by theoretical latent heat per gram alone. A finished pack is a coupled thermal system in which water mass, freezable-water fraction, fiber architecture, internal water distribution, geometry, enclosure behavior, surface area, thickness, and heat-transfer path all influence the temperature–time response at the surface. In the standard DuraTherm design the cotton network organizes and stabilizes the water rather than replacing it, so the engineering objective is to preserve pack-level thermal capacity while improving how that capacity is distributed and delivered.

13.1 Standard DuraTherm operating regime

Under a fixed total composite mass, adding dry fiber necessarily lowers the water fraction and therefore the maximum latent heat per gram. That relationship is physically valid but does not describe the standard pack, which is designed at the finished-pack level: fiber mass, water loading, enclosure volume, headspace, thickness, and internal architecture are selected together. In the current medium batch the water charge (≈ 380 g) matches the control's coolant charge, consistent with cotton being added to rather than substituted for the coolant. Theoretical calculations based only on dry-fiber mass fraction should therefore not be read as predictions of standard DuraTherm cooling duration.

13.2 Theoretical latent-heat ceiling

Theoretical calculations remain useful because they define the physical limits of fiber–ice formulations under stated assumptions. If total composite mass is fixed, increasing the dry-fiber fraction reduces the water available, and a further reduction can occur because part of the water associated with cellulose is bound or strongly confined (Section 3.4). These relationships set an upper thermodynamic ceiling (Figure 1) but do not account for whether thermal mass is evenly distributed, whether large air pockets exist, or whether the pack keeps useful contact geometry.

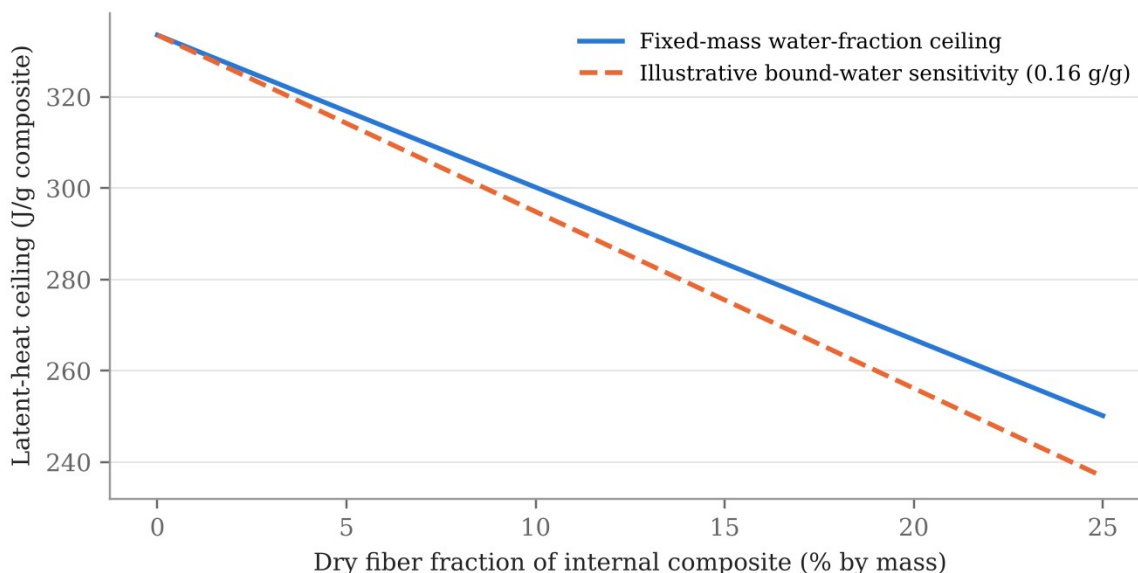


Figure 1. Conditional theoretical latent-heat ceiling versus dry-fiber fraction under a fixed-total-composite-mass assumption. The dashed curve is an illustrative bound-water sensitivity using 0.16 g bound water per gram of dry cotton; it is not measured DuraTherm data.

13.3 Constrained-volume and high-fiber regime

The fiber-loading penalty becomes important when package volume is fixed or fiber content is raised substantially. At high loading the fibers occupy enough internal volume that less water can be introduced, creating a direct tradeoff between structure and available water. The effect appears sooner in small or shallow packages, and a formulation that performs well in a larger enclosure can become fiber-crowded in a smaller one. The small-format result of the October 2026 test (Section 25.8) is consistent with, though not proof of, this regime: small units accepted only about 189–192 g of water before weeping and showed signs of incomplete wetting of the lower region during manual top filling.

13.4 Useful cooling performance and the energy budget

The relevant metric is useful cooling within the intended window, not latent heat in isolation. A useful order-of-magnitude check comes from the October 2026 batch. The ≈ 380 g water charge stores about 127 kJ of latent heat (at 333.5 J/g). Warming 71–76 g of cotton (specific heat $\approx 1.3 \text{ J g}^{-1} \text{ K}^{-1}$) through the roughly 40 K between freezer and ambient absorbs only about 4 kJ, about 3% of the latent store. The added cotton therefore cannot by itself account for the observed differences in time below the priority limits; the more plausible driver is the spatial distribution of the existing thermal mass, consistent with the uniformity evidence in Section 11.2. Finished-pack evaluation should combine water mass and freezable fraction, estimated latent and sensible heat, surface-temperature distribution, duration within the window, frozen thickness distribution, internal air or underfilled regions, and geometry during freezing and use.

13.5 Freeze time

Freeze time has not been formally characterized. Informal observation indicated that DuraTherm units froze more slowly than conventional controls when the freezer was set near -1°C ($\approx 30^\circ\text{F}$), whereas no appreciable difference was observed at approximately -18°C ($\approx 0^\circ\text{F}$). This is consistent with heat-transfer expectations: near the melting point the small driving temperature difference magnifies the effect of the composite's reduced thermal conductivity, while at conventional freezer temperatures the larger driving

difference dominates. The units observed at the near-melting set point contained no borate, so the slower freezing is attributable to the fiber phase alone; in borate-containing units, the modest freezing-point depression from dissolved borate would be expected to slow freezing further at near-melting set points. Controlled freeze-time measurement across freezer set points is identified as a validation priority.

14. Localized Damage, Penetration, and Coolant Retention

Shell puncture resistance and post-puncture coolant retention are separate properties. A strong shell can resist penetration; an internal architecture can limit fluid loss after penetration. DuraTherm testing has shown no leakage through localized holes under the conditions tested: the long-fiber network immobilizes the aqueous phase sufficiently that a localized penetration has not produced the free-liquid drainage expected from an ordinary water pack.

Fluid retention through the fill port. Fluid retention was assessed using the fill port of each prototype, an opening of approximately 12–19 mm ($\frac{1}{2}$ – $\frac{3}{4}$ in) diameter formed by removing the original seal. Over more than 60 days of prototype testing, thawed units at the end of their thermal cycle were held with the opening oriented sideways and then fully inverted on several hundred occasions, with no observed liquid extrusion. Expression of liquid required sustained manual compression of approximately 22–44 N (5–10 lbf), which released only a few grams. Because the inverted orientation places the open port directly beneath the liquid phase, these observations indicate that capillary retention within the cotton network exceeds the gravitational head across the pack. Retention is attributed to capillary sorption in a fiber network whose water loading remains below its absorbent capacity. In small-format units, near-saturation was observed at the upper region, consistent with incomplete hydration of the lower region during manual top filling; uniform distribution under production hydration is expected to restore retention margin throughout the pack.

These findings should not be generalized to unlimited hole size, catastrophic rupture, or every pressure condition. Standardized testing should define penetration size and location, frozen or thawed state, applied compression, leakage mass and rate, tear propagation, residual coolant mass, and retained useful-cooling duration. Shell failure modes and their release behavior are classified in Section 31 (Table 9).

Table 2. Consequence of a localized breach by refrigerant system

System	Localized breach consequence	Relative concern
DuraTherm	No coolant discharge demonstrated through localized holes or the open fill port under tested conditions	Low under tested localized-hole conditions
Water/ice	Free water can drain when thawed or partially thawed	Low chemical hazard; high wetting potential
Conventional hydrogel	Gel or residue release depends on formulation and breach; ionic gels liquefy on contact with saline fluids (Section 31)	Low–moderate; formulation dependent
Salt-hydrate PCM	Release can involve irritant or corrosive formulations	Moderate–high; formulation dependent
Organic/paraffin PCM	Oily hydrocarbon release; some formulations combustible	Moderate; formulation dependent
Proprietary PCM	Depends on chemistry and SDS	Variable

15. Condensation and Surface Sweating

Surface condensation occurs when a cold object is below the dew-point temperature of the surrounding air. The experimental literature shows that the temperature difference between the cold surface and humid air is a major determinant of condensation, together with relative humidity, airflow, and surface properties [68–71]. At 75 °F and 50% relative humidity, the dew point is approximately 55 °F; a 32 °F surface is about 23 °F below it and a 42 °F surface about 13 °F below it.

Correction to the previous edition. The previous edition stated that DuraTherm operates at a warmer surface temperature than conventional controls and attributed reduced sweating to a smaller dew-point deficit. The October 2026 measurements contradict the premise: medium DuraTherm faces were on average colder than controls at every read (Section 25.2). On the dew-point argument alone, DuraTherm would therefore be expected to condense at least as much water per unit area as the controls, not less.

Earlier informal observations of reduced external sweating remain unquantified. During the October 2026 test, moisture accumulation around all packs was substantial, and no gravimetric condensate measurement was made, so the test provides no evidence either way. Any real difference would have to come from mechanisms other than a warmer mean surface, for example fewer extremely cold localized regions, but the measured coldest-part temperatures were essentially the same in both groups. Reduced condensation is therefore withdrawn as a DuraTherm finding and retained only as a research question, to be tested gravimetrically with simultaneous dew-point and multi-point surface-temperature recording (Appendix D).

16. Large-Format Scaling

Pack size changes thermal and mechanical behavior. If all dimensions grow proportionally, coolant volume rises faster than external surface area while the thermal distance through the pack increases, and larger flexible packs carry more mobile coolant, increasing sag, redistribution, bulging, thickness variation, and seam loading. DuraTherm addresses the redistribution component through its fiber network but does not repeal heat-transfer physics. Broad-face growth remains the most direct way to add capacity while keeping thermal paths short, yet greater thickness is a valid design variable where more stored energy is needed, provided water distribution, expansion, geometry, and thermal distance are managed deliberately, including internal thermal-transfer pathways (Section 17).

In the October 2026 test the single large DuraTherm unit (legacy, 1,346 g post-test) was colder than the single large control (1,095 g) at every one of 39 reads, by 3.5 °F on average (range 0.6–6.8 °F), with a lower within-face standard deviation (5.2 vs. 7.3 °F). Because each type is represented by one unit, and the DuraTherm unit is heavier (its extra mass is cotton rather than water), this result is descriptive and is not evidence for or against the large format.

17. Internal Thermal-Conduit Architecture — Harrington Thesis

Harrington proposes that deeper DuraTherm units need not rely exclusively on conduction through the full fiber-ice thickness. Engineered thermal-transfer conduits could extend from the principal heat-transfer surfaces into deeper regions of the composite, creating multiple shorter thermal paths. The objective is to reduce the thickness-squared diffusion penalty of an equivalently thick homogeneous slab while retaining the greater stored energy of a deeper unit.

The engineering precedent is distinct from the DuraTherm proposal. Iftekhhar Ahmed has demonstrated temperature-controlled packaging in which refrigerant layers are thermally coupled to remote payload

regions through convective channels or heat-pipe structures [72, 73]. Harrington proposes applying the broader principle of engineered internal thermal pathways inside a thick fiber-ice architecture. The specific conduit configuration remains a thesis requiring experimental validation.

18. Dry Shipping and Final-Mile Hydration

DuraTherm can be transported dry and hydrated near the destination. This removes most of the eventual water mass from long-haul freight and turns locally available water into the dominant coolant mass only after the unit has traveled most of the supply chain.

18.1 Current 40-ft container planning comparison

For U.S. road planning the model uses a 44,000-lb cargo allowance after tractor, chassis, and container tare. This is a planning assumption rather than a statutory cargo allowance; legal operation remains subject to the 80,000-lb gross vehicle weight limit, axle limits, Bridge Formula requirements, equipment tare, and route-specific constraints.

Table 3. 40-ft container planning comparison

Metric	Conventional gel	Dry DuraTherm (current 115-ball medium)
Unit freight mass	0.9 lb	≈0.26 lb dry (116.9–122.4 g measured; 117.8 g target)
Pallet/bulk configuration	20 standard pallets	36 self-palletizing crates (≈52.4 × 45.8 × 44 in), stacked two high
Modeled units per 40-ft container	47,880	≈110,000
Relative unit count	1.00×	≈2.30×
Loaded cargo weight	≈43,100 lb (weight-limited)	≈29,600 lb including crates (volume-limited)
Water during long-haul freight	Inside the pack	Added near destination

The DuraTherm count is set by container volume rather than weight: using the medium shell's label envelope of 6.8 × 3.4 × 1.4 in, ordered packing in 36 self-palletizing crates stacked two high within the ≈89.8 in door opening yields approximately 110,900 units, rounded to 110,000 for planning. The current dry unit mass (≈0.26 lb, increased from the earlier ≈0.22 lb by the 115-ball cotton charge) raises the loaded weight to roughly 29,600 lb including crates, still well under the planning allowance. Even with no crates, the container's physical ceiling for this shell is about 127,000 units. Against a heavier 1.3-lb conventional pack (about 32,300 per container), the ratio is about 3.4. This is a logistics comparison, not a life-cycle assessment or an exact fuel or carbon claim.

18.2 Final-mile hydration process

Final-mile hydration is performed by a compact automated hydration unit (design target ≤ 800 lb) suitable for installation at regional or distribution-point facilities. Dry units are transferred from pallet or bulk box into a queue and conveyed to a submerged filling station, where each unit is aligned, immersed, held in position, and filled completely through the injection port. Immersion eliminates the air-displacement conflict inherent in top filling, in which entrained air must escape through the incoming liquid. The bottom closure is then capped at a second station. On removal from the bath, the unit is held in an inverted orientation and compressed to express liquid until a target mass is reached; release of compression draws air back into the pack, where it redistributes through the fiber network. The unit is

returned upright, fill mass is adjusted individually where required, and the unit is capped, grouped, and wrapped. Gravimetric fill control provides unit-level verification of water loading.

Borate is pre-loaded in dry form within each unit, positioned away from the injection port; the fiber network limits its migration during immersion. The bath is maintained at $\geq 1\%$ w/w borate as required, minimizing the concentration gradient that would drive diffusive loss. Supply water is treated by ultraviolet irradiation before entering the system, controlling microbial load in the incoming water, while bath borate controls contamination introduced by units during processing. Exterior surfaces should be dried before final capping and packaging. Prototype units were filled manually from the top, which accounts for the hydration difficulty observed during prototyping; this limitation is specific to the absence of production equipment.

19. Fiber Mobility During Manufacture and Hydration

Prototype manufacture has produced several observations about how the cotton phase moves before and during hydration. They are reported here as Class III observations with the mechanisms that plausibly explain them.

19.1 Cotton balls as rolled sliver

Cotton balls are not chaotic fiber clumps: they are rolled cotton sliver, coiled in the manner of a spiral roll. Sliver will therefore work as fill. The only observed behavioral difference is that very thin outer strands of a ball can partly come undone.

19.2 Dry self-redistribution

During packing, several partially filled units (packed toward the bottom and left to rest before finishing) redistributed their cotton overnight, roughly 18–25 h after packing: material moved from the densely packed region into the adjacent under-filled region. The behavior was consistent across units regardless of storage orientation, which rules out gravity as the driver. The observation is consistent with elastic recovery of the fiber assembly: cotton compressed during packing stores elastic energy in bent and buckled fibers and releases it as expansion into adjacent lower-resistance space once confinement is removed. Recovery of compressed fiber webs is a well-known property of nonwoven assemblies; the magnitude for cotton balls in a shell has not been measured.

19.3 Hydration swelling and de-convolution

Wetting adds a second, independent source of internal pressure. Cotton swells strongly in the transverse direction and very little along the fiber axis: reference values are about 20% in diameter, about 40% in cross-sectional area, and about 1.1% in length, for a volumetric swelling of about 42% [55]. As the fiber swells it reverts from a flattened, twisted ribbon toward its original cylindrical form, so the convolutions partly unwind; the degree of de-convolution is greatest when wet fibers are also stretched. Swelling into inter-fiber space reduces porosity and permeability of the assembly. That wetted compressed cotton generates useful mechanical force is established engineering practice: U.S. Navy water sensors use compressed cotton pellets whose expansion on wetting drives a piston [56], and later Navy patents cite this mechanism as prior art while noting that surface impurities can impede absorption [57, 58].

Force does not guarantee movement. Expansion relocates fiber only where there is an asymmetry, that is, a direction of lower counter-pressure; a mass of equally confined, equally swelling balls simply becomes denser and stiffer. In DuraTherm units such asymmetries demonstrably exist: incompletely filled regions,

including the triangular shoulder cavities beside the neck, are present after packing. Some redistribution toward under-filled regions on hydration is therefore physically expected, but it is not guaranteed to fill every gap, and its magnitude must be measured (Section 42).

19.4 Interior rearrangement at each stage of manufacture

The cotton layout is rearranged repeatedly during prototype manufacture, each time moving cotton from regions of greatest resistance toward regions of least resistance: (1) during filling, cotton is forced into the bottom corners first and then built upward, using a levering action to reach the top-left and top-right; (2) before water is added, units are punched and packed to remove bulges; (3) during water addition, kneading, shaking, and pounding on a surface move air. A pre-hydration bulge-correction step is part of the process: after cotton and borax are loaded and before water is added, localized dry-cotton bulges are corrected by a hammering action applied to both faces at the bulge site. Because production is intended to be automated, this step is defined as a mechanical operation rather than a manual one.

19.5 Wetting method

Hydration of the prototypes is difficult because filling is from the top, by hand, so air must escape through the incoming water. The only effective prototype method found so far is to pound and squeeze the pack heavily, so that air rises and water moves down, together with a prodding pole pushed around the pack edges to open space for water. Vacuum filling has been ruled out: it is nearly impossible with cotton and would clog filters. The planned production approach is bottom-up filling with a tight bottom seal so that air rises out, and the submerged-fill process of Section 18.2. An automated kneading device, applying constantly shifting pressure at different points in the manner of a massage device, would likely release trapped air during wetting more efficiently than manual pounding and squeezing.

19.6 Freeze-front interaction (research question)

Freeze fronts are known to push or partially displace particles ahead of the advancing interface, including partial displacement of particles that are eventually engulfed [59, 60]. Whether this produces modest movement of cotton balls toward lower-pressure zones (air or water pockets) during freezing of a DuraTherm unit is untested at cotton-ball scale and is listed only as future work.

PART III

THE OCTOBER 2026 COMPARATIVE INFRARED TEST

20. Objectives, Hypotheses, and Design

Part II describes behavior observed across months of prototype work. This part reports the first controlled comparison designed to test that behavior quantitatively: a 14-hour infrared (IR) thermography study conducted on October 3–4, 2026, in which DuraTherm units and commercial gel packs in the same shell family were removed from the same freezer at the same time and imaged repeatedly while they warmed in still room air.

The test addressed four questions, framed as working hypotheses (Class III) from earlier prototype observations:

- H1 (temperature). The whole-face mean temperature of medium DuraTherm units is lower than that of medium gel controls during warming.
- H2 (uniformity). DuraTherm faces show smaller within-face temperature variation than control faces.
- H3 (duration). DuraTherm units remain below the priority limits of the reference window (40, 45, and 51 °F) for longer than controls.
- H4 (spatial pattern). Warm regions on control faces are associated with the end zones of the shell, where coolant and air redistribute, whereas DuraTherm faces show fewer such regions.

The medium format (23 DuraTherm units, 27 controls) was the primary comparison. A small-format arm (4 DuraTherm units, 6 controls) was run as an auxiliary comparison, and one large unit of each type was included for description only. The design is a parallel-group comparison with repeated measures on each unit; the unit (pack) is the statistical unit throughout.

The results are reported in the order adopted for this test program: bulge measurements (Section 24), temperature analysis with one subsection per analysis type (Section 25), and special comments, which collect all qualitative observations (Section 26). Limitations follow in Section 27 and a summary in Section 28.

21. Test Articles and Pre-Test Conditioning

21.1 Units and identification

Each unit carried an identifier composed of a two-digit number, a size letter (M, S, or L), and C for control or D for DuraTherm (for example, 11MD or 02SC). Identification tags were attached with wire. Table 4 lists the groups. Size names follow the investigator's convention; the shell manufacturer (Altor Solutions, maker of the FreezPAK line) designates the same shells one size smaller (investigator "small" = Altor "Mini", "medium" = "Small", "large" = "Medium").

Table 4. Test articles (October 3–4, 2026)

Group	IDs	n	Construction	Post-test mass (g)
Medium DuraTherm, current batch	01–20MD	20	Drilled and cleaned medium FreezPAK shell; 115 cotton balls; borax 1–2% w/w; $\approx$ 380 g water (Table 1)	485.0–516.5; mean 508.4 ± 6.1
Medium DuraTherm, legacy	21–23MD	3	Earlier build; 100 balls (21, 22) or 115 balls (23); no borax	486.0, 487.5, 500.0
Medium control	01–27MC	27	Unaltered medium FreezPAK (sodium polyacrylate gel), factory sealed	408.0–436.0; mean 421.4 ± 7.1
Small DuraTherm	01–04SD	4	Drilled small shell; dry unit 69.2–70.6 g; $\approx$ 189–192 g water	269.9–273.4
Small control	01–06SC	6	Unaltered small FreezPAK	215.4–244.4
Large DuraTherm (legacy)	01LD	1	Earlier build, unmodified	1,346
Large control	01LC	1	Unaltered large FreezPAK	1,095

Masses are means $\pm$ SD where given. Post-test masses were taken after the units reached room temperature and were towel-dried; for small units the 1.1 g wire tag was subtracted. DuraTherm masses include the silicone sealant, which could not be quantified separately.

21.2 Pre-test conditioning

Pre-test conditioning differed by build history and is stated here because it affects water content:

- Medium units 01–20MD and small units 01–04SD were put through one deliberate freeze–thaw cycle (removed from the freezer on the night of September 30) so that each could express any excess liquid before the test.
- Legacy units 21MD and 22MD had previously been allowed to express over three freeze–thaw cycles and had been sealed permanently for months. Unit 23MD, a more recent build, had expressed over at least ten cycles and was sealed for the first time on the night of October 1.
- The large DuraTherm unit is a legacy unit that had expressed over three freeze–thaw cycles; it was sealed on October 1.
- Controls were unaltered commercial units.

21.3 Sealing

All DuraTherm units were sealed for this test so that any absence of bulging could not be attributed to an open fill port. Sealing used 100% silicone sealant (GE Silicone 2+, clear), applied as a thin bead to the dried opening, and was complete by approximately 11:50 p.m. on October 1. Because several units were still cold when sealed, a number of seals were drawn inward into the neck overnight; one partially unsealed seal was repaired and a few others were touched up before freezing. All seals were judged sound before the units entered the freezer.

21.4 Freezing

Units were placed in the freezer between about 8 and 9 a.m. on October 2 and removed together at 3:00 p.m. on October 3 (approximately 30 h). They were arranged so that DuraTherm units could be removed in sequence and controls two at a time. Nine controls remained in their original shipping packaging in the freezer until removal. The freezer set point was not recorded in the test log.

22. Test Environment and Procedure

22.1 Environment

Units rested on R-6 insulation panels with plain sheets; blankets were deliberately avoided to reduce thermal variance and air circulation around the units. No fans were operated, the air-conditioning grille was closed, and air movement was limited to incidental movement of the investigator. The room temperature was 73.6 °F and was read aloud to camera at intervals throughout the test; it remained at that value. Relative humidity was not recorded. Two LED lighting units purchased for the test illuminated the bench, and sheets were hung to cover distracting areas of the room. The full procedure was video-recorded with a spoken narrative.

22.2 Schedule

Units were removed from the freezer at 3:00 p.m.; bulge measurements were taken first (Section 24). IR reads were scheduled every 15 minutes from 4:00 p.m. Each read imaged the medium units first, then the small and large units, in a fixed order. The actual scan time of every image was taken from the image file; times are never interpolated. Where the schedule departed from the plan:

- The 5:46 p.m. read imaged the medium units only.
- No images were taken at 10:00 p.m. or at 4:00 a.m.
- The 10:30 p.m. read was excluded from analysis: its images were not processed within the pre-declared analysis deadline, and one set of six medium DuraTherm units was not imaged in that read.
- The 12:15 a.m. read was taken late, between 12:24 and 12:27 a.m., after the units had been turned back to the correct face.
- The 1:00 a.m. read was taken at 1:15 a.m.; thereafter reads were taken every 30 minutes.
- Later reads were spaced further apart because the investigator's pre-existing service-related injuries limited prolonged standing.

In all, 40 reads were analyzed, from 4:00 p.m. on October 3 to 5:00 a.m. on October 4 (Appendix E).

22.3 Handling and face orientation

Only the rear face of each unit was imaged (Section 23.1). Units were turned over at each 15-minute period, so that each face alternately rested on the insulation and was exposed to room air; this also subjected both pack types to repeated handling. In periods in which the rear face was already uppermost, units were imaged first and then turned. In periods in which units lay label side up, they were turned and then imaged. From 6:30 p.m., in the latter periods, all units were first turned in sequence and then imaged in the same order, so that each newly exposed face had several minutes to settle before it was imaged. At 10:15 p.m. the units were accidentally turned an extra time and were returned to the correct face before the 10:30 p.m. period; the 10:15 p.m. images are flagged.

At 6:30 p.m. the first ten medium controls and first ten medium DuraTherm units were imaged three times: in the normal round, again a few minutes later, and a third time after the small and large units had been imaged. These repeat images quantify how quickly a newly exposed face changes (Section 25.10).

22.4 Stopping criteria

The test followed the investigator's standing procedure for these comparisons: imaging continues until the test is essentially complete, meaning that one unit remains or a significant number of units have finished and the remainder are clearly on track to finish. A unit is considered finished when its whole-face

mean temperature reaches 70 °F, or when three consecutive reads agree within 0.5 °F at or above 65 °F (a plateau), in which case the finish time is backdated to the first of the three reads. All readings, including those after a unit finished, remain in the data set. The small-format arm, as an auxiliary comparison, is concluded when all but one small unit has finished or plateaued; this occurred after the 1:30 a.m. read. Imaging of the medium and large units ended after the 5:00 a.m. read, 14 hours after removal from the freezer, when 14 of 27 medium controls had reached 70 °F and the investigator, after 20 hours awake, judged that most remaining units would finish by about 5:30 a.m.

23. Infrared Thermography and Image Analysis

23.1 Instrument and imaged face

Images were taken with a handheld thermal imager (EXIF: AccuMEMS TT27D) that saves 640 × 480 pixel JPEG images in an ironbow palette with an on-screen temperature scale, a center-spot readout ("Cen"), and the active settings; the displayed emissivity setting was 0.95.

Infrared thermography was performed on the rear face of each unit only. Labels and adhesive tags on the front face have emissivity different from the HDPE shell and produced unreliable apparent temperatures; the rear face, free of labeling, provided a uniform surface for measurement.

The imager was held by hand. Distance, angle, and framing therefore varied between images, and the camera's orientation sensor stored many images rotated or inverted relative to the intended neck-up framing (Section 23.4).

23.2 Outlines

Pack boundaries could not be found reliably by automatic segmentation, particularly once faces approached the temperature of the insulation (Section 26). For every read, the investigator drew the long sides of each pack on a copy of the image (one-pixel lines in Paint on early reads; colored lines from a marking tool thereafter), with end lines or arrows where needed. The analysis software located these lines as the pixels that differ between the marked copy and the raw image, joined line segments drawn in several pieces, and closed the outline at the pack ends. Where part of a pack lay outside the frame, the missing part was reconstructed from the measured pack width and the median width-to-length ratio of complete outlines (0.531 for medium and small units, 0.813 for large units) and was counted as off-frame: no temperature was assigned to it. Images with less than 60% of the pack inside the frame were rejected. Seven difficult cases were decided by inspection and are listed in the data-gap record (Appendix E).

Repeatability of the outlines was measured directly: all 62 images of the 7:30 p.m. read were outlined a second time, independently, by the investigator (Section 23.9).

23.3 Conversion of image color to temperature

Each pixel inside the outline was matched to the nearest color of the image's own color scale and scaled between the minimum and maximum temperatures printed beside the scale. Pixels covered by on-screen overlays (readout boxes, scale, crosshair, toolbar, time stamp) or with colors outside the palette were excluded. Because the palette is not perceptually linear, the color-position-to-temperature relationship was calibrated against the imager's own center-spot readout: on 2,436 images the 7 × 7-pixel crosshair region was converted and compared with the displayed "Cen" value, and a monotonic (isotonic) calibration curve was fitted. After calibration the median difference between converted and displayed spot values was 0.00 °F (mean -0.24 °F; interquartile range -0.52 to +0.40 °F; 78.9% of images within ±1

°F, 91.7% within ± 2 °F, $n = 2,434$). Spot-to-spot scatter of this size is expected because a single 7×7 -pixel spot often straddles an edge; zone and face values average hundreds to thousands of pixels.

23.4 Orientation and identification of the neck end

The neck end of each unit was identified from the orientation tag that the imager stores in each image (tag 6: neck up; tag 8: image stored upside down; tag 1: neck to the left). This rule reproduced every orientation the investigator had marked by hand (12 rotated copies at 9:30 p.m., 16 rotated or flipped copies at 3:30 a.m., and two marked with arrows). It showed that 383 images had been stored upside down; an earlier workbook that assumed the top of each marked image was the neck had top and bottom exchanged for those images, and is superseded by the present analysis.

Unit identity was assigned from photographing order, which followed a fixed sequence, and checked against the reads before and after. In four reads the number of images was one fewer or one more than the number of units in a row (5:00 p.m., the 8:00 p.m. small units, the 9:00 p.m. controls, and the first DuraTherm row at 9:30 p.m.); the best-fit assignment was kept and those readings are flagged.

23.5 Zones

Each outline was mapped onto a rectangle with the neck end at the top (Figure 2). The face was divided into five zones: a center zone containing the middle 80% of the face area (89.4% of length and of width), and four edge bands outside it: top (the full-width band at the neck end, including the neck and the shoulder cavities beside it), bottom, left, and right. The investigator expected the top and bottom zones, where cotton is hardest to place and where coolant and air collect in conventional packs, to be the principal problem zones. A zone value was reported only if at least 50% of its pixels were readable; 213 readings had one or more zones unreadable (mostly the bottom band under the imager's toolbar) and are flagged as partial.

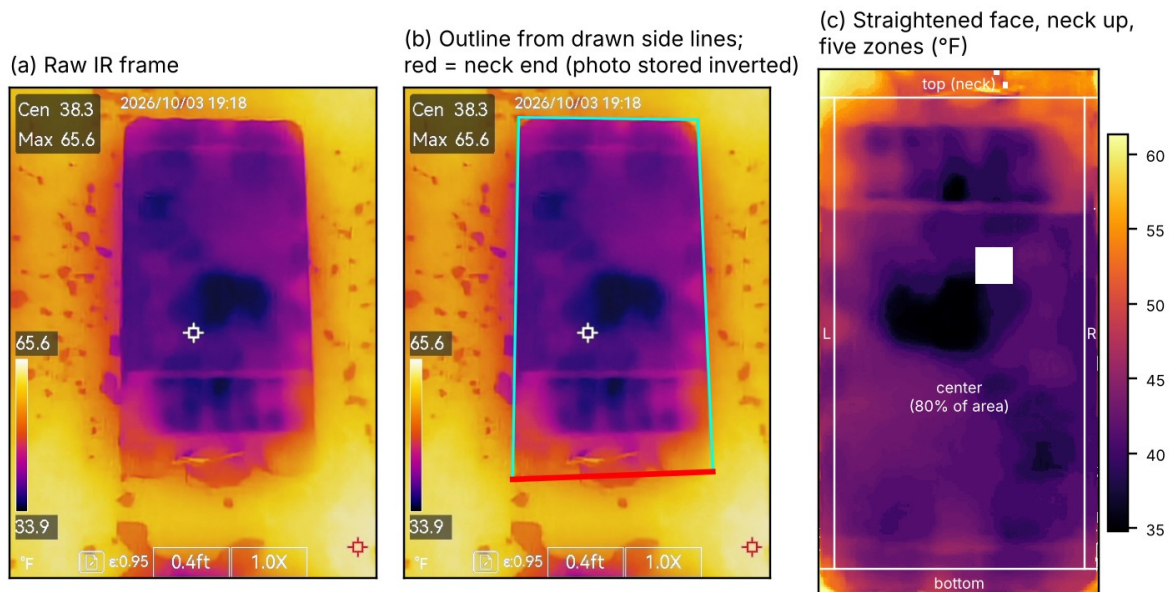


Figure 2. Image-analysis steps for unit 05MD at the 7:15 p.m. read. (a) Raw image with the imager's overlays (center-spot readout, color scale, displayed settings). (b) Outline built from the investigator's drawn side lines; the red line marks the neck end, identified from the stored orientation tag (this image was stored upside down). (c) Face mapped with the neck at the top, showing the center zone (80% of area) and the four edge bands; white areas are excluded overlays.

23.6 Uniformity metrics

Four uniformity measures were computed for every scan:

- Within-face standard deviation (SD) of all readable face pixels.
- Spread: the difference between the 99th and 1st percentiles of face temperature.
- Cold-uniform share: the percentage of the face within ± 2.5 °F of the coldest part, where the coldest part is the mean of the coldest 10% of face pixels.
- Warm plateau: the largest percentage of the face contained in any 5 °F window.

The cold-anchored criterion was adopted because a pack that is uniformly warm is not performing well; uniformity is useful only when it is uniformity near the cold end. Each scan was classified as cold-uniform when more than 50% of the face lay within ± 2.5 °F of the coldest part; as warm-uniform when it was not cold-uniform but more than 50% of the face lay within one 5 °F window; and otherwise as non-uniform. Cold-uniform is ranked above warm-uniform.

23.7 Temperature bands and end criterion

Whole-face means were compared with the limits 40, 45, and 51 °F, which bound the priority bands 34–39.9, 40–44.9, and 45–50.9 °F within the reference window, and with 60 and 70 °F. For each unit and limit, two durations were recorded from the freezer pull at 3:00 p.m., using actual scan times: first exit, the last scan before the first scan at or above the limit; and final exit, the last scan below the limit at any time. Final exit is less sensitive to a single warm reading caused by handling (Section 25.10); first exit is more conservative. The end criterion is that of Section 22.4.

23.8 Statistical analysis

For each read, group means, SDs, and 95% confidence intervals ($t \times \text{SD}/\sqrt{n}$) were computed for each measure, and the DuraTherm-minus-control difference was tested with Welch's unequal-variance t-test, with Welch 95% confidence intervals [61]. Because the same units were imaged at every read, per-read tests are not independent and are reported descriptively, without correction for multiplicity. The primary inferential comparison for each measure uses one value per unit (the unit's mean over all its scans), compared between groups by Welch's test. Band durations were compared with the Mann–Whitney U test. The normal round of each read is used throughout; the 6:30 p.m. repeat images are analyzed separately. Analysis was performed with custom Python scripts developed with an AI assistant (Claude, Anthropic) under the investigator's direction; every per-image value is retained in the raw-data record.

23.9 Measurement uncertainty

The image-analysis uncertainty of each reported value was built from three measured components (Table 5): outline repeatability, from the 62 independently re-outlined images of the 7:30 p.m. read ($1.96 \times \text{SD}$ of the differences); calibration, taken as half of the 95th-percentile difference between curves fitted to two random halves of the calibration data (0.70 °F), that is 0.35 °F; and reading of the scale limits to 0.1 °F (0.05 °F). The components were combined in quadrature. The imager's absolute accuracy is not included: it shifts all units in the same way and does not affect comparisons between groups. Group comparisons use the confidence intervals of Section 23.8, which reflect unit-to-unit variation and are larger than the image-analysis uncertainty.

Table 5. Image-analysis margin of error (95%) per measured value

Value	Outline SD (°F)	Calibration (°F)	Scale (°F)	Margin of error (±)
Whole-face mean	0.22	0.35	0.05	0.56 °F
Center 80%	0.20	0.35	0.05	0.53 °F
Top (neck) zone	0.96	0.35	0.05	1.92 °F
Bottom zone	0.51	0.35	0.05	1.06 °F
Left zone	0.40	0.35	0.05	0.86 °F
Right zone	0.64	0.35	0.05	1.30 °F
Cold-uniform share	1.76 points	—	—	3.4 points

23.10 Data completeness

The image record contains 2,463 images, of which 20 were wide shots, duplicates, or unassigned extras and 2,443 were pack images (2,403 in normal rounds and 40 repeat images at 6:30 p.m.). Nine pack images yielded no data: six were rejected because too little of the pack was in frame, one was not outlined, one could not be outlined because no part of the pack could be identified, and one was too far out of frame to reconstruct. In addition, five unit-reads were not imaged (two units at 5:00 p.m., one small control at 8:00 p.m., one control at 9:00 p.m., and 17MC at 11:45 p.m.). For the medium comparison, 1,075 control scans and 916 DuraTherm scans were analyzed; the minimum per read was 26 controls and 22 DuraTherm units.

24. Bulge Measurements

24.1 Caliper measurements

Pack thickness was measured with large calipers on camera after removal from the freezer and before IR imaging. The caliper readings are held in the video record and have not yet been transcribed. No numerical bulge result is therefore reported in this edition; the transcribed caliper series, with nominal and frozen thickness, maximum bulge height, and between-group statistics, will be added in the next revision. Qualitative bulge observations are reported in Section 26.1.

24.2 Tape measurements

Sewing-tape measurement of the bulged area was planned. It proved impractical on test day and was abandoned after a few attempts; no tape data are reported.

24.3 Contour-gauge images

Contour-gauge profiles were planned for extraction from the video. The method proved impractical on test day and was abandoned after a few attempts; no contour data are reported.

25. Temperature Analysis

25.1 Data set and summary

The analysis uses the medium units unless stated otherwise. Table 6 summarizes the principal medium-format results; per-read statistics are tabulated in Appendix E.

Table 6. Summary of medium-format results (23 DuraTherm, 27 controls; 40 reads)

Measure	DuraTherm	Control	Comparison
Whole-face mean, unit means (°F)	47.5	50.1	-2.7 °F; $p = 0.001$
Reads with DuraTherm mean below control	40 of 40	—	$p < 0.05$ at 30 reads
Center 80%, scan mean (°F)	46.5	49.1	-2.6 °F
Coldest part (coldest 10%), scan mean (°F)	42.7	42.9	$p < 0.05$ at 6 of 40 reads
99th-percentile temperature, scan mean (°F)	58.5	61.6	-3.1 °F
Spread, 99th – 1st percentile (°F)	17.0	19.7	lower at 40 of 40 reads; $p \approx 8 \times 10^{-6}$
Within-face SD (°F)	3.8	5.2	lower at 40 of 40 reads; $p \approx 4 \times 10^{-10}$
Median time below 40 °F, final exit (h)	4.8	3.5	$p = 0.0001$
Median time below 45 °F, final exit (h)	6.3	5.5	$p = 0.008$
Median time below 51 °F, final exit (h)	8.3	8.0	$p = 0.31$
Median time below 60 °F, final exit (h)	9.8	10.3	$p = 0.34$
Units reaching 70 °F by 5:00 a.m.	0 of 23	14 of 27	—
Whole-face mean at 5:00 a.m. (°F)	67.2 (64.8–69.1)	70.3 (66.7–75.4)	ambient 73.6 °F

p values for unit means and SD are from Welch's test on one value per unit; band p values are from the Mann-Whitney U test. Durations are hours from removal from the freezer.

25.2 Whole-face mean temperature

The medium DuraTherm group mean was below the control group mean at every one of the 40 reads (Figure 3). The mean difference across reads was -2.7 °F (range -0.02 to -5.4 °F), and the per-read Welch test gave $p < 0.05$ at 30 reads. Over the whole test, the mean face temperature of DuraTherm units was 47.5 °F against 50.1 °F for controls (one value per unit; Welch $p = 0.001$). The center zone alone showed the same difference (-2.6 °F). At the first read, about 1.1 h after removal, 14 of 27 controls already read 40 °F or above, against 1 of 23 DuraTherm units. H1 is supported.

The group curves are not smooth. During the first ten reads both groups alternated between colder and warmer reads; this reflects which face had just been exposed to room air and is analyzed in Section 25.10. The difference between groups was largest on faces that had been exposed for a full period and smallest on faces that had just been turned up from the insulation. After about 8 h the two curves converged; between 9 and 11 h the difference was small and often not significant, and in the final reads DuraTherm again ran about 2 °F colder, as controls approached room temperature.

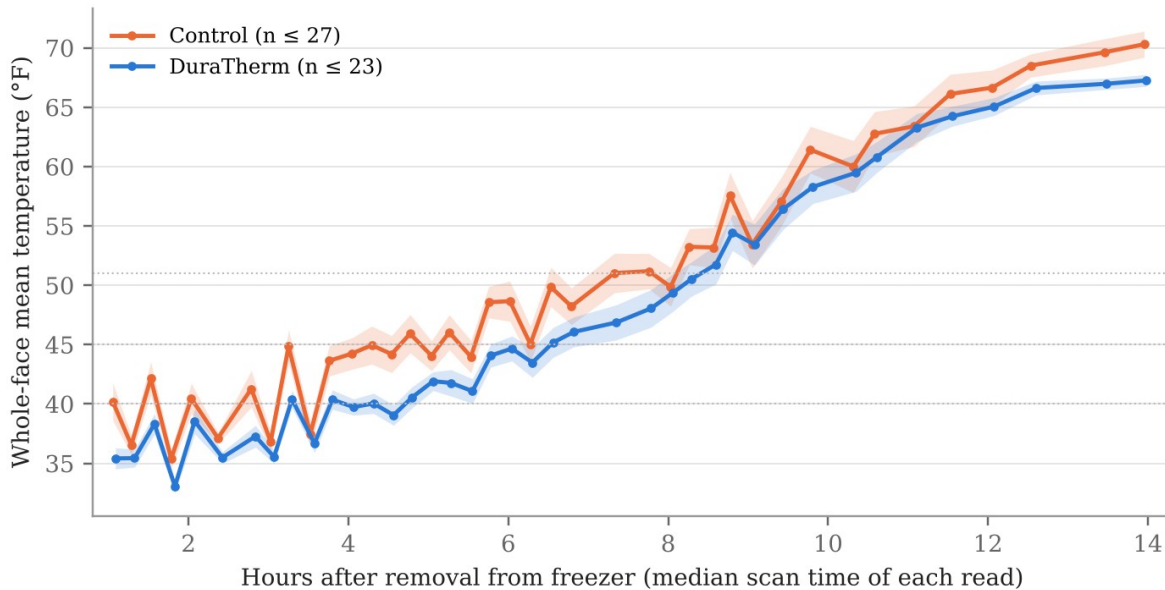


Figure 3. Whole-face mean temperature of medium units by read, with 95% confidence bands (controls, $n \leq 27$; DuraTherm, $n \leq 23$). Each point is placed at the median scan time of the read. Dotted lines mark 40, 45, and 51 °F.

25.3 Coldest part and warmest regions

The coldest part of the face, the mean of its coldest 10%, was nearly identical in the two groups: 42.7 °F for DuraTherm and 42.9 °F for controls, averaged over all scans. It differed significantly at only 6 of 40 reads, with the sign varying between reads. The 1st-percentile temperature was likewise similar (41.4 vs. 41.9 °F). The warm tail differed consistently: the 99th-percentile temperature averaged 58.5 °F in DuraTherm and 61.6 °F in controls, and the spread between the 1st and 99th percentiles was smaller in DuraTherm at every read (17.0 vs. 19.7 °F; unit-level Welch $p \approx 8 \times 10^{-6}$).

The colder DuraTherm average therefore arose from warm regions being less warm, not from a colder frozen core. This is the pattern predicted by the mass-distribution mechanism of Section 11 and is not what a uniformly greater cooling capacity would produce.

25.4 Within-face uniformity

The within-face SD of DuraTherm units was lower than that of controls at every read (Figure 5), significantly so at 34 of 40 reads, and averaged 3.8 °F against 5.2 °F (unit-level Welch $p \approx 4 \times 10^{-10}$). The control SD alternated strongly during the first ten reads, in step with the handling effect of Section 25.10, while the DuraTherm SD varied much less. Both SDs fell steadily after about 8 h as the units approached room temperature. Of the ten units with the highest cold-uniform rankings, eight were DuraTherm units. H2 is supported for dispersion-based measures.

The cold-anchored classification (Section 23.6) gives a more qualified result. Over all scans, 25% of DuraTherm scans and 19% of control scans were cold-uniform, 45% and 29% were warm-uniform, and 30% and 52% were non-uniform. However, much of the cold-uniform difference comes from the final reads, when faces above 60 °F were close to thermal equilibrium (99% of such DuraTherm scans and 62% of such control scans were cold-uniform). Restricted to the useful range, scans with a whole-face mean below 51 °F (616 DuraTherm and 659 control scans):

- Within-face SD was 4.5 °F for DuraTherm and 6.3 °F for controls ($p \approx 8 \times 10^{-12}$).

- The largest 5 °F window held 59% of the DuraTherm face and 46% of the control face ($p \approx 3 \times 10^{-11}$); 59% of DuraTherm scans and 27% of control scans were warm-uniform, and 33% and 65% were non-uniform.
- The share of the face within ± 2.5 °F of the coldest part did not differ (28% vs. 27%; $p = 0.52$), and few scans of either group were cold-uniform (7% vs. 8%).

Within the useful range, therefore, DuraTherm faces had a tighter main body of temperature and fewer warm outliers, but both pack types usually carried a distinct cold region, more than 2.5 °F below the bulk of the face. By the cold-anchored criterion the groups were not distinguishable while the faces were below 51 °F.

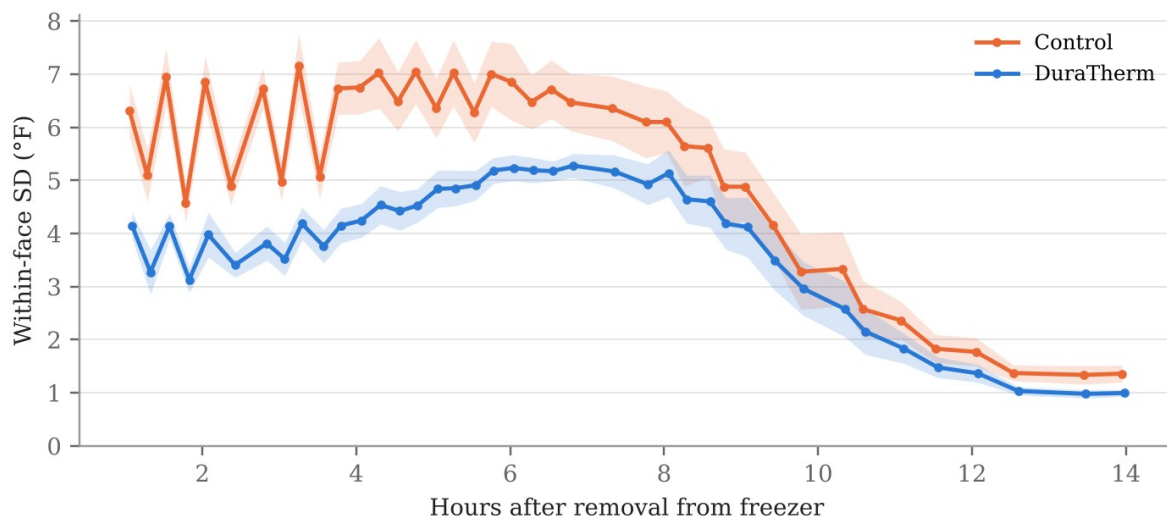


Figure 5. Within-face standard deviation of medium units by read, with 95% confidence bands.

25.5 Zone analysis

The neck (top) zone was the warmest zone in both groups (Figure 6). Averaged over reads, the top zone exceeded the center zone by 8.9 °F in DuraTherm units and 8.1 °F in controls; the difference between groups in this excess is smaller than the 1.9 °F margin of error of the top-zone value. Among scans in which all five zones were readable, the top zone was the warmest zone in 91% of DuraTherm scans ($n = 838$) and 58% of control scans ($n = 984$).

Controls ran warm at the bottom zone. The bottom zone was the controls' warmest zone in 29% of their scans, against 9% for DuraTherm, and control bottom zones averaged 3.0 °F warmer than DuraTherm bottom zones at the same reads. Relative to their own center zones, the bottom excess was 4.3 °F in controls and 3.9 °F in DuraTherm units. Controls were warmer than DuraTherm units in every zone: by 2.7 °F over the whole face, 2.6 °F in the center, 1.8 °F at the top, 3.0 °F at the bottom, 4.1 °F on the left, and 3.6 °F on the right. The side zones of controls were warmer relative to their centers (left +4.9, right +3.5 °F) than those of DuraTherm units (+3.4 and +2.5 °F), so warm regions in controls were distributed around the edges rather than confined to the neck. A left-over-right excess of about 1 °F occurred in both groups and is more likely a feature of the setup than of the units.

The DuraTherm neck excess was examined against the build record. Units 01–20MD were sealed while cold and their sealant was drawn down into the neck (Section 21.3), which could create a locally different structure at the neck. However, the legacy units 21–23MD, sealed dry, showed a similar top excess (+9.2 °F,

against +8.9 °F for 01–20MD), and the controls, which have factory closures, showed +8.1 °F. Most of the neck warmth is therefore common to the shell design, consistent with the neck and its flanking shoulder cavities (Section 8.4) being a thermal weak point in all units. H4 is partly supported: warm edge regions were more extensive in controls, but the neck end was a common weak point rather than a control-specific one.

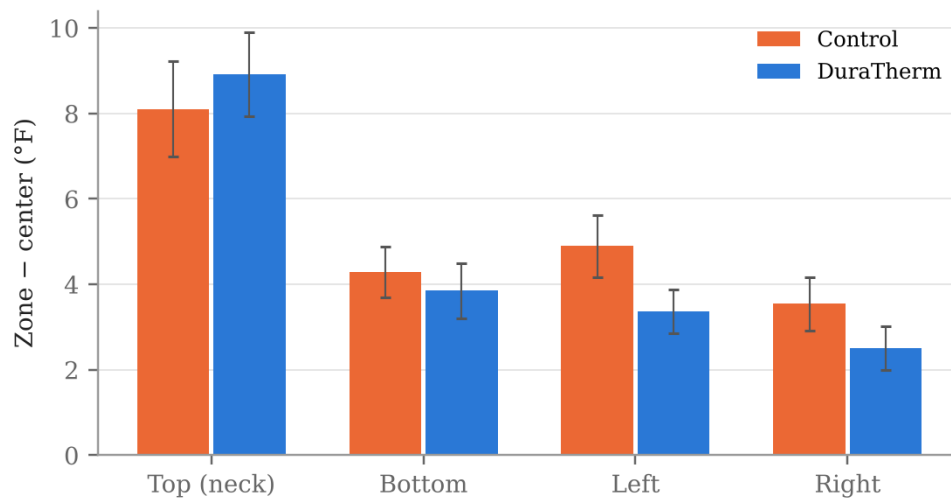


Figure 6. Mean excess of each edge zone over the center zone, medium units, averaged over reads. Error bars are 95% confidence intervals across reads.

25.6 Duration below the priority limits

Figure 4 shows the fraction of units still reading below each limit (final exit) as a function of time. By final exit, the median DuraTherm unit stayed below 40 °F for 4.8 h against 3.5 h for controls (Mann–Whitney $p = 0.0001$) and below 45 °F for 6.3 h against 5.5 h ($p = 0.008$). Below 51 °F the medians were 8.3 and 8.0 h ($p = 0.31$), and below 60 °F 9.8 and 10.3 h ($p = 0.34$).

By first exit, which ends a unit's time below a limit at its first scan at or above it, the differences were larger: 3.1 vs. 1.8 h below 40 °F, 6.3 vs. 5.2 h below 45 °F, and 8.3 vs. 6.8 h below 51 °F. Units already at or above a limit at their first scan have no first-exit duration; 14 controls and 1 DuraTherm unit were excluded on that basis at 40 °F and 3 controls at 45 °F. Counting those units as zero duration, the first-exit differences were significant at 40, 45, and 51 °F (Mann–Whitney $p \approx 6 \times 10^{-6}$, 4×10^{-6} , and 0.003) but not at 60 °F ($p = 0.08$).

H3 is supported for 40 and 45 °F by both measures and for 51 °F by first exit only. Expressed as time observed inside each band (first to last in-band scan), DuraTherm units spent a mean of 3.5 h in the 34–39.9 °F band against 2.5 h for controls, and less time in the 45–50.9 and 51–59.9 °F bands (1.6 and 1.5 h against 3.7 and 3.0 h). Part of the longer control spans arises because control faces moved in and out of these bands from read to read with the handling alternation (Section 25.10), which lengthens the first-to-last interval; the band spans are therefore descriptive.

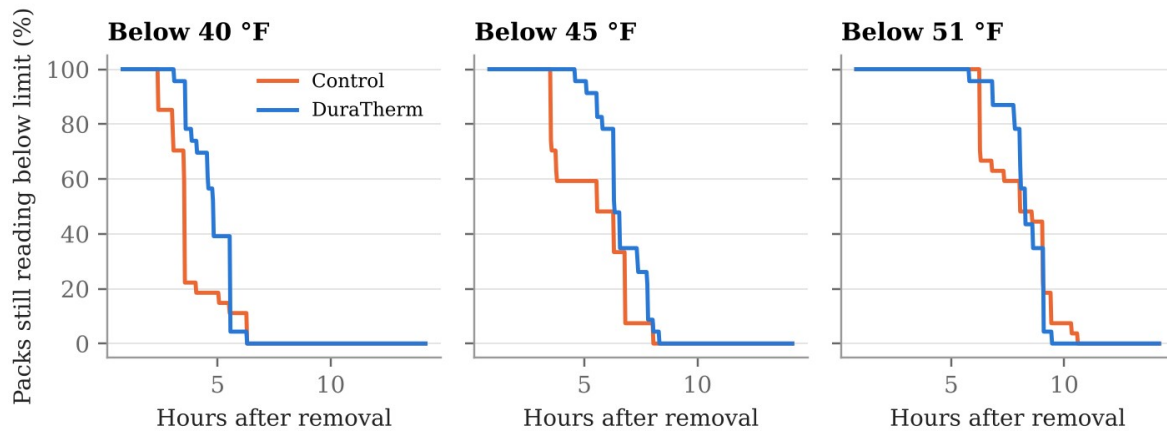


Figure 4. Percentage of medium units still reading below 40, 45, and 51 °F (final exit) versus hours after removal from the freezer.

25.7 End criterion and late-phase warming

By 5:00 a.m., 14 of 27 controls had reached 70 °F (between 2:29 and 4:56 a.m., 11.5–14.0 h after removal) and one further control (27MC) had plateaued at about 67.2 °F from 2:05 a.m. No DuraTherm unit reached 70 °F. Five DuraTherm units met the plateau criterion (05MD, 13MD, 18MD, 19MD, and 21MD), with plateaus between 64.6 and 69.2 °F beginning between 2:07 and 3:36 a.m.; the remaining 18 were still rising slowly. At the last read the whole-face mean was 67.2 °F (range 64.8–69.1) for DuraTherm units and 70.3 °F (66.7–75.4) for controls.

Warming rates were estimated for each unit by least-squares slopes of whole-face mean against time. From 4:00 to 10:45 p.m. the rates did not differ (DuraTherm 1.9 °F/h, control 2.0 °F/h; $p = 0.36$). Between 1:15 and 5:00 a.m. DuraTherm units warmed more slowly (2.1 vs. 2.6 °F/h; $p = 0.012$). The late difference is partly a consequence of controls nearing room temperature, where warming necessarily slows; the reason DuraTherm units remained 4.5–9 °F below room temperature at 14 h was not determined (Section 27).

25.8 Small format

The small-format arm (4 DuraTherm units, 6 controls; 33 reads from 4:00 p.m. to 1:30 a.m., with no small-unit images at 5:46 p.m.) did not reproduce the medium result (Figure 7). Small DuraTherm units were slightly colder than small controls in the first reads (mean difference -1.3 °F before 3.5 h) but warmer afterwards (mean $+2.5$ °F after 3.5 h, maximum $+5.5$ °F), and they were warmer at 26 of 33 reads. By final exit, median times below the limits were shorter for small DuraTherm units: 2.4 vs. 3.6 h below 40 °F, 4.3 vs. 4.7 h below 45 °F, 5.7 vs. 6.2 h below 51 °F, and 7.1 vs. 8.3 h below 60 °F. The small DuraTherm units remained more uniform: their within-face SD was lower at 32 of 33 reads (mean 3.6 vs. 4.9 °F; unit-level Welch $p \approx 6 \times 10^{-4}$).

The small DuraTherm units accepted only about 189–192 g of water before they began to weep during manual top filling (target 193 g), and in prototype work the lower region of small units has shown signs of incomplete wetting (Section 14). The result is consistent with, but does not demonstrate, a fill or wetting limitation in the small shell (Section 13.3). With four and six units, the comparison is indicative; it is reported as a negative result for the small format under the present build method.

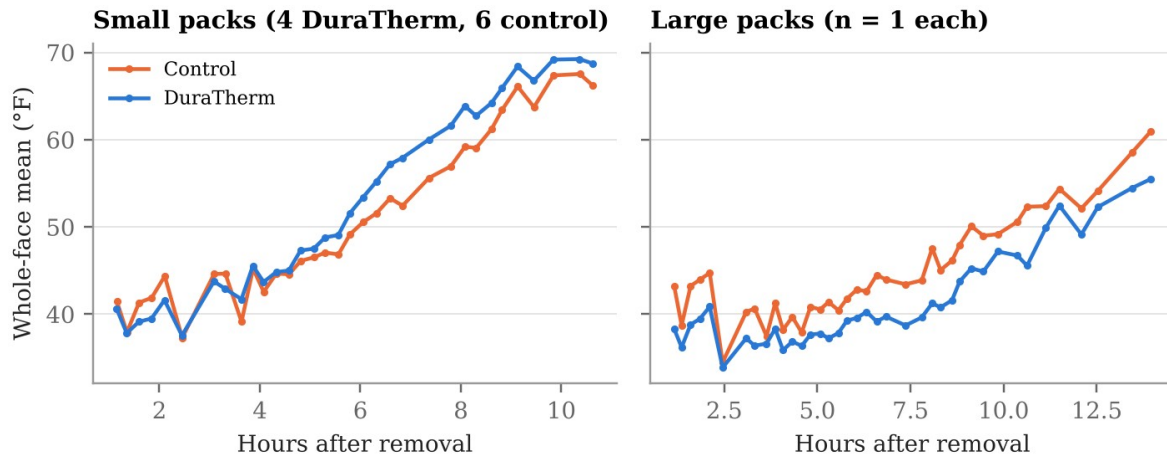


Figure 7. Whole-face mean temperature of small units (group means; 4 DuraTherm, 6 controls) and of the single large unit of each type.

25.9 Large format

The single large DuraTherm unit was colder than the single large control at every one of 39 reads, by 3.5 °F on average (range 0.6–6.8 °F), and had a lower within-face SD (5.2 vs. 7.3 °F). At 5:00 a.m. the two units read 55.5 and 60.9 °F; neither approached the end criterion. With one unit per type, and a DuraTherm unit that is heavier (1,346 vs. 1,095 g, the difference being cotton rather than additional water), this result is descriptive only and is not evidence for or against the large format.

25.10 Handling (flip) effect

The 6:30 p.m. repeat images quantify how fast a newly exposed face changes (Figure 8). The same ten controls and ten DuraTherm units, first imaged immediately after being turned, read 5.0 °F warmer in both groups when re-imaged 3–8 minutes later (controls 40.5 – 45.5 °F; DuraTherm 35.6 – 40.5 °F). The cold-uniform share fell from 38% to 22% in controls and from 43% to 29% in DuraTherm units. The coldest part changed little in controls (34.6 – 34.2 °F) but rose in DuraTherm units (32.2 – 35.6 °F).

The same mechanism explains the alternation of the early group curves. The handling routine (Section 22.3) alternated between reads in which the imaged face had been exposed to room air for about 15 minutes and reads in which it had just been turned up from the insulation; the logged 6:15 and 6:30 p.m. reads are of the first and second kind, and earlier reads are classified from the strict alternation of the record. Over the first ten reads:

- On freshly turned faces (4:15, 4:45, 5:21, 6:00, and 6:30 p.m.), controls averaged 36.7 °F and DuraTherm units 35.2 °F (difference –1.4 °F), and the cold-uniform share was the same in both groups (44%).
- On faces exposed for a full period (4:00, 4:30, 5:00, 5:46, and 6:15 p.m.), controls averaged 41.8 °F and DuraTherm units 38.0 °F (difference –3.8 °F), with cold-uniform shares of 26% and 29%.

A face that has rested on insulation is shielded from convective heat gain and presents a transiently cold, comparatively uniform surface in both pack types. The difference between pack types appears as that face equilibrates with room air, which is the condition relevant to use. Because both groups were handled identically within each read, per-read comparisons are matched for handling state. After the procedure change at 6:30 p.m. the alternation became much smaller. Future tests turn each unit a fixed, timed interval (10 minutes) before it is imaged (Appendix D).

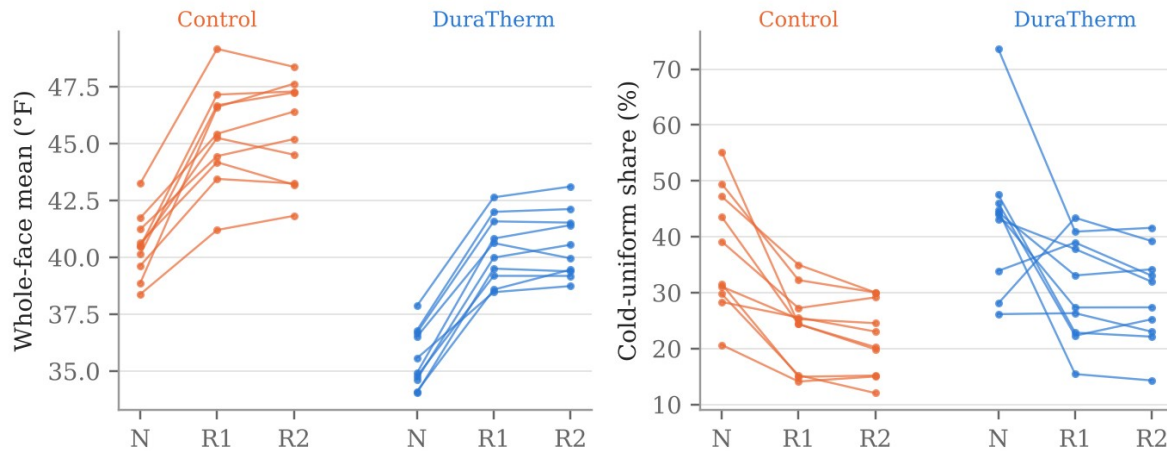


Figure 8. The 6:30 p.m. handling test: whole-face mean and cold-uniform share for the first ten medium controls and first ten medium DuraTherm units in the normal round (N) and when re-imaged minutes later (R1, R2).

25.11 Build history and fill-mass covariates

The three legacy DuraTherm units, which contain no borax and had expressed water over more cycles, ran 0.7 °F warmer on average than units 01–20MD, with a similar coldest part (42.7 °F in both) and similar uniformity; with three units, the difference is within unit-to-unit variation. Among controls, heavier units ran colder: post-test mass correlated with each unit's mean face temperature ($r = -0.40$, $p = 0.04$). No such relation was found among DuraTherm units ($r = -0.10$, $p = 0.66$), whose water charge was set by tare and whose mass also includes cotton and sealant. Variation in gel charge is therefore one source of the larger unit-to-unit spread among controls.

26. Special Comments

This section collects the qualitative observations made during the test and during image processing, as reported by the investigator. They are recorded here, rather than in the results, in keeping with the reporting structure of this test program. Quantitative checks are cross-referenced where they exist.

26.1 Bulging

- On caliper inspection, control bulges were sharper and more localized ("spiky"), whereas DuraTherm bulges usually spread across the whole face.
- The investigator judges that the current batch carries a heavier cotton fill than preferred (about 4–5% of pack mass above the intended level) and attributes a larger overall bulge in the batch units to that fill. Legacy units 21MD and 22MD reflect a different, thinner standard. A lower-fill offset batch is planned (Appendix D).

26.2 Thermal appearance of the two pack types

- In the IR images a control and a DuraTherm unit could be told apart about 95% of the time, because controls show very warm sections against the comparatively uniform DuraTherm faces.
- Many DuraTherm units showed a top slightly warmer than the rest of the face, with the remainder uniform. The neck (top) is the hardest area to fill with cotton, which the investigator gives as the reason for the warmer tops. The zone analysis confirms the warm neck in DuraTherm units but finds a comparable neck excess in controls (Section 25.5).

- Controls showed substantial internal deviation, readily seen in the images, with additional areas outside a general temperature range.

26.3 Neck sealant

Units 01–20MD were sealed while cold, and in most of them the sealant was drawn down into the neck: large beads applied on top ended as very small beads, and four or five units had to be retouched because the seal was not thorough. The legacy units were sealed dry, without cold. The investigator regards the warm DuraTherm necks as explained by this sealing history; the zone data show that the legacy units and the controls also have warm necks (Section 25.5), so the sealant is at most a partial contributor.

26.4 Controls warm at the bottom

Controls ran warm at the bottom zone. This is reported as observed and is confirmed quantitatively in Section 25.5.

26.5 Post-flip uniformity

Immediately after a unit was turned, the newly exposed face showed good temperature uniformity, which faded within minutes; this was seen on several DuraTherm units before half of them had been imaged at 6:30 p.m. The effect appears only when a unit is imaged immediately after being turned. Its cause is undetermined. Convection was considered but may be an over-hasty explanation at less than 3 h into the readings; gravity or another factor is possible. The repeat images of Section 25.10 quantify the effect.

26.6 Moisture, condensation, and insulation

- Moisture generated during the test was substantial and often collected around the units, especially during turning and with minor movements. Droplets were visible in the IR images and, as the units warmed, their temperature approached that of the units.
- Excess water ran through the joints between insulation panels and soaked the bed beneath.
- Unit spacing appears adequate: a thermal bridge between adjacent units rarely formed.
- Slight temperature variation was visible on the insulation near the units, but it does not appear to have disrupted the unit temperatures significantly.
- The insulation helped. Because only the room air, not a cold surface, drove the temperature of the surrounding moisture, the moisture around all units aged at the same rate; this made it easy to tell when a unit had been turned and which droplets came from which unit.

26.7 Boundary identification and image processing

- When units began to fail (above roughly 60 °F in some areas), their warmer regions blended into the background, typically within 5–10 °F of the insulation beneath and in places up to 20 °F or more. The boundary remained mostly discernible to the eye but not to automatic methods.
- This required hand-drawn outlines. The adopted standard is a light-blue or green line along each long side of the pack, whose ends mark the top and bottom of the pack. Drawing these lines took about 10–15 minutes per read for all active units. One-pixel lines were used for most images; thicker lines were used on the third and fourth reads when time was short and were discontinued.
- For some units, part of the boundary had to be triangulated from other visible parts, for example where one side of a small unit blended completely into the insulation. This was common.
- In some images a side wall was captured along with the rear face. Usually the side stands out clearly; in others it required two to three times the normal outlining time.

- Identification wires are thermally conductive and disturbed a small part of some faces. In a few images a tag, from the unit itself or a neighbor, overlapped the face.
- When a unit was very cold, the insulation glowed with more color than usual (almost-white yellow to gold); as it turned orange, the unit was close to the temperature of the insulation. Droplets distorted the sides in some cold images. Both effects confounded automatic boundary detection.

26.8 Camera handling

- The lack of a stable camera platform was the largest practical problem: not all images are centered, and in some a fair part of the unit lies outside the frame (for example, the image taken at 11:48 p.m. on October 3, where a cold spot just above the frame edge could be mistaken for the unit).
- Some images were taken leaning over the bench at an angle.
- The imager switched between portrait and landscape orientation, so that some images were stored with the neck to the left or upside down. This was not corrected during the test, in order to keep to schedule. In almost all cases the neck is identifiable, and where it was not obvious it was marked by hand (Section 23.4).

26.9 Read-specific events

- 6:45 p.m.: the first image of 01MD was poor and was retaken.
- 10:15 p.m.: units were accidentally turned an extra time and were turned back before 10:30 p.m.
- 10:30 p.m.: the next-to-last set of six medium DuraTherm units was not imaged; the read was excluded (Section 22.2).
- 11:45 p.m.: 17MC was not imaged.
- 12:15 a.m.: the read was missed; units were turned back to the correct face and imaged at 12:24–12:27 a.m.
- 1:00 a.m.: imaged at 1:15 a.m. instead.
- 5:00 a.m.: in the investigator's field note at the final read, units felt even front to back, with no hidden cold pockets, and most would have finished by about 5:30 a.m.

26.10 Labels and identification after the test

Cardboard tags degraded in the meltwater. The unit first tagged 21 (with 22 scratched out) was re-identified as 23MD (500 g); the confirmed 21MD weighs 486 g; an unlabeled unit in the freezer was identified as 17MD; and a 423.0 g unit first recorded as 23MD was identified by elimination as control 27MC (reweighed at 421 g). Every control is to receive a permanent individual tag so that any future test or sample can be traced to the exact unit.

26.11 Investigator's overall assessment

The investigator's assessment is that the test supports a proper evaluation of DuraTherm against the FreezPAK, which uses a sodium polyacrylate superabsorbent gel, and that DuraTherm performed better, with a closer margin in the small format; the large units cannot serve as proof either way. The quantitative analysis supports the assessment for the medium format, finds that the small format reversed after about 3.5 h (Section 25.8), and agrees that the large result is descriptive.

27. Limitations and Threats to Validity

- **Scope.** This is a single test in one session by one investigator. Replication with independent preparation, and with blinding of outline drawing to unit identity, is required before the effect sizes are treated as general.
- **What is compared.** The comparison is between finished products, not between fiber and no fiber in an otherwise identical system. The DuraTherm units contain water with borax and cotton; the controls contain a sodium polyacrylate gel. DuraTherm units were built from drilled shells, conditioned through a deliberate freeze–thaw cycle, and sealed with silicone at the neck, whereas controls were factory sealed. Each of these differences could contribute to the result.
- **Fill and storage.** The current batch carries more cotton than intended (Section 26.1), and the gel charge of the controls varied by unit (Section 25.11). Nine controls were frozen in their original shipping packaging, which may have affected how cold they were at removal.
- **Repeated measures.** Per-read tests are not independent and are not corrected for multiplicity; unit-level tests are the primary inference.
- **Handling state.** Face temperature depended strongly on how recently a face had been exposed (Section 25.10). Comparisons within each read are matched for handling state, but absolute values and durations depend on the routine.
- **Imaging.** The imager was handheld, with variable distance and angle; absolute accuracy of the imager is not included in the margin of error. Late in the test some control faces read above the 73.6 °F room temperature (maximum 75.4 °F at 5:00 a.m.), indicating radiant heating from the lights, an absolute offset, or both; either affects both groups. Moisture and droplets were present on and around the units.
- **Environment.** Relative humidity and the freezer set point were not recorded; the room temperature was read from a single instrument.
- **Surface versus use temperature.** Rear-face temperature is not payload or skin temperature (Section 6.8).
- **Identification.** Unit identity is uncertain by one position in four reads (Section 23.4); these readings are flagged and do not change the group results materially.
- **Missing data.** The 10:30 p.m. read is excluded, the 5:46 p.m. read covers medium units only, and small units were not imaged after 1:30 a.m.
- **Bulge.** Numerical bulge results are pending (Section 24).
- **Late-phase gap.** The reason DuraTherm units stayed several degrees below room temperature at 14 h (residual ice, a difference in emissivity or surface moisture, or evaporative cooling) was not determined.
- **Small and large formats.** Four and six small units give limited power; the large comparison has one unit per type.

28. Summary of the October 2026 Test

1. In the medium format, DuraTherm units were colder than SAP-gel controls on average at all 40 reads (–2.7 °F; unit-level $p = 0.001$; $p < 0.05$ at 30 reads).
2. DuraTherm faces were less dispersed at every read (within-face SD 3.8 vs. 5.2 °F; spread 17.0 vs. 19.7 °F). Within the useful range, the main body of the DuraTherm face was tighter (59% vs. 46% of the face within one 5 °F window), but the share of the face within ± 2.5 °F of its coldest part did not differ.

3. The coldest part of the face was the same in both groups; the advantage came from smaller and fewer warm regions.
4. DuraTherm units stayed below 40 and 45 °F longer (median 4.8 vs. 3.5 h and 6.3 vs. 5.5 h, final exit), and below 51 °F longer by first exit. No DuraTherm unit reached 70 °F within 14 h; 14 of 27 controls did.
5. The neck end was the warmest zone in both groups; controls also ran warm at the bottom and sides.
6. The small format did not show the medium-format advantage in temperature or duration after about 3.5 h, although it remained more uniform. The large comparison (one unit each) favored DuraTherm and is descriptive.
7. Handling history strongly affects measured surface temperature; future tests standardize the interval between turning and imaging.

PART IV

EXTENDED SCIENCE, ENGINEERING, AND RESEARCH**29. Freeze–Thaw Durability and Aging**

Repeated phase change imposes mechanical, thermal, and packaging cycles on every reusable cold pack regardless of internal coolant. Ice formation changes volume and internal stress; thawing removes solid support and permits redistribution. The relevant durability question is therefore not only whether the coolant remains chemically stable, but whether the complete pack preserves geometry, internal distribution, seal integrity, and useful thermal performance over repeated cycles.

29.1 DuraTherm cycling mechanisms

In DuraTherm, repeated freezing can move fibers locally, expand pores, generate microcracks in the ice phase, redistribute trapped gas, and compact or relax portions of the fiber network. Thawing removes ice support and allows the network to recover, settle, or reorganize depending on entanglement, wetting, confinement, and shell geometry. Native cotton sliver therefore requires direct cycle testing even though related cellulose sponge, hydrogel, and fiber–ice systems provide encouraging durability precedents.

For native cotton, principal aging variables include sliver compaction, fiber migration near walls, local densification, bubble redistribution, changes in interfiber friction, microbial growth if nonsterile water remains warm for long periods, shell abrasion at concentrated contacts, and seal contamination during filling. None should be assumed severe without evidence, but each is measurable.

Prototype records add two cycle-related observations (Class III). First, units with an open port express excess liquid over their first freeze–thaw cycles and then stabilize: the legacy units of the October 2026 test had expressed over three or more cycles, after which no further mass change was observed, and all current units were given one deliberate expression cycle before sealing (Section 21.2). Second, a seal applied while a unit is still partly frozen can be drawn inward overnight, plausibly because melting of the remaining ice contracts the internal contents while the sealant is uncured (Section 21.3). Both observations bear on how a production unit should be filled, conditioned, and closed (Section 34).

29.2 Flexible gel-pack comparison

Soft or flexible gel packs experience their own freeze–thaw geometry cycle. Because the enclosure permits substantial shape change, gel can sag, pool, redistribute, and freeze into different local thicknesses from cycle to cycle. Repeated flexing also loads films, seams, corners, and any regions where frozen material creates concentrated bending or point loads. A flexible shell exposes internal redistribution as visible bulging and thickness variation, making geometry drift an important durability metric in addition to leakage or gel chemistry.

29.3 Hard-shell gel-pack comparison

Rigid or semi-rigid hard-shell gel packs control external bulging more effectively because the enclosure constrains the outside shape. That does not necessarily eliminate internal redistribution. Gel, headspace, and trapped air can still occupy the rigid enclosure unevenly, producing coolant-rich and coolant-poor regions even when the exterior dimensions remain fixed. The rigid shell therefore changes the failure mode: external deformation is reduced, while internal distribution, wall stress, closure integrity, impact damage, and repeated expansion loading become more important.

The distinction is important for DuraTherm comparisons. A soft conventional pack can reveal uncontrolled redistribution through bulging, whereas a hard shell can hide the same class of internal distribution problem behind a fixed exterior geometry. The warm bottom and side zones of the semi-rigid controls in the October 2026 test (Section 25.5) are consistent with such hidden redistribution. DuraTherm instead uses the fiber network to control coolant distribution internally, so the comparison should examine internal thermal-mass distribution as well as external package shape.

29.4 Standardized freeze-thaw comparison

A standardized cycle program should compare DuraTherm, flexible gel packs, and hard-shell gel packs through repeated identical freeze and thaw histories. Measurements should include mass change, maximum and minimum thickness, external profile, internal air or underfilled regions where observable, surface-temperature spread, useful-window duration, seam or closure condition, puncture and drop survival, shell cracking or flex damage, and any permanent coolant redistribution. The purpose is to determine not merely whether a pack survives a stated number of cycles, but whether it retains the geometry and thermal behavior that defined its original performance.

30. Microbiology, Water Quality, and Antimicrobial Considerations

Cotton and water are not intrinsically sterile. Freezing suppresses microbial growth but is not sterilization. DuraTherm designs intended for prolonged hydrated storage, medical environments, food logistics, or repeated reuse therefore require a microbiological control strategy appropriate to the application. Variables include source-water quality, antimicrobial chemistry, shell cleanliness, warm-dwell time, hydration procedure, seal integrity, and cycle history.

The internal aqueous phase contains disodium tetraborate decahydrate at 1–2% w/w, which serves as an antimicrobial agent to prevent contamination introduced by the water or cotton from propagating through the solution. Microbial growth is suppressed while the pack is frozen; the borate is required principally during extended dwell in the thawed state, where its solubility (~4.8% w/w at 20 °C) ensures full dissolution at the specified concentration. Near 0 °C solubility falls to ~2.2% w/w, and freeze concentration during ice formation may transiently crystallize borate within the fiber network; this occurs in the temperature regime where microbial growth is already minimal, and the borate redissolves on warming. Antimicrobial efficacy at the specified concentration remains to be confirmed by standard preservative-effectiveness testing.

Other preservatives, such as sodium benzoate or potassium sorbate, show that antimicrobial chemistry can be inexpensive at low concentrations, but any alternative chemistry and concentration must be established by compatibility, efficacy, toxicology, intended-use, and regulatory testing. A material-cost illustration is not a formulation recommendation. Under final-mile hydration (Section 18.2), supply water is treated by ultraviolet irradiation and the hydration bath carries borate, so microbial control acts on both the incoming water and the units in process.

31. Regulatory and Safety Considerations: Potential Dermal or Open-Wound Contact

Thermal therapy packs are routinely applied to traumatized or post-surgical tissue, where the integrity of the skin barrier may be compromised. Under these conditions, failure of the primary containment shell introduces a secondary exposure pathway: direct contact between the internal phase and dermal or open-wound tissue. The toxicological significance of such contact depends on the composition of the internal

phase, the quantity of mobile liquid available for transfer, and the physicochemical response of that phase to physiological fluids. Barrier-compromised skin exhibits substantially greater permeability than intact stratum corneum, so constituents of negligible concern under normal use may become relevant in this scenario. This section evaluates the borate-containing internal phase of the DuraTherm fiber-ice composite against applicable U.S. and EU regulatory frameworks, and characterizes the electrolyte-dependent behavior of conventional hydrogel cold packs under equivalent failure conditions for comparison.

31.1 DuraTherm: borate content

The internal aqueous phase contains disodium tetraborate decahydrate ($\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$; CAS 1303-96-4) at 1–2% w/w, equivalent to 0.65–1.30% w/w as boric acid. The fluid is enclosed within the polymer shell and retained by capillary sorption in the cotton fiber matrix, which limits free-liquid release on shell compromise. Applicable frameworks were assessed against this formulation (Table 7) [62–67].

Table 7. Regulatory status of borate content

Framework	Provision	Threshold / scope	Status
EU CLP (EC) 1272/2008	Repr. 1B (H360FD), specific concentration limit	$\geq 8.5\%$ w/w	Below threshold; mixture not classified
EU REACH Annex XVII (Reg. 109/2012)	Restriction on supply to the general public	$\geq$ specific concentration limit	Not applicable
EU REACH Art. 33	SVHC in articles	$> 0.1\%$ w/w of article	Applicable; disclosure obligation only (safe-use information, SCIP notification)
EU MDR 2017/745, Annex I §10.4.1	CMR substances in device materials	Body-contacting or substance-delivering materials, $> 0.1\%$ w/w	Not applicable; enclosed, non-contacting phase
US FDA 21 CFR 890.5700 / 890.5710	Cold pack, Class I	General controls; 510(k)-exempt	Applicable; biocompatibility limited to body-contacting shell
US OSHA 29 CFR 1910.1200	Hazard Communication	Workplace handling; "article" exemption	Applies to manufacturing only; finished unit qualifies as an article
US CPSC 16 CFR 1500 (FHSA)	Acute oral toxicity ("toxic")	$\text{LD}_{50} \leq 5 \text{ g/kg}$	Estimated mixture LD_{50} well above limit; not hazardous
US DOT 49 CFR	Hazardous materials transport	Hazmat table listing	Not regulated

The MDR and OSHA determinations rest on fluid retention by the fiber matrix. Contact between the borate phase and tissue requires catastrophic failure of the shell beyond the matrix's retention capacity. The shell failure modes of Section 31.3 and the fill-port retention observations of Section 14 bear on this; quantitative fluid-release data under controlled shell compromise remain to be obtained (Section 42).

31.2 Comparative assessment: hydrogel cold packs

Commercial gel packs use either covalently crosslinked polyelectrolyte networks or dissolved cellulose-ether thickeners. Ionic networks swell through Donnan osmotic pressure generated by fixed carboxylate charges. External electrolyte screens those charges, lowers the osmotic driving force, and produces electrolyte-induced deswelling with syneresis (expulsion of free liquid). Blood and wound exudate ($\sim 0.9\%$ NaCl) and sweat (~ 0.2 – 1% NaCl) are sufficient to induce this response.

On shell rupture over an open wound, contact with saline physiological fluid can therefore convert retained gel into mobile liquid, increasing transport of the gel phase and its additives (preservatives, dyes, glycols) into the wound bed. The hazard is rated ultra-light to light, conditional on concurrent shell rupture, an open wound, and sufficient electrolyte exposure.

Table 8. Electrolyte sensitivity by gelling agent

Gelling agent	Structure	Electrolyte sensitivity
Sodium polyacrylate (SAP)	Crosslinked anionic network	High; network collapse with syneresis
Sodium carboxymethyl cellulose (CMC)	Dissolved anionic polymer	Moderate; viscosity reduction
Hydroxyethyl cellulose (HEC)	Dissolved non-ionic polymer	Minimal
Ethylene / diethylene glycol formulations	Glycol antifreeze phase	Not electrolyte-driven; separate systemic toxicity concern

31.3 Shell failure modes

The consequence of shell damage depends on its form. Table 9 classifies hypothetical failure modes of a DuraTherm unit in order of increasing severity, with the expected fluid-release behavior of each. The classification is a Class III engineering assessment based on prototype handling; release thresholds remain to be measured.

Table 9. Hypothetical shell failure modes, ordered by increasing severity

Rank	Failure mode	Origin	Fluid release behavior
1	Pinhole perforation	Incidental external puncture; rare manufacturing defect	Negligible; release requires deliberate application of substantial compressive force
2	Crack	Impact loading (e.g., drop); stochastic propagation path	Small: negligible. Medium to large: release under moderate compressive force, scaling with crack dimension
3	Seam failure	Separation along a heat-sealed seam; propagation constrained to the seam with potential for progressive enlargement	Low risk. Release occurs under compressive loading, or during freezing where unbound liquid pools adjacent to the seam or local fiber saturation exceeds nominal levels; volumetric expansion on freezing displaces that liquid through the seam
4	Seal or cap breach	Dislodgement of the closure	None at rest; release possible during refreezing or under applied force
5	Catastrophic failure	Gross loss of shell integrity	Composite (fiber–water or gel) contact with skin and surrounding surfaces is likely; unit is considered void and must be withdrawn from human and food-contact use

32. Cold Injury and Conditioning Before Use

Units withdrawn directly from a low-temperature freezer present a cold-injury hazard: such a unit has exterior freezer burn, meaning a pack surface cold enough to cause cold injury on skin contact. Units should be conditioned before skin application, either by a rest period at ambient temperature or by

storage of frozen units in a refrigerated holding environment at approximately 1–2 °C (33–35 °F). Because this holding temperature lies only slightly above the melting point, phase change proceeds slowly, preserving latent capacity while raising the surface temperature toward 0 °C. The cotton phase and the shell also insulate the frozen mass, which further slows melting during holding. Holding duration, application time, and barrier requirements will be established by testing and specified in product labeling. Pack-surface temperature is not tissue temperature, and clinical interface measurements remain necessary (Section 6.8).

33. Shell Materials and Thermal Resistance

The shell is simultaneously a structural enclosure, thermal resistance, moisture barrier, seal system, puncture barrier, and repeated-flex component. Raw resin price alone is therefore a poor selection criterion. Candidate materials include HDPE, LDPE, LLDPE, PP, flexible PVC, TPU, PA6/nylon, PET/BOPET, and multilayer combinations (Table 10).

Table 10. Candidate shell materials

Material	Primary strengths	Principal concern for DuraTherm
HDPE	Low cost, chemical resistance, established rigid/semi-rigid packaging	Flex/puncture balance depends on wall geometry
LDPE	Excellent cold flexibility and sealing	Lower stiffness/strength
LLDPE	Excellent freezer flexibility and puncture resistance	Film construction may require multilayer support
PP	Low density, good processability	Cold brittleness in some grades
Flexible PVC	Flexible, heat-sealable	Plasticizer/regulatory considerations
TPU	Excellent abrasion, puncture, and flex durability	Higher material cost
PA6 / Nylon	High puncture strength; useful barrier layer	Moisture sensitivity; often best in laminate
PET / BOPET	High tensile strength and dimensional stability	Repeated-flex limitations; usually needs sealant layer

For a uniform wall of thickness t and thermal conductivity k , the one-dimensional area-normalized thermal resistance is

$$R'' = t / k \quad (\text{m}^2\text{K/W}) \quad (8)$$

and for a specified heat-transfer area A the corresponding total conduction resistance is $R = t/(kA)$. Finished-shell evaluation should combine thermal resistance with shell mass, puncture and tear performance, low-temperature flexibility, sealability, water barrier, freeze–thaw durability, manufacturability, and cost. The October 2026 test identified the neck and its shoulder cavities as the warmest zone in both DuraTherm and control units (Section 25.5); shell geometry at the neck is therefore a design variable for thermal performance as well as for storage fit.

34. Closure and Fill Port

Prototype units are made from commercial shells whose original seal is drilled out, leaving a fill port of approximately 12–19 mm ($\frac{1}{2}$ – $\frac{3}{4}$ in). The port is used for filling and, in prototype testing, has been left open to demonstrate fluid retention (Section 14). For the October 2026 test the ports were closed with silicone

sealant; seals applied to units that were still cold were drawn inward overnight, and the neck zone was warm in all unit types (Sections 21.3 and 25.5).

The production closure has not been finalized; selection will follow manufacturer consultation and prototyping, evaluated against seal integrity through freeze–thaw cycling, compatibility with automated submerged filling, resistance to dislodgement, and tamper evidence. As a first step, the investigator has decided to obtain shells with screw-on lids for a matched-fill comparison; the lids are to be leak-tested with PTFE thread-seal tape on water-filled units before use (Appendix D).

35. Material Substitution and Supply Resilience

DuraTherm is not inherently dependent on a single fiber or enclosure material. Cotton and HDPE represent the current working embodiment, but other fibers and polymer systems can be qualified where they provide the required water distribution, structural continuity, freeze–thaw durability, and enclosure performance. This provides a pathway for material substitution in response to availability, cost, or supply-chain disruption.

36. Manufacturing the Long-Fiber Architecture

The principal manufacturing challenge identified by prospective packaging collaborators is repeatably placing the required cotton mass throughout the enclosure at production speed. Existing pharmaceutical cotton-insertion machinery establishes strong industrial precedent for the underlying operations: continuous fiber-coil feeding, programmable metering, cutting, multiple sequential insertion, controlled insertion depth, and automated verification.

DuraTherm does not require invention of an entirely new fiber-insertion process. It requires adaptation of established operations to a substantially larger cotton charge, a shallow rectangular shell, and a distributed internal network. The current medium charge is 115 cotton balls, about 71–76 g by difference in the October 2026 batch (the earlier 100-ball reference was 62.3 g). Because cotton balls are themselves rolled sliver (Section 19.1), continuous sliver is a natural production feed. Manufacturing approaches can include a single formed fiber charge, multiple sequential insertions, or other automated placement methods capable of producing the required internal fiber distribution, including placement into the bottom corners and shoulder cavities that are hardest to fill by hand (Sections 19.4 and 25.5). The engineering problem is to determine the most efficient combination of sliver linear density, charge mass, forming or folding geometry, insertion method, depth and location control, shell fixturing, cycle time, and quality control. A mechanical pre-hydration bulge-correction step and an automated kneading step during wetting (Sections 19.4 and 19.5) belong in the same production line.

37. Temporary Water-Soluble Fiber Restraint

A proposed water-soluble restraint addresses a practical insertion problem: unrestrained sliver can expand, snag, fold unpredictably, and obstruct later insertions. Predetermined sliver sections can be temporarily wrapped, banded, sleeved, or otherwise restrained for automated handling and placement. Following final-mile hydration, the restraint dissolves or disintegrates and releases the cotton to hydrate and occupy the designed internal volume.

The proposed process is: continuous cotton sliver → meter → form or fold → temporary soluble restraint → cut → insert → position → repeat → verify cotton mass → ship dry → add water → dissolve restraint →

hydrate fiber network. Film chemistry, thickness, dissolution temperature, residue, hydration rate, and compatibility require validation under actual DuraTherm fill conditions.

Polyvinyl alcohol (PVA/PVOH) restraints are incompatible with borate-containing formulations: borate ions cross-link dissolved PVA through its 1,3-diol groups, forming a viscoelastic gel rather than a clean solution, which could obstruct hydration and create localized gel regions within the pack. Restraint materials must therefore be borate-compatible. Candidates include hydroxypropyl methylcellulose (HPMC) films (cold-water soluble, negligible borate cross-linking), pullulan films, and starch-based films; galactomannan (guar) and alginate films are excluded. Non-film alternatives include water-dispersible cellulose tissue bands, which share the chemistry of the fiber phase and disintegrate during wetting and kneading, and withdrawn insertion sleeves analogous to existing pharmaceutical cotton-insertion practice, which eliminate the restraint entirely. Compatibility of the selected material with the borate phase must be verified before adoption.

38. Composition Variability, Product Grading, and Material-Yield Efficiency

DuraTherm need not be treated as a purely binary pass/fail formulation system. If testing establishes multiple validated composition and performance regions corresponding to different commercial SKUs, a unit that falls outside the intended SKU specification may still satisfy another validated SKU rather than automatically becoming scrap.

The scientific and manufacturing sequence is: production variance → measurement and QC → validated composition and performance classification → alternate qualified SKU when appropriate. Classification can ultimately incorporate dry fiber mass, final water mass, geometry, and measured or validated-predicted thermal response. Units outside all validated regions, or units with shell, seal, contamination, or other defects, remain subject to rework or rejection. The objective is not zero loss; it is reduction of composition-related manufacturing loss through performance-based grading. The October 2026 batch illustrates the inputs: fifteen units were topped up with cotton to 116.9–117.7 g against a 117.8 g dry target, five units already above target (118.2–122.4 g) were used as built, and water was set by tare to 379.1–381.3 g against 380 g (Table 1).

39. Extensions and Modifications to the Base Pack

The DuraTherm base pack is a self-contained refrigerant unit whose thermal behavior is governed by its fiber-ice architecture, enclosure, and geometry. Some applications, particularly clinical cooling of irregular anatomy and extended-duration use where intense cooling is not needed, may benefit from modifying the interface between the pack and its target. This section describes two such extensions. Both are external add-on features that can be paired with the base pack. Neither is incorporated into the current base-pack embodiment, and their description here does not limit the scope of the DuraTherm patent portfolio. Both are Class III proposals that have not been experimentally validated.

39.1 Conformable saline interface

The first extension is an external bladder of thin, highly compliant film, partially filled with isotonic saline ($\approx 0.9\%$ w/v NaCl), placed between the base pack and the treatment site. Film thickness and fill volume are chosen so the bladder wraps fully around small-radius anatomy, including individual digits, as well as the hand, wrist, ankle, and limbs, which a semi-rigid pack contacts poorly. The bladder is stored at ambient temperature and applied after the base pack is withdrawn from the freezer. Because the thin film

limits durability, the bladder may be designated a single-use device, and its use is recommended only where conformal contact cannot be achieved with the base pack alone.

The interface has three relevant properties:

- Secondary containment. The borate-containing internal phase is separated from tissue by two independent barriers. Exposure therefore requires concurrent failure of both the pack shell and the bladder.
- Benign release fluid. If the bladder ruptures over an open wound, the released fluid is isotonic saline, physiologically compatible and analogous to wound-irrigation solution.
- Electrolyte stability. Because the fluid is not a hydrogel, it does not undergo the electrolyte-induced deswelling described for ionic gels in Section 31.2.

Ambient-temperature storage limits the risk of the saline freezing at the pack interface, but it adds an initial sensible-heat load that delays the onset of cooling. Minimizing fill volume reduces this delay. Ambient storage also means the bladder must be a sealed, sterile-grade enclosure to prevent microbial growth. The bladder film is the body-contacting material and is therefore the component subject to ISO 10993 biocompatibility evaluation. The interface also adds conductive resistance between pack and tissue, so tissue temperature will sit above the pack-surface temperature (cf. Section 6.8).

39.2 Ventilated thermal-moderation attachment

The second extension is a grille- or radiator-type attachment that creates a controlled air-exchange region between the cooling assembly and its target. It is designed for open-air operation. Heat moves through the assembly by conduction and internal convection, while controlled exchange with ambient air raises the delivered interface temperature.

The attachment is intended for applications that need moderate cooling over a longer period rather than maximum cooling intensity. Raising the interface temperature lowers the temperature difference driving heat into the pack from the target. However, exchange with ambient air also introduces a parallel heat load from the surroundings. The net effect on useful duration therefore depends on vent area, attachment geometry, and ambient conditions, and has to be established empirically. Proposed characterization would measure interface temperature and useful-window duration across several vent configurations and ambient conditions (e.g., 70, 75, and 85 °F), benchmarked against the unmodified base pack.

39.3 Attachment

Either extension may be affixed to the base pack by one of two methods. (1) Adhesive: a pressure-sensitive adhesive layer protected by a peel-off release liner. Candidate adhesives must retain tack at sub-zero temperatures, bond to low-surface-energy polyolefin shells, and tolerate surface condensation or frost. At typical thicknesses the layer contributes negligible thermal resistance. (2) Mechanical: integrated straps positioned outside the primary heat-transfer face, tensioned around the base pack by single-use locking ties (e.g., cable-tie or medical-grade equivalents). After use the ties are cut and disposed of as appropriate. Mechanical attachment is independent of surface temperature, moisture, and shell surface energy. The relative merits of adhesive and mechanical attachment have not yet been evaluated.

40. End of Life

Spent or damaged units should be mechanically ruptured (e.g., by crushing or compaction) to release the fiber phase. Where recycling is available, the HDPE shell can be recovered through polyolefin recycling streams and the cotton fiber directed to composting, where it is biodegraded by ordinary soil and compost

microorganisms. Residual borate (approximately 4–8 g of borax per medium unit at 1–2% w/w) is water-soluble and is progressively diluted by precipitation; boron is a plant micronutrient at low concentrations, though disposal of large quantities at a single site should be avoided.

41. Experimental Methods, Standardized Testing, and Cold-Chain Qualification

41.1 Standardized test families

Table 11 lists the test families required to move DuraTherm claims from prototype observation to validated specification. The October 2026 test (Part III) is the first implementation of the thermal-mapping family; its lessons are incorporated in the protocols of Appendix D.

Table 11. Standardized DuraTherm test families

Test family	Primary outputs
Thermal mapping	IR maps of a label-free face at fixed distance and a timed interval after turning; whole-face and zone means, within-face SD, cold-anchored uniformity, warming curve, useful-window duration
Geometry and bulging	Thickness map, maximum bulge, volume distribution, seam deformation
Penetration	Leakage mass and rate, tear propagation, retained coolant, retained useful cooling
Condensation	Condensate g/m ² and g/(m ² ·h), dew-point deficit, spatial wetting
Freeze–thaw aging	Mass change, geometry drift, thermal performance, seal condition, fiber redistribution
Hydration QC	Dry mass, water mass, fill tolerance, hydration time, distribution repeatability
Freeze time	Time to complete freezing at defined freezer set points
Scale comparison	Small, medium, and large surface-area-to-volume ratio, thickness, freeze time, temperature spread, duration

A publishable program should report raw geometry and mass, environmental conditions (including relative humidity and freezer set point), freezer history, sensor placement and calibration, control-pack identity, replicate count, uncertainty, and predefined pass/fail or comparison metrics. DuraTherm-specific claims should remain tied to the conditions actually tested.

41.2 Shell baseline and internal volume

Control shells were drilled, emptied, rinsed, soaked, drained, and tilt-dried for over 36 hours to clear water retained in the shoulder cavities; the lightest of 20 medium and 4 small shells was adopted as the baseline. Internal volume was determined by water fill, repeated four times to eliminate air pockets and account for shell expansion, with exterior surfaces dried before weighing. Air volume was calculated as filled-shell mass minus unaltered pack mass, which is independent of the shell baseline. Gel density was measured at 1.0 g/ml by 5 ml volumetric sample. Using the lightest shell makes the gel mass an upper bound with respect to shell-to-shell variation; the air-volume uncertainty is limited to plastic-mass variation between the filled shell and the unaltered pack, on the order of a few grams.

41.3 Cold-chain qualification pathway

For pharmaceutical, biologic, and other temperature-sensitive shipping applications, DuraTherm can progress from laboratory thermal testing to complete-package qualification using established cold-chain

methodologies [74, 75]. The purpose is to move from the question "how long does the refrigerant stay cold?" to "can the complete insulated shipping system maintain a defined payload within its required temperature range under standardized transportation conditions?"

- Bench thermal characterization of DuraTherm refrigerant units.
- Controlled insulated-shipper testing with an instrumented representative payload.
- Summer, winter, or otherwise appropriate external environmental profiles.
- ISTA 7E thermal-profile testing.
- Complete package design and qualification using the appropriate ISTA Standard 20 methodology.
- Real-lane performance qualification and validation where required by the customer or regulated application.

A particularly informative future experiment would compare a conventional gel or PCM shipper and a DuraTherm shipper using the same payload, insulation, external profile, and target temperature range, while measuring payload excursions, coolant mass and volume, refrigerant count, package weight, and usable payload volume. DuraTherm is not represented here as currently ISTA-qualified; this section defines the professional route to that qualification.

42. Remaining Research Questions and Validation Priorities

Priorities arising from the October 2026 test:

- Transcribe and analyze the October 2026 caliper series (Section 24).
- Replicate the medium-format comparison with timed turning, a fixed camera mount, recorded humidity and freezer set point, and outlines drawn without knowledge of unit identity.
- Run the matched-fill comparison in screw-cap shells and the lower-fill offset comparison (Appendix D) to separate the effects of cotton loading, coolant chemistry, and headspace.
- Determine why the small format underperformed after about 3.5 h, beginning with wetting of the lower region and fill limits in the small shell (Section 25.8).
- Reduce the warm neck and shoulder zone common to all units (Section 25.5) by fill placement or shell geometry, and confirm by frozen cross-section whether fiber and ice occupy the shoulder cavities.
- Determine why DuraTherm units remained several degrees below room temperature at 14 h (Section 25.7).
- Define uniformity metrics for specifications: dispersion-based (SD, 5 °F window) and cold-anchored measures gave different answers within the useful range (Section 25.4).

Continuing priorities:

- Quantify the relationship between fiber architecture, water distribution, and surface-temperature variance, including internal imaging.
- Establish standardized bulge and thickness metrics across conventional and DuraTherm pack sizes.
- Determine long-term freeze-thaw cycle life and dry-storage aging behavior.
- Measure condensation gravimetrically under controlled temperature, humidity, and airflow to determine whether any difference exists (Section 15).
- Measure freeze time across freezer set points (Section 13.5).

- Define localized-penetration limits for no measurable coolant discharge and obtain quantitative fluid-release data for each failure mode of Table 9.
- Confirm antimicrobial efficacy of the borate specification by preservative-effectiveness testing.
- Measure the magnitude of hydration-driven fiber redistribution and test for freeze-front displacement of cotton at ball scale (Sections 19.3 and 19.6).
- Optimize sliver geometry, fiber-charge forming, insertion method or sequence, and borate-compatible temporary restraint for automated manufacturing.
- Validate shell materials, multilayer structures, and the production closure for puncture, flex, seal, thermal resistance, and cost.
- Test large-format packs with adequate replication and the proposed Harrington internal-conduit architecture.
- Establish cold-chain package performance through ISTA-based and real-lane qualification.
- Obtain unfilled shells to replace the drilled-shell baseline with a true empty-shell mass, and measure the internal volume of any DuraTherm-specific shell.
- Determine bound and freezable water in the actual formulation by DSC.

PART V

DEPLOYMENT AND BUSINESS-RELEVANT ENGINEERING

43. Material Purchasing and Production Inputs

The following values are preliminary high-volume material-purchase estimates for the standard medium pack. They are not landed manufacturing cost and intentionally exclude freight and delivery, labor, machinery, tooling amortization, quality control, scrap, overhead, and margin. The current 115-ball medium reference unit has a filled mass of about 497–502 g before sealing (Table 1) at roughly 7 in × 3.6 in × 1.6 in. The cotton estimate in Table 12 was made for the earlier 62.3 g charge and scales approximately in proportion to cotton mass.

Table 12. Indicative material-purchase basis per standard unit

Input	Working purchase-price basis per standard unit
Cotton sliver	≈\$0.10 working estimate (62.3 g basis); ≈\$0.07–\$0.15 plausible high-volume range
HDPE outer shell	\$0.15
Antimicrobial (borax, 1–2% w/w)	< \$0.01
Internal soluble restraint (borate-compatible)	≈\$0.01–\$0.02
Temporary dry closure	≈\$0.005–\$0.01
Water	< \$0.001
Bulk shipping box allocation	≈\$0.005–\$0.01
Indicative materials subtotal	≈\$0.27–\$0.30 per unit

Cotton purchasing should specify the required physical form rather than unnecessarily buying premium textile quality. The critical requirement is a cohesive, untwisted or sliver-like long-fiber feed that survives storage, handling, metering, cutting, and insertion while preserving the network architecture. Off-grade or waste-card sliver can therefore be economically attractive if it meets DuraTherm functional specifications.

44. Emergency, Strategic, and Military Stockpiling

Dry DuraTherm units create a stockpiling model in which cooling capacity can be manufactured and stored without warehousing most of the eventual water mass. The deployment sequence is manufacture dry → store dry → transport dry → hydrate from an approved or suitable water source near the point of use → freeze → deploy. A specific dry shelf-life duration should not be claimed until accelerated-aging and long-term storage testing establish it.

44.1 Local emergency reserves

Hospitals, EMS and public-health systems, cooling centers, municipalities, counties, utilities, shelters, and local disaster-response organizations can maintain lightweight reserve cooling inventory for heat emergencies, medical response, infrastructure disruptions, and shelter operations, subject to application-specific qualification.

44.2 State, regional, and national strategic stockpiles

Larger reserves can support surge deployment across affected regions without storing and moving the full hydrated mass of conventional packs. The model is relevant to heat disasters, emergency medical logistics, infrastructure failures, and other events requiring rapid distribution of large quantities of cooling capacity.

44.3 Military and strategic reserves

Military and civil-defense organizations can store dry units as deployable cooling capacity and hydrate and freeze them near the operational point where suitable water and freezing capability are available. This reduces the mass that must be held and transported before activation.

44.4 International and humanitarian deployment

International emergency shipments can move DuraTherm dry by air, sea, or ground and add water near the destination. The mass advantage is especially relevant to air transport, where payload capacity is tightly constrained. Avoiding the shipment of water already sealed inside cooling packs can allocate aircraft payload to additional cooling units or other critical medical and emergency supplies. Exact fuel, cost, carbon, and mission-capacity savings require route- and aircraft-specific analysis.

44.5 Business and procurement significance

Strategic stockpiling is a procurement category distinct from ordinary recurring cold-pack consumption. Potential institutional purchasers include healthcare systems, local and state emergency-management organizations, federal agencies, military organizations, humanitarian NGOs, utilities, and other large institutions. Local, national, military, and international stockpiles should be evaluated as distinct deployment and procurement scales rather than one generic emergency market.

45. Application and Deployment Classes

- Medical and therapeutic cooling, subject to clinical and interface validation for the intended use.
- Occupational and personal heat management.
- Biologic and pharmaceutical cold chain, subject to complete-package qualification.
- Food and temperature-controlled logistics.
- Emergency, disaster, humanitarian, and strategic-reserve cooling.

These application classes do not share one universal temperature specification. Pack-surface temperature, skin or interface temperature, and protected-payload temperature can differ materially. Each commercial use therefore requires its own validated performance specification.

46. FDA Classification and Regulatory Pathway

FDA classifies reusable hot-or-cold packs under 21 CFR § 890.5700 as Class I medical devices. The current regulation expressly exempts the device from 510(k) premarket-notification requirements and, unlike a number of neighboring Part 890 exemptions, § 890.5700(b) does not condition that exemption on the limitations of § 890.9. FDA's current Product Classification database identifies the corresponding generic device as "pack, hot or cold, reusable," product code IME, Class I, 510(k) exempt [53].

The 510(k) exemption means that a manufacturer in this classification does not need to submit and obtain clearance of a 510(k) premarket notification before marketing the device. Establishment registration and device listing remain separate FDA requirements. Safety considerations specific to the borate-containing internal phase are reviewed in Section 31.

There is no separate FDA "production license" fee for this Class I cold-pack category. The recurring production-side fee is the annual medical-device establishment registration fee. For FDA fiscal year 2027 (October 1, 2026 through September 30, 2027), the annual establishment registration fee is \$13,785 per establishment, up from \$11,423 in fiscal year 2026 [54].

47. Translation from Research to Commercial Qualification

The transition from prototype to commercial product should preserve the evidence hierarchy used throughout this paper: mechanism → controlled bench test → repeatability → durability and failure testing → application-specific qualification → production QC → field performance. The October 2026 test moved the surface-temperature claims of the medium format from prototype observation to a first controlled bench test; repeatability is the next step. Commercial claims should be derived from validated specifications rather than from the broadest plausible interpretation of the underlying science, and should state the format and conditions to which they apply: the October 2026 medium-format result does not extend to the small format.

APPENDICES

Appendix A. Evidence Matrix: Fiber–Ice and Related Material Systems

Table A1. Evidence matrix

Family	Scale/type	Primary relevance to DuraTherm
Pykrete / sawdust	Wood particles / pulp	Foundational toughness and crack-control precedent; topology differs from sliver
Cotton–ice	Staple cotton	Direct evidence for cotton reinforcement across loading rates
Pulp-fiber ice	Short cellulose fibers	Strength, shear, tension, and fracture mechanisms
Nanocellulose ice	Nanoscale network	High interface area and network continuity; different transport scale
Natural-fiber hybrids	Sisal, flax, pulp combinations	Interlocking, pull-out, and hybrid reinforcement
Cellulose sponge / hydrogel PCM	Crosslinked porous networks	Water retention, phase-change behavior, cycling analogues
DuraTherm	Long staple/sliver network in a sealed shell	Pack-scale water distribution, geometry control, thermal-interface engineering; first controlled IR comparison October 2026 (Part III)

Appendix B. DuraTherm Prototype Data

Values superseded by later measurement are retained for traceability and marked as such.

Table B1. Prototype and test-batch data

Item	Recorded value / observation
Reference pack geometry	7 in × 3.6 in × 1.6 in (measured outside); FreezPAK medium label 6.8 in × 3.4 in × 1.4 in (Altor designation "Small")
Empty shell, medium	36.8 g (lightest of 20 cleaned shells; supersedes the earlier 51.05 g value, which retained residual gel)
Empty shell, small	32.9 g (lightest of 4 cleaned shells; lower confidence than the medium baseline)
Unaltered FreezPAK medium (0.75 lb label)	410.0 g; label 3.4 × 1.4 × 6.8 in
Unaltered FreezPAK small (0.45 lb label)	228.5 g; label 2.6 × 1.2 × 5.1 in
Internal volume, medium / small	495.7 ml / 241.6 ml (water capacity)
Gel density	1.0 g/ml (5.0 g per 5 ml)
Control fill, medium	373.2 ml gel (75.3%); 122.5 ml air (24.7%)
Control fill, small	195.6 ml gel (81.0%); 46.0 ml air (19.0%)
Cotton ball mass	≈0.72–1.0 g each (heavier than the 0.62 g planning figure)

Item	Recorded value / observation
Borax	Specification 1–2% w/w of the aqueous phase; a level teaspoon weighed 4.6 g; an earlier 2.6% batch was a prototyping deviation, not a standard
Medium standard (from September 27, 2026)	115 cotton balls (previously 100)
Medium batch, October 2026 (units 1–20)	Dry unit 116.9–122.4 g (target 117.8 g); water 379.1–381.3 g; filled 496.5–502.0 g before sealing; cotton ≈71–76 g by difference; ≈87% of internal volume occupied before freezing, ≈6% free after
DuraTherm fill, 100-ball medium (superseded)	≈381–386 g water + 62.3 g cotton; ≈85–86% occupied; finished mass ≈480–485 g
100-ball packs, earlier	≈492–494 g (superseded)
Small batch, October 2026 (S1–S4)	Dry unit 69.2–70.6 g; filled 258.5–261.5 g; ≈189–192 g water (filling stopped at weeping; target 193 g)
Post-test masses, October 2026	Medium DuraTherm 485.0–516.5 g (mean 506.2 g); medium controls 408.0–436.0 g (mean 421.4 g); small DuraTherm 269.9–273.4 g; small controls 215.4–244.4 g; large DuraTherm 1,346 g; large control 1,095 g
Large 280-ball unit (earlier record)	≈1,381 g after final squeeze; earlier higher fill drained
Control gel packs (earlier record)	≈409.5 g reference competitor (≈0.903 lb); other controls ≈409–419 g
August 21 test timing	Removed from freezer 2:30 a.m.; official testing 3:30 a.m.; 30-min intervals to ≈10:30 a.m.
October 3–4 test timing	Removed from freezer 3:00 p.m.; IR reads 4:00 p.m. to 5:00 a.m.; 40 reads analyzed (Part III)
Temperature mapping	August 2026: five positions on large packs, DuraTherm generally tighter than controls. October 2026: full-face IR, Part III
Localized holes and fill port	No coolant discharge demonstrated under tested conditions; expression through the open port required ≈22–44 N (5–10 lbf) and released a few grams

Appendix C. Comparative Geometry and Scaling

Table C1. Scaling issues and DuraTherm design responses

Scaling issue	Conventional flexible gel/water	DuraTherm design response
Increasing coolant mass	More sagging and redistribution	Fiber network limits large-scale redistribution
Freeze expansion	Can amplify local bulges	Expansion remains; distributed geometry is intended to reduce localization (current batch: distributed rather than localized bulging; magnitude pending)
Thickness increase	Longer thermal path; larger gradients	Broad-face growth preserves shorter paths; deeper designs remain possible with deliberate geometry and internal thermal-transfer pathways
Air/underfilled regions	Can create warm surface zones	Fuller internal-space utilization is intended to reduce large voids
Neck and shoulder cavities	Warm zone (October 2026)	Also a warm zone in DuraTherm (October 2026); requires fill placement or shell redesign
Large-format uniformity	Increasing geometric heterogeneity risk	Fiber architecture supports more stable internal distribution (large-format evidence n = 1)
Very deep designs	Diffusion penalty grows strongly with thickness	Future internal-conduit architecture proposed

Appendix D. Proposed Test Protocols

D.1 Condensation

Test the cold packs in a fixed room or controlled-temperature test environment, with ambient air temperature and relative humidity maintained at defined conditions such as 70 °F/40% RH, 75 °F/50% RH, 80 °F/60% RH, and 85 °F/70% RH. These values represent the surrounding test environment, not the cold-pack temperature. The packs should begin from a standardized frozen condition, with actual pack-surface temperatures measured separately throughout the test. Use identical exposed area, orientation, airflow, and starting condition; record multi-point surface temperatures and gravimetric condensate at 15–30 minute intervals. Report condensate per unit area and per unit area-time together with the calculated dew point and each pack surface temperature difference below dew point.

D.2 Penetration

Standardize hole or tear size, face, corner, or seam location, frozen, part-thawed, or thawed state, applied compression, drop or impact condition, and post-damage flex cycling. Report leakage mass and rate, percentage coolant loss, spread, tear propagation, residual mass, and retained useful-cooling duration, for each failure mode of Table 9.

D.3 Scaling

Compare small, medium, and large DuraTherm and conventional controls for coolant mass, face area, maximum thickness, surface-area-to-volume ratio, bulge height, thickness variation, temperature spread, freeze time, useful-window duration, seam deformation, drop survival, and cycle life, with enough units per format for statistical comparison.

D.4 Infrared thermography (revised after October 2026)

- Image only a label-free face. Turn each unit a fixed, timed interval (10 minutes) before it is imaged, and record turn and scan times.
- Use a standardized 20-minute read interval from the start, rather than starting at 15 minutes and lengthening later.
- Mount the imager on a stable fixture at fixed distance and angle, with the image orientation locked so that the neck is always at the top of the frame.
- Rest units on raised, slightly tilted platforms above the insulation with a drainage gap beneath, so that meltwater and condensate drain away. The planned rig uses R-6 boards cut into V-shaped props bolted through the board (three-point support, nuts on the back), two boards of 12 stations each, with no bolt touching a unit; additional R-6 panels are required.
- Use permanent, non-conductive identification that survives meltwater, and give every control a permanent individual tag.
- Record ambient temperature and relative humidity with a logger, and record the freezer set point and freezer residence time.
- Draw outlines without knowledge of unit identity where practical, and re-outline a full read to measure repeatability.

D.5 Lower-fill offset comparison

Twelve DuraTherm units with a lighter but uniform cotton charge (larger headspace), twelve being the minimum count for judging uniformity. New control units are drilled and emptied, and each shell receives three rinse-and-dry cycles, using long swabs to clear liquid from the bottom, before the shells are brought to near-uniform mass. Water is set 5% below the average control liquid charge (average control mass minus the 36.8 g shell baseline). The objective is to control bulging and determine whether lighter units retain thermal performance.

D.6 Matched-fill comparison in screw-cap shells

An alternative design under consideration starts from empty shells with screw-on lids, which allow uniform ingredient masses in both groups. Ten units are filled with gel transferred from commercial FreezPAK units (controls) and ten are built as DuraTherm units with lighter cotton and the same water mass. Forty shells are to be obtained so that spares are available; lids are first leak-tested on water-filled units with PTFE thread-seal tape.

D.7 Bulge measurement

Measure thickness with calipers on a defined grid on every unit before freezing, at removal, and at defined times during warming, recording the values directly rather than from video. Report nominal and frozen thickness, maximum bulge height, thickness range, and coefficient of variation per unit and group.

Appendix E. October 2026 Test: Per-Read Statistics and Data Record

Tables E1–E3 give the per-read group statistics for the October 3–4, 2026 test. Table E4 summarizes the data record by read. The complete per-unit, per-read tables and the per-image raw data (2,463 images) are held in the companion analysis workbook, "DuraTherm Analysis A1".

Table E1. Medium units: whole-face mean temperature by read (°F)

Read	Scan window	h	n (C/D)	Control mean (SD)	DuraTherm mean (SD)	D – C	Welch 95% CI	p
4:00 p.m.	16:00–16:09	1.07	27/23	40.2 (4.0)	35.4 (2.0)	–4.8	–6.6 to –3.0	<0.0001
4:15 p.m.	16:15–16:21	1.30	27/23	36.5 (2.0)	35.4 (1.7)	–1.1	–2.2 to –0.0	0.044
4:30 p.m.	16:30–16:35	1.55	27/23	42.1 (3.5)	38.3 (2.0)	–3.8	–5.4 to –2.2	<0.0001
4:45 p.m.	16:45–16:51	1.80	27/23	35.4 (2.1)	33.1 (1.3)	–2.3	–3.3 to –1.4	<0.0001
5:00 p.m.	17:00–17:06	2.05	26/22	40.5 (3.1)	38.6 (2.5)	–1.9	–3.5 to –0.3	0.023
5:21 p.m.	17:21–17:27	2.39	27/23	37.1 (1.2)	35.5 (1.1)	–1.6	–2.3 to –1.0	<0.0001
5:46 p.m.	17:45–17:51	2.81	27/23	41.3 (3.9)	37.3 (2.1)	–4.0	–5.8 to –2.3	<0.0001
6:00 p.m.	18:00–18:05	3.05	27/23	36.8 (2.0)	35.5 (1.3)	–1.3	–2.2 to –0.3	0.010
6:15 p.m.	18:14–18:19	3.27	27/22	44.8 (3.5)	40.4 (1.6)	–4.4	–6.0 to –2.9	<0.0001
6:30 p.m.	18:30–18:38	3.54	26/22	37.5 (2.8)	36.7 (1.7)	–0.8	–2.1 to +0.5	0.228
6:45 p.m.	18:44–18:52	3.77	27/23	43.6 (3.3)	40.4 (1.9)	–3.3	–4.8 to –1.8	<0.0001
7:00 p.m.	19:02–19:04	4.05	27/23	44.2 (3.3)	39.7 (1.6)	–4.5	–6.0 to –3.0	<0.0001
7:15 p.m.	19:16–19:19	4.30	27/23	45.0 (4.1)	40.0 (2.0)	–4.9	–6.7 to –3.1	<0.0001
7:30 p.m.	19:31–19:34	4.55	27/23	44.2 (3.9)	39.1 (2.0)	–5.1	–6.9 to –3.4	<0.0001
7:45 p.m.	19:45–19:48	4.78	27/23	45.9 (4.1)	40.6 (2.1)	–5.4	–7.2 to –3.6	<0.0001
8:00 p.m.	20:01–20:04	5.05	26/22	44.1 (3.1)	41.9 (1.8)	–2.1	–3.6 to –0.7	0.005
8:15 p.m.	20:15–20:18	5.27	27/23	46.0 (3.7)	41.8 (2.6)	–4.3	–6.1 to –2.5	<0.0001
8:30 p.m.	20:31–20:33	5.54	27/23	44.0 (3.5)	41.1 (2.4)	–2.9	–4.6 to –1.2	0.001
8:45 p.m.	20:44–20:47	5.77	27/23	48.6 (3.4)	44.1 (2.2)	–4.5	–6.1 to –2.9	<0.0001
9:00 p.m.	21:00–21:03	6.03	26/23	48.7 (4.2)	44.7 (2.4)	–4.0	–5.9 to –2.0	0.0002
9:15 p.m.	21:15–21:19	6.29	27/23	45.0 (3.8)	43.5 (2.9)	–1.6	–3.5 to +0.3	0.106
9:30 p.m.	21:30–21:35	6.54	27/23	49.9 (4.2)	45.2 (2.9)	–4.7	–6.7 to –2.7	<0.0001
9:45 p.m.	21:46–21:50	6.80	27/23	48.2 (3.9)	46.1 (2.9)	–2.2	–4.1 to –0.2	0.030
10:15 p.m.	22:18–22:22	7.34	27/23	51.0 (4.2)	46.9 (3.4)	–4.2	–6.3 to –2.0	0.0003
10:45 p.m.	22:45–22:48	7.77	27/23	51.2 (3.8)	48.1 (3.7)	–3.1	–5.2 to –1.0	0.005
11:00 p.m.	23:01–23:04	8.04	27/23	49.9 (4.1)	49.4 (3.7)	–0.5	–2.7 to +1.7	0.650
11:15 p.m.	23:15–23:18	8.28	27/23	53.2 (3.8)	50.5 (3.3)	–2.7	–4.8 to –0.7	0.010
11:30 p.m.	23:33–23:36	8.58	27/23	53.2 (4.3)	51.7 (3.8)	–1.4	–3.7 to +0.9	0.220
11:45 p.m.	23:45–23:49	8.78	26/23	57.6 (4.7)	54.5 (3.5)	–3.1	–5.5 to –0.8	0.011
12:00 a.m.	00:02–00:08	9.06	27/23	53.4 (5.1)	53.4 (4.0)	–0.0	–2.6 to +2.6	0.986
12:15 a.m. (taken 12:24)	00:24–00:27	9.43	27/23	57.0 (5.2)	56.4 (4.0)	–0.6	–3.2 to +2.0	0.639
12:45 a.m.	00:46–00:50	9.79	27/23	61.4 (5.0)	58.3 (3.3)	–3.1	–5.5 to –0.8	0.010

Read	Scan window	h	n (C/D)	Control mean (SD)	DuraTherm mean (SD)	D – C	Welch 95% CI	p
1:15 a.m.	01:17–01:22	10.33	27/23	60.0 (5.5)	59.5 (3.6)	–0.5	–3.2 to +2.1	0.689
1:30 a.m.	01:34–01:37	10.59	27/23	62.8 (4.7)	60.8 (3.0)	–2.0	–4.2 to +0.3	0.082
2:00 a.m.	02:03–02:08	11.09	27/23	63.4 (4.3)	63.3 (2.7)	–0.1	–2.1 to +1.9	0.917
2:30 a.m.	02:29–02:33	11.54	27/23	66.1 (4.2)	64.2 (1.9)	–1.9	–3.7 to –0.1	0.044
3:00 a.m.	03:02–03:05	12.06	27/23	66.6 (3.7)	65.0 (1.7)	–1.6	–3.2 to +0.0	0.054
3:30 a.m.	03:31–03:36	12.55	27/23	68.5 (2.5)	66.6 (1.3)	–1.9	–3.0 to –0.8	0.001
4:30 a.m.	04:26–04:29	13.46	27/23	69.6 (2.9)	67.0 (1.1)	–2.7	–3.9 to –1.4	<0.0001
5:00 a.m.	04:56–04:59	13.96	27/23	70.3 (2.8)	67.2 (1.2)	–3.1	–4.2 to –1.9	<0.0001

h = hours from removal from the freezer (median scan time of the read). D – C = DuraTherm minus control. Times are actual scan times; the 10:30 p.m. read is excluded (Section 22.2).

Table E2. Medium units: dispersion and tails by read (°F)

Read	Within-face SD, C	Within-face SD, D	p (SD)	Coldest part, C	Coldest part, D	99th pct, C	99th pct, D
4:00 p.m.	6.31	4.15	<0.0001	31.5	30.2	54.3	49.6
4:15 p.m.	5.10	3.27	<0.0001	31.7	31.9	54.1	48.3
4:30 p.m.	6.94	4.14	<0.0001	32.8	33.1	56.5	51.6
4:45 p.m.	4.58	3.13	<0.0001	31.1	30.0	52.2	47.0
5:00 p.m.	6.86	3.98	<0.0001	31.8	33.5	55.1	51.2
5:21 p.m.	4.90	3.41	<0.0001	32.6	32.1	55.4	51.0
5:46 p.m.	6.73	3.81	<0.0001	32.3	32.9	55.0	49.6
6:00 p.m.	4.98	3.52	<0.0001	32.2	32.0	55.4	49.3
6:15 p.m.	7.16	4.18	<0.0001	35.7	35.5	59.4	53.6
6:30 p.m.	5.07	3.76	<0.0001	32.6	32.8	55.6	51.6
6:45 p.m.	6.73	4.15	<0.0001	35.0	35.4	57.2	53.2
7:00 p.m.	6.75	4.24	<0.0001	35.7	34.8	58.7	53.9
7:15 p.m.	7.02	4.54	<0.0001	36.0	34.6	58.5	53.7
7:30 p.m.	6.49	4.42	<0.0001	35.9	33.9	58.4	53.2
7:45 p.m.	7.05	4.53	<0.0001	36.3	34.9	59.0	53.7
8:00 p.m.	6.36	4.84	<0.0001	35.7	36.1	58.3	56.4
8:15 p.m.	7.02	4.85	<0.0001	36.3	35.7	58.4	54.9
8:30 p.m.	6.28	4.91	<0.0001	35.4	34.9	58.3	55.1
8:45 p.m.	7.00	5.18	<0.0001	38.0	37.4	60.6	57.8
9:00 p.m.	6.85	5.23	0.0001	38.2	37.7	60.8	58.3
9:15 p.m.	6.47	5.19	<0.0001	35.6	36.8	58.2	57.2
9:30 p.m.	6.71	5.17	<0.0001	39.2	38.4	61.3	58.3
9:45 p.m.	6.47	5.28	0.0002	38.5	38.9	60.7	59.1

Read	Within-face SD, C	Within-face SD, D	p (SD)	Coldest part, C	Coldest part, D	99th pct, C	99th pct, D
10:15 p.m.	6.35	5.17	0.0010	40.5	39.8	62.1	58.9
10:45 p.m.	6.10	4.93	0.003	41.0	41.0	61.4	59.2
11:00 p.m.	6.10	5.13	0.009	40.4	42.1	61.7	61.1
11:15 p.m.	5.65	4.64	0.024	43.4	43.7	62.9	61.2
11:30 p.m.	5.61	4.60	0.008	43.9	45.0	64.3	62.5
11:45 p.m.	4.88	4.18	0.101	49.0	48.2	66.1	63.9
12:00 a.m.	4.88	4.12	0.074	45.5	47.4	63.0	62.8
12:15 a.m. (taken 12:24)	4.15	3.49	0.109	50.7	51.3	66.3	64.7
12:45 a.m.	3.28	2.96	0.453	56.1	54.0	67.8	65.7
1:15 a.m.	3.33	2.58	0.081	54.7	56.0	67.4	66.1
1:30 a.m.	2.57	2.16	0.211	58.7	58.0	68.3	66.7
2:00 a.m.	2.36	1.83	0.021	60.2	61.2	69.6	68.7
2:30 a.m.	1.83	1.48	0.032	63.5	62.7	70.5	68.9
3:00 a.m.	1.77	1.37	0.012	64.3	63.7	71.5	69.4
3:30 a.m.	1.37	1.03	0.0002	66.6	65.5	71.8	69.9
4:30 a.m.	1.34	0.98	0.0005	67.8	65.9	73.0	70.0
5:00 a.m.	1.36	0.99	0.0001	68.2	66.0	73.4	70.2

Coldest part = mean of the coldest 10% of the face. p from Welch's test on the within-face SD.

Table E3. Small and large units by read: whole-face mean (°F)

Read	n (SC/SD)	Small control	Small DuraTherm	SD – SC	01LC	01LD	LD – LC
4:00 p.m.	6/4	41.4	40.6	–0.8	43.2	38.3	–4.9
4:15 p.m.	6/4	37.9	37.8	–0.1	38.7	36.2	–2.5
4:30 p.m.	6/4	41.3	39.1	–2.2	43.2	38.8	–4.4
4:45 p.m.	6/4	41.9	39.5	–2.4	44.0	39.5	–4.5
5:00 p.m.	6/4	44.4	41.6	–2.8	44.7	40.9	–3.9
5:21 p.m.	6/4	37.3	37.6	+0.3	34.5	33.9	–0.6
5:46 p.m.	—	—	—	—	—	—	—
6:00 p.m.	6/4	44.6	43.7	–0.8	40.3	37.2	–3.0
6:15 p.m.	6/4	44.6	42.9	–1.7	40.6	36.4	–4.3
6:30 p.m.	6/4	39.1	41.7	+2.6	37.5	36.6	–0.9
6:45 p.m.	6/4	45.2	45.5	+0.3	41.3	38.3	–2.9
7:00 p.m.	5/4	42.6	43.7	+1.1	38.2	35.9	–2.3
7:15 p.m.	6/3	44.7	44.8	+0.2	39.7	36.9	–2.8
7:30 p.m.	6/4	44.6	45.0	+0.4	37.9	36.4	–1.5

Read	n (SC/SD)	Small control	Small DuraTherm	SD – SC	01LC	01LD	LD – LC
7:45 p.m.	6/3	46.1	47.3	+1.2	40.8	37.7	-3.2
8:00 p.m.	5/4	46.5	47.5	+1.0	40.5	37.8	-2.8
8:15 p.m.	6/4	47.1	48.8	+1.7	41.4	37.2	-4.2
8:30 p.m.	6/4	46.8	49.1	+2.2	40.4	37.8	-2.6
8:45 p.m.	6/3	49.2	51.6	+2.4	41.8	39.3	-2.5
9:00 p.m.	6/4	50.6	53.4	+2.8	42.8	39.6	-3.2
9:15 p.m.	6/4	51.6	55.2	+3.6	42.6	40.3	-2.4
9:30 p.m.	6/4	53.3	57.2	+3.9	44.5	39.2	-5.3
9:45 p.m.	6/4	52.4	57.9	+5.5	44.0	39.7	-4.2
10:15 p.m.	6/4	55.6	60.0	+4.4	43.4	38.7	-4.7
10:45 p.m.	6/4	57.0	61.6	+4.6	43.9	39.6	-4.2
11:00 p.m.	6/4	59.2	63.9	+4.7	47.6	41.2	-6.3
11:15 p.m.	6/4	59.1	62.7	+3.7	45.1	40.8	-4.3
11:30 p.m.	6/4	61.2	64.2	+3.0	46.1	41.6	-4.6
11:45 p.m.	6/4	63.4	65.9	+2.5	47.9	43.7	-4.2
12:00 a.m.	6/4	66.1	68.4	+2.3	50.1	45.3	-4.8
12:15 a.m. (taken 12:24)	6/4	63.7	66.7	+3.0	49.0	44.9	-4.1
12:45 a.m.	6/4	67.4	69.2	+1.8	49.2	47.2	-2.0
1:15 a.m.	6/4	67.5	69.2	+1.7	50.6	46.7	-3.9
1:30 a.m.	6/4	66.2	68.7	+2.5	52.3	45.6	-6.8
2:00 a.m.	—	—	—	—	52.4	49.9	-2.5
2:30 a.m.	—	—	—	—	54.4	52.4	-1.9
3:00 a.m.	—	—	—	—	52.1	49.1	-3.0
3:30 a.m.	—	—	—	—	54.1	52.3	-1.8
4:30 a.m.	—	—	—	—	58.5	54.5	-4.1
5:00 a.m.	—	—	—	—	60.9	55.5	-5.4

Small units were not imaged at 5:46 p.m. or after 1:30 a.m. (arm concluded); large units were not imaged at 5:46 p.m. The large comparison is n = 1 per type and is descriptive only.

Table E4. Data record by read

Read	Pack readings	Notes
4:00 p.m.	62	Two wide shots excluded
5:00 p.m.	60	60 images for 62 units; 20MC and 23MD placed as not imaged (identity flagged); one wide shot excluded
5:46 p.m.	50	Medium units only
6:15 p.m.	61	06MD rejected (about half out of frame)
6:30 p.m.	60	Normal round plus two repeat rounds of 01-10MC and 01-10MD; 25MC and 11MD rejected (out of frame)

Read	Pack readings	Notes
6:45 p.m.	62	Poor first image of 01MD retaken
7:00 p.m.	61	05SC not outlined
7:15 p.m.	61	03SD rejected (55% in frame); one 01SD side placed at the visible edge
7:45 p.m.	61	03SD rejected (53% in frame)
8:00 p.m.	59	16MC rejected (55% in frame); 17MD rejected (geometry undetermined); one small unit not imaged (identity flagged)
8:45 p.m.	61	02SD: no part of the unit identifiable
9:00 p.m.	61	One control not imaged (identity flagged)
9:30 p.m.	62	One extra image in the first DuraTherm row left unassigned (identity flagged)
10:15 p.m.	62	Units accidentally turned an extra time this period
10:30 p.m.	—	Excluded: not processed by the analysis deadline; one set of six medium DuraTherm units not imaged
11:45 p.m.	61	17MC not imaged
12:15 a.m.	62	Imaged 12:24–12:27 a.m. after units were turned back
1:15 a.m.	62	Taken in place of 1:00 a.m.; 30-minute reads thereafter
2:00–5:00 a.m.	52 per read	Small units concluded after 1:30 a.m.; no read at 4:00 a.m.

All other reads: 62 pack readings with no exclusions. Readings with one or more unreadable zones (213 in all) are retained as partial readings.

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