

# Heat Regulation Glove Using Phase Change Materials (PCM)

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**Abstract:** Phase change materials (PCMs) provide thermal energy storage through latent heat absorption during phase transition and therefore offer potential for wearable thermal protection. This study investigates the integration of a gel-based PCM into a multilayer glove to improve protection against high-temperature exposure while limiting additional bulk. A prototype incorporating an approximately 1 cm PCM layer with a melting point near 68 °C was evaluated using controlled convection-oven heating and compared with a glove without PCM. Three replicate trials were performed for each configuration, with the time required for the inner glove layer to reach 60 °C used as the principal protection metric. The PCM-integrated configuration produced a thermal-buffering region and extended the observed protection time to approximately 60 to 100 s, compared with approximately 30 s for the control. Finite-element analysis qualitatively supported the experimentally observed thermal-buffering behaviour. The results demonstrate the potential of PCM integration for improving glove thermal protection, while standardized heat-exposure, durability, and dexterity testing remains necessary before operational application.

**Keywords:** Phase change materials, thermal protection, latent heat, firefighting gloves, thermal energy storage, gel PCM

## List of Abbreviations

| Abbreviation | Meaning                                        |
|--------------|------------------------------------------------|
| PCM          | Phase change material                          |
| PPE          | Personal protective equipment                  |
| TPP          | Thermal protective performance                 |
| FEM          | Finite-element method                          |
| CAD          | Computer-aided design                          |
| NFPA         | National Fire Protection Association           |
| EN           | European Norm (standard)                       |
| ISO          | International Organization for Standardization |
| LDPE         | Low-density polyethylene                       |
| TPU          | Thermoplastic polyurethane                     |

## Nomenclature

| Symbol              | Description                                     | Unit              |
|---------------------|-------------------------------------------------|-------------------|
| T                   | Temperature                                     | °C, K             |
| T <sub>pc</sub>     | Phase-change (melting) temperature              | °C                |
| t                   | Time                                            | s                 |
| h                   | Specific enthalpy                               | J/g               |
| cp                  | Specific heat at constant pressure              | J/(g·K)           |
| cs                  | Specific heat of solid-state PCM                | J/(g·K)           |
| cv                  | Specific heat of solid-state PCM (heat-balance) | J/(g·K)           |
| m                   | Mass of PCM sample                              | g                 |
| ms                  | Mass of the calorimeter/sample holder           | g                 |
| ΔT                  | Temperature rise/interval                       | K                 |
| Δt                  | Time interval                                   | s                 |
| Q <sub>r</sub>      | Heat absorbed by the reference/holder           | J                 |
| Q <sub>el</sub>     | Electrical heat supplied to the system          | J                 |
| Q̇ <sub>el</sub>    | Electrical heating power                        | W                 |
| Q <sub>PCM</sub>    | Heat absorbed by the PCM                        | J                 |
| Q <sub>fusion</sub> | Specific heat of fusion of the PCM              | J/g               |
| k                   | Thermal conductivity                            | W/(m·K)           |
| ρ                   | Density                                         | kg/m <sup>3</sup> |
| α                   | Thermal diffusivity                             | m <sup>2</sup> /s |
| Bi                  | Biot number                                     | —                 |
| Fo                  | Fourier number                                  | —                 |
| δ                   | Layer thickness                                 | mm, cm            |

## 1. Introduction

### 1.1 Background and Motivation

Thermal protective equipment forms the last line of defence between a worker and a hazardous thermal environment. Among the various pieces of personal protective equipment (PPE) used in high-risk occupations, gloves occupy a uniquely difficult design space: the hand must simultaneously be shielded from extreme heat and retain the fine dexterity needed to operate valves, tools, ropes, hoses, and rescue equipment. This tension between protection and usability has persisted despite decades of incremental improvement in flame-resistant textiles, and it motivates the exploration of active or semi-active thermal-buffering strategies rather than relying purely on passive bulk insulation.

Phase change materials (PCMs) offer a promising route out of this trade-off. Because a PCM absorbs or releases a large quantity of latent heat while remaining at a nearly constant temperature during its phase transition, a comparatively thin PCM layer can deliver a thermal-buffering effect that would otherwise require several times the thickness of conventional insulation. This property has already been exploited commercially in mattresses, outdoor jackets, footwear, and spacecraft thermal control systems, and it is a natural candidate for extension into structural firefighting gloves, cold-chain logistics gloves, and arctic expedition mittens.

This work is motivated by the specific case of structural firefighting, where hand-surface temperatures during flashover or direct flame contact can rise well beyond the threshold associated with second-degree burns within a matter of seconds. Existing thick multilayer gloves delay this rise through low thermal conductivity and trapped air, but the resulting bulk compromises grip strength, tactile feedback, and fine motor control- all of which are safety-critical during

a rescue. A gel-based PCM insert, embedded as a discrete middle layer, was therefore investigated as a means of extending the safe exposure window without a comparable increase in glove thickness.

## 1.2 Problem Statement

Conventional structural firefighting gloves rely almost exclusively on the sensible-heat capacity and low conductivity of thick, multilayered textiles to delay the transfer of heat from the external fire environment to the wearer's skin. Because sensible-heat storage scales with mass and temperature rise rather than with a fixed phase-change enthalpy, achieving a meaningful delay this way requires substantial material thickness, which in turn increases glove stiffness and reduces dexterity. The central problem addressed in this study is whether a thin, encapsulated gel PCM layer, chosen to melt just below the skin-damage threshold, can extend the safe exposure time of a glove by a meaningful margin under the tested conditions, while adding minimal thickness and preserving the glove's flexibility.

## 1.3 Objectives of the Study

- To review the theoretical basis of latent-heat thermal energy storage and identify PCM selection criteria relevant to wearable thermal protection.
- To design and fabricate a prototype glove incorporating a 1-cm-thick gel-based PCM layer with a melting point near 68 °C.
- To develop and apply a convection-oven-based experimental protocol for quantifying the thermal protection time of the prototype relative to a conventional control glove.
- To formulate the governing heat-balance equations used to determine the specific heat and heat of fusion of the tested PCM.
- To validate the experimental observations against a finite-element thermal simulation of the layered glove structure.
- To discuss the broader applicability, economic feasibility, and limitations of PCM-integrated gloves for firefighting, arctic, and industrial use.

## 1.4 Scope and Limitations

The scope of this study is restricted to a single-finger/glove-scale prototype tested under a controlled convective heating protocol using a domestic convection oven as a laboratory-accessible surrogate for radiant and convective fire exposure. The work does not attempt to replicate the full radiative flux, flame contact, or moisture conditions of an actual structural fire, nor does it evaluate the mechanical durability of the PCM layer under repeated flexing, laundering, or long-term thermal cycling. These aspects are identified as directions for future work in Section 16.

## 1.5 Organization of the Paper

The remainder of this paper is organized as follows. Section 2 reviews prior literature on PCM thermal energy storage and PCM-integrated protective textiles. Section 3 develops the theoretical background of conduction, latent heat, and moving-boundary phase-change formulations. Section 4

classifies PCM types and establishes selection criteria. Sections 5 and 6 describe thermal insulation requirements in clothing systems and the functional mechanism of PCM layers in garments. Section 7 details the design and fabrication of the prototype. Section 8 presents the governing calculations. Section 9 describes the experimental methodology, and Section 10 the finite-element simulation methodology. Section 11 presents and discusses the results. Sections 12–16 discuss applications, economics, safety/sustainability, limitations, and future work, and Section 17 concludes the paper.

## 1.6 Contribution of This Work

The specific contribution of this work, relative to the prior literature reviewed in Section 2, is threefold. First, it packages a complete, reproducible, low-cost experimental protocol-spanning fabrication, convection-oven testing, and heat-balance data reduction- that an academic project team can execute without access to specialised fire-testing facilities, addressing the literature gap identified in Section 2.5. Second, it pairs this experimental protocol with an explicit theoretical treatment (Section 3) linking the observed thermal plateau directly to the moving-boundary and enthalpy-method formulations underlying more sophisticated commercial simulation tools, making the connection between simple hand-calculation and full finite-element modelling explicit and pedagogically transparent, including the worked finite-difference illustration of Appendix D. Third, it extends the discussion beyond raw thermal-protection numbers to the applications, economics, safety, and standards-compliance considerations (Sections 12–16) that determine whether a laboratory result of this kind could plausibly progress toward real-world adoption, framing the prototype's contribution honestly as a proof-of-concept rather than an operational-readiness claim.

## 1.7 Relationship Between Theory, Experiment, and Simulation

A distinguishing feature of the approach taken in this paper is the deliberate triangulation between three largely independent lines of evidence for the same underlying physical mechanism: the closed-form and dimensionless-group theoretical arguments of Section 3 and Appendix F, the empirical convection-oven measurements of Section 9, and the finite-element simulation of Section 10. Each of these three lines of evidence has its own characteristic strengths and blind spots- the theory is exact but relies on simplifying assumptions (one-dimensionality, idealised boundary conditions); the experiment captures real material and fabrication imperfections but is limited by instrumentation resolution and sample-to-sample variability (Section 8.4); and the simulation resolves the full layered geometry but depends on literature-typical rather than directly measured material properties (Section 10.3). The qualitative consistency observed across all three approaches in Sections 11.4 and 11.8- a pronounced thermal plateau near the PCM's melting point, and a two- to threefold extension in protection time relative to a non-PCM baseline- is presented not as proof that any single method is individually definitive, but as converging, mutually reinforcing evidence for the central physical claim of this paper: that a thin PCM layer measurably

delays the transfer of dangerous heat levels to the wearer's hand.

## 2. Literature Review

### 2.1 Historical Development of PCM Research

Interest in latent-heat thermal energy storage dates back several decades, driven initially by solar-thermal and building energy-storage applications, where a compact medium for storing and releasing heat at a near-constant temperature was highly desirable. Comprehensive reviews of this literature, most notably by Zalba et al. [8] and by Sharma et al. [9], catalogue over a hundred candidate PCM formulations and summarise the heat-transfer enhancement techniques- fins, encapsulation, and dispersed conductive fillers- that have been developed to counteract the inherently low thermal conductivity of most organic PCMs. Farid et al. [10] extended this review specifically to materials and applications, noting that the choice of PCM is rarely governed by latent heat capacity alone but by a composite of melting point, cost, corrosivity, and cyclic stability.

These foundational reviews collectively establish the vocabulary and classification (organic, inorganic, eutectic) used throughout the present study, and they motivate the selection criteria discussed in Section 4.

### 2.2 PCM in Thermal Energy Storage Systems

Beyond building and solar applications, PCM-based thermal storage has been applied to cold-chain packaging, electronics thermal management, and battery thermal management, wherever a bounded temperature excursion is required despite a variable or intermittent heat load. The common thread across these applications is the use of the phase-change plateau to buffer a system against a transient thermal insult- precisely the function required of a protective glove during brief, intense heat exposure.

### 2.3 PCM in Textile and Clothing Applications

The application of PCM to clothing and textiles has been studied since at least the early 2000s. Pause [3] examined nonwoven protective garments with thermo-regulating properties and demonstrated that microencapsulated PCM coatings could measurably delay heat transfer through a fabric assembly. Mondal [11] provides a broad overview of PCM incorporation into smart textiles via coating, lamination, and fibre-embedding routes, noting the trade-offs between add-on weight, wash durability, and thermal-buffering capacity. Salaün et al. [7] focused specifically on the formulation of microencapsulated PCM for clothing applications, an approach that offers finer distribution of PCM through a fabric at the cost of a lower effective latent-heat density compared with a bulk gel layer such as the one used in this study.

Song et al. [5] modelled heat and moisture transport in thermal protective clothing under flash-fire conditions, underscoring that moisture content and vapour transport within a garment assembly can significantly alter the effective thermal response- a factor that the present convection-oven

protocol does not directly capture but that is discussed as a limitation in Section 15.

### 2.4 PCM in Personal Protective Equipment for Firefighting

The most directly relevant prior work is that of Wang et al. [1], who conducted an experimental study on the thermal protection enhancement achieved by integrating a novel PCM structure into firefighting gloves under high-heat exposure, reporting a measurable extension of the time to reach a critical skin-temperature threshold. Fonseca et al. [6] modelled the thermal performance of a PCM-integrated firefighting suit across transient fire-exposure, post-fire-exposure, and resting phases, highlighting that the benefit of a PCM layer is not confined to the active heating phase- it also moderates the post-exposure cooling rate, which affects wearer comfort and secondary burn risk during doffing and recovery. These findings directly parallel the heating-and-cooling protocol adopted in Section 9 of the present study.

Sutterlin [2] and Dzindziora et al. [4] provide complementary practical perspectives: the former compares vegetable-based and paraffin-based PCM chemistries from a formulation standpoint, and the latter surveys energy-accumulation applications of PCM more broadly, both reinforcing those aspects of PCM selection- non-toxicity, chemical stability, and ease of encapsulation- that guided the material choice described in Section 4.6.

### 2.5 Summary of Literature Gaps

While the literature establishes both the thermal-storage principles of PCM and their prior application to protective textiles and firefighting suits, comparatively few studies report a simple, reproducible, laboratory-accessible experimental protocol- of the kind an academic project group can execute without specialised fire-testing facilities- for quantifying the thermal protection benefit of a PCM glove insert relative to a matched control. This gap motivates the convection-oven-based methodology adopted here, which trades some fidelity to real fire conditions for repeatability, low cost, and direct comparability between PCM and non-PCM samples.

### 2.6 Summary Table of Reviewed Literature

Table I consolidates the reviewed literature by primary focus area and principal relevance to the present study, providing a compact cross-reference for the discussion in Sections 3–12.

**Table I:** Summary of reviewed literature

| Ref. | Primary Focus                       | Relevance to This Study                          |
|------|-------------------------------------|--------------------------------------------------|
| [1]  | PCM structural firefighting gloves  | Directly comparable prototype and test rationale |
| [2]  | Vegetable- vs. paraffin-based PCM   | Informs organic PCM chemistry selection          |
| [3]  | Thermo-regulating nonwoven garments | Textile-level PCM integration precedent          |
| [4]  | PCM energy accumulation, general    | Broader thermal-storage context                  |
| [5]  | Heat/moisture transport, flash fire | Highlights moisture-transport limitation         |

|      |                                         |                                         |
|------|-----------------------------------------|-----------------------------------------|
| [6]  | PCM firefighting suit, transient phases | Motivates heating+cooling test protocol |
| [7]  | Microencapsulated PCM in clothing       | Alternative encapsulation route         |
| [8]  | PCM review — materials/heat transfer    | Foundational classification, Section 4  |
| [9]  | PCM review — applications               | Foundational classification, Section 4  |
| [10] | PCM review — materials/applications     | Selection criteria, Section 4.6         |
| [11] | PCM for smart textiles overview         | Textile-integration methods, Section 7  |

## 2.7 Positioning of the Present Study

Positioned against Table I, the present study sits closest to reference [1] in application focus (PCM-integrated structural firefighting gloves) while drawing its theoretical scaffolding primarily from the broader thermal energy storage reviews [8]-[10] and its encapsulation-strategy context from the textile-focused literature [3], [7], [11]. This positioning is deliberate: rather than proposing a fundamentally new PCM chemistry or encapsulation technique, the contribution of this work - as summarised in Section 1.6- lies in the integration of established theory, a reproducible low-cost test protocol, and a numerical cross-check into a single, coherent, project-scale study, together with an unusually candid treatment of the gap between this proof-of-concept result and standards-grade operational readiness (Sections 3.9, 11.10, and Appendix G).

## 3. Theoretical Background

### 3.1 Fundamentals of Heat Transfer

Heat transfer through the layered glove structure occurs through a combination of conduction across the solid textile and PCM layers, and convection at the outer surface (exposed to the oven's hot circulating air) and at the inner surface (exposed to the wearer's hand or the ambient test environment). Radiative exchange also contributes at the outer boundary, particularly for the elevated oven-wall and air temperatures used in this study, although it is treated implicitly through an effective convective heat-transfer coefficient in the simplified analysis that follows.

For a plane multilayer wall in steady conduction, the heat flux is governed by Fourier's law,  $q'' = -k(dT/dx)$ , and for the composite glove assembly the effective thermal resistance is the series sum of the resistances of the outer shell, thermal barrier (PCM layer), moisture barrier, and base layer, together with the convective resistances at each exposed face. Because the PCM layer undergoes a phase change during the test, however, the assembly cannot be treated as a simple steady-state resistance network for the duration of melting; a transient, latent-heat-aware formulation is required, as developed below.

### 3.2 Latent Heat and Sensible Heat

Sensible heat storage raises or lowers a material's temperature in proportion to its specific heat,  $Q = m \cdot c_p \cdot \Delta T$ , and is the mechanism by which conventional insulating textiles delay heat transfer. Latent heat storage, by contrast, occurs at a nearly constant temperature as the material undergoes a phase

transition, with the energy absorbed or released given by  $Q = m \cdot Q_{\text{fusion}}$ , where  $Q_{\text{fusion}}$  is the specific enthalpy of fusion. Because  $Q_{\text{fusion}}$  for common PCMs is one to two orders of magnitude larger than the sensible-heat capacity per degree of temperature rise, a PCM layer can absorb a disproportionately large amount of heat while its own temperature- and, by extension, the temperature at its boundary with the base layer-remains close to the melting point,  $T_{\text{pc}}$ .

### 3.3 The Stefan Problem and Moving-Boundary Formulation

The classical mathematical description of solid-liquid phase change is the Stefan problem, in which a moving interface separates the solid and liquid regions of the PCM, and the position of that interface,  $s(t)$ , is itself an unknown to be solved for as part of the boundary-value problem. At the interface, an energy balance couples the conductive heat fluxes on either side to the rate of latent-heat absorption:

$$k_l(\partial T_l / \partial x) - k_s(\partial T_s / \partial x) = \rho \cdot Q_{\text{fusion}} \cdot (ds/dt) \quad (1)$$

where the subscripts  $l$  and  $s$  denote the liquid and solid phases respectively. This moving-boundary character is what gives PCM-based systems their characteristic thermal plateau: as long as unmelted PCM remains at the interface, the local temperature stays pinned near  $T_{\text{pc}}$ , and only after the entire layer has transitioned does the temperature begin to rise (or fall) sensibly again - consistent with the ideal heating/cooling profile shown in Fig. 1.

### 3.4 Enthalpy Method for Phase-Change Modelling

Because an explicit moving-boundary solution is analytically tractable only for simplified one-dimensional geometries, numerical treatments- including the finite-element simulation described in Section 10- commonly adopt the enthalpy method, in which a single enthalpy field,  $h(T)$ , is solved over the whole domain without explicitly tracking the interface position. The enthalpy is defined as a piecewise function of temperature that includes a step (or a steep but continuous ramp, for a mushy-zone formulation) of magnitude  $Q_{\text{fusion}}$  at  $T = T_{\text{pc}}$ , consistent with the  $h(T)$  curve illustrated in Fig. 1. The governing transient energy equation is then written in enthalpy form as:

$$\rho \cdot (\partial h / \partial t) = \nabla \cdot (k \nabla T) \quad (2)$$

This formulation conveniently unifies the sensible and latent contributions to the thermal response and is well suited to the mixed-material, multilayer geometry of the glove, where the PCM coexists with textile layers that do not undergo a phase transition over the temperature range of interest.

### 3.5 Governing Equations for the Glove System

For the purposes of experimental data reduction (Section 8), the multilayer glove is treated as a lumped calorimetric system exchanging heat with the convective oven environment. The overall heat balance partitions the electrical/convective heat input between the heat absorbed by the reference holder or sensible glove mass,  $Q_r$ , and the heat absorbed by the PCM,  $Q_{\text{PCM}}$ , as detailed in the equations of

Section 8. A dimensionless check on the validity of the lumped-system assumption is provided by the Biot number,

$$Bi = h \cdot \delta / k \quad (3)$$

where  $h$  is the convective coefficient at the glove surface,  $\delta$  is the characteristic layer thickness, and  $k$  is the layer's thermal conductivity. For  $Bi \ll 1$ , internal conduction resistance is small relative to surface convective resistance and a lumped or near-lumped treatment is reasonable; for the PCM gel layer used here (low  $k$ , moderate  $\delta$ ),  $Bi$  is not negligible, and this is reflected in the finite spatial temperature gradient captured by the finite-element model of Section 10 rather than assumed away entirely in the experimental data reduction.

### 3.6 Convective and Radiative Boundary Conditions

At the outer glove surface exposed to the convection oven, heat transfer is described by Newton's law of cooling,  $q''_{\text{conv}} = h(T_{\infty} - T_s)$ , where  $T_{\infty}$  is the oven air temperature and  $T_s$  is the instantaneous outer-surface temperature, together with a radiative contribution from the oven walls approximated by the Stefan–Boltzmann relation,  $q''_{\text{rad}} = \varepsilon \sigma (T_{\text{wall}}^4 - T_s^4)$ , where  $\varepsilon$  is the surface emissivity and  $\sigma$  is the Stefan–Boltzmann constant. Because the oven walls and circulating air are both close to the 180 °C set-point, these two contributions were not separated experimentally in this study; instead, a single effective convective coefficient,  $h_{\text{eff}}$ , lumps the combined convective-and-radiative exchange for the purposes of the boundary condition applied in the finite-element model of Section 10. This lumping is a standard simplification for enclosed, well-mixed convection-oven environments where the air and wall temperatures are similar, and it avoids the need for a separate view-factor calculation that would otherwise be required to resolve the radiative component in isolation.

### 3.7 Skin Burn Injury Criteria

The 60 °C inner-layer threshold used as the test-termination criterion in Section 9 is grounded in the well-established relationship between skin temperature, exposure duration, and burn injury. The classical Henriques burn-injury integral [15] expresses cumulative thermal damage,  $\Omega$ , as a time integral of an Arrhenius-type rate expression evaluated at the basal-layer skin temperature,  $T_{\text{skin}}(t)$ :

$$\Omega = \int P \cdot \exp[-\Delta E / (R \cdot T_{\text{skin}}(t))] dt \quad (4)$$

where  $P$  is a pre-exponential frequency factor,  $\Delta E$  is an activation energy for the relevant tissue-damage process, and  $R$  is the universal gas constant. A value of  $\Omega = 1$  is conventionally associated with the threshold for a second-degree (partial-thickness) burn. In practice, published tolerance-time data derived from this framework indicate that skin exposed to a steady 60 °C surface temperature can be expected to sustain a second-degree burn within a matter of seconds to tens of seconds, sharply shorter than the tolerance time at lower temperatures- which is why even the modest, 30–70 second extension in exposure time achieved by the PCM layer in this study (Section 11) is operationally meaningful rather than marginal. The 60 °C criterion adopted for the experimental protocol is therefore a conservative,

literature-consistent proxy for the onset of clinically significant burn injury, rather than an arbitrary round-number cutoff.

### 3.8 Analytical Reference Solution: Semi-Infinite Solid

A useful analytical reference point for the transient conduction behaviour of the glove's outer layers, prior to the arrival of the melting front at the PCM layer, is the classical semi-infinite-solid solution for a step change in surface temperature. For a semi-infinite solid initially at uniform temperature  $T_i$ , suddenly exposed at  $x = 0$  to a fixed surface temperature  $T_s$ , the transient temperature field is given by the complementary error function solution:

$$[T(x,t) - T_s] / [T_i - T_s] = \text{erf}(x / (2 \cdot \sqrt{(\alpha \cdot t)})) \quad (5)$$

where  $\alpha = k/(\rho \cdot cp)$  is the thermal diffusivity of the layer. This solution is strictly valid only for early times, before the finite thickness of the outer shell and thermal-barrier layers becomes significant (i.e., while the Fourier number based on the full assembly thickness remains small, per Section 8.5), but it provides a useful closed-form check on the initial rate of temperature rise predicted by both the lumped heat-balance equations of Section 8 and the full finite-element model of Section 10, and it explains qualitatively why the earliest portion of the oven-temperature and glove-surface curves in Fig. 7 rise steeply before the curves begin to bend over as the finite layer thicknesses and, for the PCM sample, the latent-heat plateau start to dominate the response.

### 3.9 Relevant Protective Equipment Standards

Structural firefighting gloves in many jurisdictions are certified against standards such as NFPA 1971 [12] (Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting; since 2024 consolidated into NFPA 1970, which retains the 1971 designation) in the United States, and EN 407 [13] (Protective gloves against thermal risks) together with ISO 17493 [14] (Clothing and equipment for protection against heat- test method for convective heat resistance) in Europe and internationally. These standards specify, among other requirements, minimum thermal protective performance (TPP) ratings, radiant heat resistance, and convective heat resistance test methods broadly analogous in spirit- though far more rigorously controlled- to the convection-oven protocol used in this study. Framing the present results against this standards landscape underscores both the promise of the PCM approach and the additional standardized testing that would be required before a PCM-integrated glove could be certified for operational structural firefighting use, as discussed further in Section 15.

### 3.10 Comparison of Numerical Solution Methods

Three broad families of numerical method are commonly used for transient, phase-change heat-conduction problems of the kind discussed in this section: the finite-difference method (FDM), illustrated in the explicit scheme of Appendix D; the finite-element method (FEM), used for the layered-glove simulation of Section 10; and the finite-volume method (FVM), widely used in computational-fluid-dynamics-coupled thermal problems where the convective boundary

condition itself must be resolved rather than prescribed. The table below summarises the qualitative trade-offs among these three families as they pertain to a layered, multi-material, phase-change domain such as the glove assembly studied here.

| Method | Geometric Flexibility     | Phase-Change Handling            | Typical Use Here                      |
|--------|---------------------------|----------------------------------|---------------------------------------|
| FDM    | Low (structured grids)    | Enthalpy method, straightforward | Pedagogical illustration (Appendix D) |
| FEM    | High (unstructured mesh)  | Enthalpy method, well supported  | Layered-glove simulation (Section 10) |
| FVM    | High, conservative fluxes | Enthalpy method, common in CFD   | Not used in this study                |

FEM was selected for the present simulation primarily because of the ready availability of a cloud-based platform (SimScale) supporting layered-solid thermal analysis with minimal meshing overhead for the simplified coupon geometry of Section 10.1, rather than because of any fundamental unsuitability of FDM or FVM for this class of problem; all three methods, correctly applied with a consistent enthalpy-method phase-change treatment, would be expected to converge to comparable predictions for the same governing equations and boundary conditions.

## 4. Classification and Selection of PCM

### 4.1 Organic PCMs

Organic PCMs include paraffin waxes and non-paraffin organics such as fatty acids and esters. Their principal advantages are chemical stability across repeated melt-freeze cycles, negligible supercooling, non-corrosiveness toward common encapsulation materials, and generally low toxicity. Their main drawbacks are flammability, comparatively low thermal conductivity (typically 0.15–0.3 W/(m·K) in the solid state), and a volumetric latent-heat density lower than that of many inorganic salts. Paraffin wax remains the most extensively studied organic PCM owing to the wide commercial availability of grades spanning a broad range of melting points.

### 4.2 Inorganic PCMs

Inorganic PCMs are dominated by hydrated salts (salt hydrates), which offer higher latent-heat density per unit volume and higher thermal conductivity than most organics, along with non-flammability. Their disadvantages include a tendency toward supercooling and phase segregation over repeated cycles, and corrosivity toward metallic encapsulation materials, which constrains the choice of packaging for long-term use.

### 4.3 Eutectic PCMs

Eutectic PCMs are mixtures of two or more organic, inorganic, or organic–inorganic components formulated to melt and freeze congruently at a single, tailored temperature, rather than over the range typical of a single-component mixture. This allows the melting point to be tuned to a specific

application temperature- such as the skin-damage-adjacent 68 °C target used in this study- without necessarily sacrificing the stability advantages of the base chemistries.

### 4.4 Metallic PCMs

Metallic PCMs, typically low-melting-point alloys, offer melting ranges from roughly 150 °C to 800 °C and very high thermal conductivity, making them suitable for rapid, high-power heat-transfer applications such as concentrated solar power receivers. Their high density and cost make them impractical for a wearable application such as a glove, and they are included here for completeness of the classification rather than as a candidate material.

### 4.5 Comparative Overview of PCM Categories

Table II summarises the qualitative trade-offs among the four PCM categories discussed above, drawing on the classification schemes used in prior reviews [8]– [10].

**Table II:** Comparative overview of PCM categories

| Category                 | Melting Range | Latent Heat | Key Advantages                        | Key Drawbacks                              |
|--------------------------|---------------|-------------|---------------------------------------|--------------------------------------------|
| Organic (paraffin)       | 20–70 °C      | 150–250 J/g | Stable, low toxicity, no supercooling | Flammable, low k                           |
| Organic (fatty acid)     | 30–65 °C      | 150–210 J/g | Biodegradable, reproducible melting   | Odour, moderate cost                       |
| Inorganic (salt hydrate) | 10–120 °C     | 200–300 J/g | High latent heat, non-flammable       | Supercooling, corrosive                    |
| Eutectic                 | Tunable       | Varies      | Melting point tailored to need        | Formulation complexity                     |
| Metallic                 | 150–800 °C    | 20–150 J/g  | Very high k, rapid response           | Heavy, costly, unsuitable for skin contact |

### 4.6 Selection Criteria for Glove Application

For a wearable, skin-adjacent application, the selection criteria extend beyond thermal performance alone. The PCM must be non-toxic and chemically inert in the event of encapsulation failure, must not be corrosive to the encapsulating film or adjacent metallic hardware, should exhibit minimal supercooling so that its warming function in cold environments is reliable, and should be available in a gel or paste form compatible with flexible-bag encapsulation. A gel-based organic PCM with a melting point of approximately 68 °C- chosen to sit just below the second-degree-burn threshold of 60–70 °C referenced in the experimental protocol of Section 9, while remaining comfortably above typical ambient and body-surface temperatures to avoid unintended melting during normal wear- was selected on this basis for the present prototype.

### 4.7 Comparison with Alternative Insulation Strategies

PCM integration is one of several strategies available for improving the thermal protection of a glove without simply adding bulk textile mass. Table III contrasts the PCM approach with three commonly used alternatives- aerogel-based insulation, extra air-gap layering, and reflective/low-

emissivity outer coatings- across the dimensions most relevant to a wearable, dexterity-sensitive application.

**Table III:** Comparison of alternative insulation strategies

| Strategy                 | Mechanism                               | Thickness Penalty     | Notable Limitation                            |
|--------------------------|-----------------------------------------|-----------------------|-----------------------------------------------|
| PCM layer                | Latent-heat buffering at $T_{pc}$       | Low ( $\approx 1$ cm) | Finite reservoir; melts out                   |
| Aerogel insulation       | Very low $k$ , sensible-heat resistance | Low–moderate          | Brittle, dusty, costly                        |
| Extra air-gap layering   | Trapped-air sensible resistance         | Moderate–high         | Adds bulk, reduces dexterity                  |
| Reflective outer coating | Reduced radiative absorption            | Negligible            | Ineffective against direct/conductive contact |

As Table III indicates, the PCM strategy and the alternative approaches are not mutually exclusive: a reflective outer coating combined with a PCM thermal-barrier layer, for instance, could in principle address both the radiative and conductive/ convective components of a fire-exposure heat load simultaneously. Such hybrid strategies are noted as a promising direction for future glove designs in Section 16, though they were outside the single-variable scope of the present prototype study.

#### 4.8 Microencapsulation as an Alternative Integration Route

An alternative to the discrete bulk-gel layer used in this study is microencapsulation, in which the PCM is enclosed within micron-scale polymeric shells (commonly melamine-formaldehyde, polyurea, or acrylic-based) that can subsequently be coated onto or spun directly into textile fibres, as reviewed by Salaün et al. [7] and Mondal [11]. Microencapsulation offers finer, more uniform distribution of the PCM through the fabric, improved mechanical durability of the individual PCM domains against puncture (since damage to any single microcapsule affects only a tiny fraction of the total PCM inventory), and compatibility with conventional textile finishing and laundering processes. Its principal drawback relative to the bulk-gel approach used here is a lower achievable PCM loading fraction per unit fabric mass, and consequently a lower total latent-heat reservoir for a given garment thickness- a trade-off that favours bulk-gel encapsulation for the present application, where maximising the protection-time extension from a thin, spatially concentrated layer was the primary design objective, but that may favour microencapsulation for applications prioritising launderability and long-term durability over peak single-event thermal buffering capacity.

A hybrid approach- a discrete bulk-gel core layer supplemented by a microencapsulated PCM finish on the inner base layer - represents a further design variant that combines a portion of both approaches' advantages, and is noted alongside the hybrid insulation strategies of Section 4.7 as a candidate direction for future prototype iterations.

## 5. Thermal Energy Storage and Insulation in Clothing Systems

### 5.1 Comparative Magnitude of Latent versus Sensible Heat

The amount of heat absorbed by a PCM during an actual phase change, relative to the heat absorbed in an ordinary heating process, can be illustrated by taking water as an example PCM. The melting of ice into water absorbs a latent heat of nearly 335 J/g. If the resulting water is subsequently heated further, only about 4 J/g of sensible heat is required to raise its temperature by one degree. The latent heat absorbed during the ice-to-water phase change is therefore roughly a hundred times greater than the corresponding sensible-heat absorption. This order-of-magnitude comparison is the central physical justification for embedding a thin PCM layer rather than simply adding more sensible-heat-storing textile mass to a glove design.

[Figure not present in source PDF – please insert]

**Figure 1:** Ideal phase change behaviour: heating/cooling profile and  $h(T)$ ,  $cp(T)$  curves.

### 5.2 Activity-Dependent Insulation Requirements

The thermal insulation required of a clothing system depends primarily on the wearer's physical activity level and on ambient conditions such as temperature and relative humidity. The rate of heat produced by the human body varies considerably with activity, ranging from about 100 W at rest to over 1000 W during maximal physical performance. During cooler seasons (approximately 4–5 °C), the recommended thermal insulation is set to keep the body adequately warm at rest. During strenuous activity- often the case in winter sports or active firefighting- body temperature rises with increased heat production, and the body perspires to withdraw excess energy through evaporative cooling and keep this rise within safe limits.

If the thermal insulation of the clothing is reduced during physical activity, a portion of the generated heat can instead be removed by convection, reducing the need for the body to perspire as heavily. This activity dependence implies that an ideal glove insulation system should, in principle, be adaptive rather than fixed- a property that a PCM layer partially delivers by virtue of its buffering action, since it absorbs excess heat from either the body or the environment only once its threshold temperature is approached, rather than continuously impeding heat flow in both directions as a purely resistive insulator would.

## 6. Mechanism of PCM Functionality in Garments

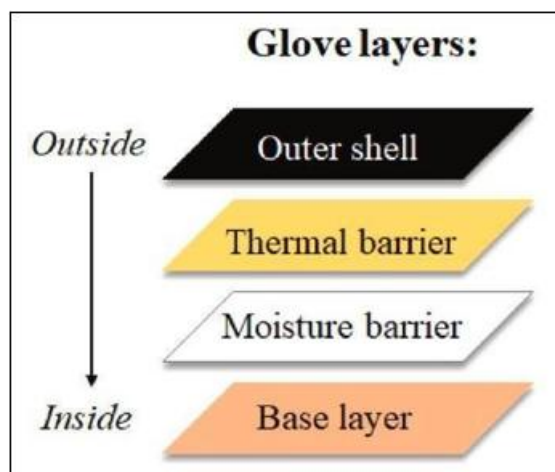
### 6.1 Thickness, Density, and Layered Design

The quality of thermal insulation provided by a garment, for both heat and cold, is largely governed by the thickness and density of its constituent fabrics. In general, greater thickness combined with lower density improves insulation by trapping

air within the material, and thermal performance is often further enhanced by air gaps between garment layers. However, the effectiveness of such insulation diminishes under extreme external temperatures, whether very high or very low.

A key challenge in garment design is balancing insulation against wearability: thicker fabrics offer better protection but tend to be heavier and to restrict the wearer's mobility. To address this trade-off, intelligent fabrics materials capable of adapting to external temperature changes- present a promising route to superior thermal protection without sacrificing comfort.

One potential design approach constructs the glove as a multi-layered structure: top and bottom layers made from a 35% cotton / 65% polyester interlock-fabric blend, a middle layer incorporating a PCM-coated fabric, and an outer protective layer made from a PANEX woven carbon fabric. This configuration leverages the thermal-buffering properties of PCMs to improve wearer comfort.



**Figure 2:** Schematic representation of the multilayer glove structure, consisting of an outer shell, thermal barrier, moisture barrier, and base layer.

## 6.2 Heating-Phase Behaviour

During exposure to heat, the PCM absorbs thermal energy at its melting point, transitioning from solid to liquid and creating a short-term cooling effect within the glove layers; this absorbed heat may originate from the body or from the external environment. Once the PCM is fully melted, further thermal storage ceases, and the temperature at the inner glove surface begins to rise more rapidly again- the end of the thermal plateau visible in the temperature-versus-time curves of Fig. 7.

## 6.3 Cooling-Phase Behaviour

Conversely, in cold environments where the fabric temperature falls below the PCM's freezing point, the liquid PCM solidifies, releasing its stored heat and producing a temporary warming effect. Such a design creates a thermal-buffering system within the garment, minimising fluctuations in skin temperature and enhancing thermal comfort for the wearer across varying environmental conditions. This dual-direction buffering is what allows the same PCM layer to

serve both a firefighting-heat-protection role and an arctic-cold-protection role, as discussed further in Section 12.

## 6.4 Comparative Note on Simultaneous Heat and Cold Protection

It is worth emphasising that the heat-protection and cold-protection functions described in Sections 6.2 and 6.3 are not simultaneously active in the same operational instance — a given PCM charge can either absorb heat (while melting) or release heat (while freezing) at any one time, not both. A single glove insert therefore serves these two roles sequentially across different missions or phases of an operation, rather than providing continuous bidirectional buffering within a single continuous exposure event. This distinction matters for the applications discussion of Section 12: the firefighting use case (Section 12.1) relies on the PCM being in its solid, heat-absorption-ready state at the start of an incident, whereas the cold-weather use case (Section 12.2) relies on the PCM having been pre-melted beforehand so that it is primed to release heat on solidification — an operational sequencing requirement rather than a limitation of the underlying physics.

## 7. Design and Fabrication of the Prototype Glove

### 7.1 Material Selection and Layer Architecture

Prototype gloves were fabricated using a layered structure. The outer layer was a cotton–polyester blend, while the core thermal layer contained encapsulated gel PCM. A PCM with a melting point around 68 °C was chosen for its suitability in firefighting and other high-heat scenarios, consistent with the selection criteria discussed in Section 4.6. The layer architecture mirrors the generic outer-shell / thermal-barrier / moisture-barrier / base-layer structure used in commercial structural firefighting gloves (Fig. 2), with the PCM gel occupying the thermal-barrier position.

### 7.2 Encapsulation Strategy

The PCM gel was sealed inside flexible bags. After initial melting to remove trapped air, the PCM was evenly distributed, and the bag was fully sealed to ensure a uniform thickness of approximately 1 cm. Removing trapped air prior to sealing is important both to achieve a uniform layer thickness- and hence a predictable thermal response- and to avoid localised air pockets that would otherwise act as unwanted additional thermal resistances or, conversely, as weak points prone to rupture under flexing.



**Figure 4:** PCM gel encapsulated within flexible bags, moulded into the glove shape

### 7.3 Fabrication Process

The encapsulated PCM insert was moulded into the shape of the glove's palm and finger regions prior to assembly into the full multilayer structure. This moulding step ensures that the PCM layer conforms to the hand geometry rather than bunching at the fingertips or wrist, which would otherwise create thin spots with reduced local thermal protection.

### 7.4 Design Considerations for Dexterity

Because the PCM insert is confined to a thin, discrete layer rather than distributed through a thickened bulk textile, the overall glove profile remains close to that of a standard single-layer work glove. This is the central design rationale distinguishing the present approach from simply thickening conventional insulation: dexterity-limiting bulk is avoided by concentrating the thermal-storage function in a material with a disproportionately high energy density per unit thickness, namely the PCM's latent heat of fusion.

### 7.5 Encapsulation Film Material Candidates

The choice of flexible-bag film for encapsulating the PCM gel governs puncture resistance, flexibility, heat resistance, and long-term seal reliability. Table IV summarises the qualitative trade-offs among commonly available flexible-packaging film candidates considered for this role, informed by general packaging-film engineering practice rather than by material tests conducted specifically for this study.

**Table IV:** Encapsulation film material candidates

| Film Type               | Flexibility | Heat Resistance | Notable Trait                        |
|-------------------------|-------------|-----------------|--------------------------------------|
| LDPE                    | High        | Moderate        | Low cost, easy heat-sealing          |
| Nylon/PE laminate       | Moderate    | Good            | Better puncture resistance           |
| TPU film                | Very high   | Good            | Elastic, conforms well to hand shape |
| Aluminised barrier film | Moderate    | Very good       | Adds reflective outer benefit        |

For the present prototype, a simple flexible bag consistent with the LDPE/TPU family was used, prioritising ease of hand-fabrication and reliable heat-sealing over the puncture resistance and reflective benefits offered by the laminate and aluminised alternatives. A production-oriented design would likely favour a nylon-laminate or TPU film for improved durability, consistent with the future-work direction noted in Section 16.

### 7.6 Specific Organic PCM Candidates by Chemical Family

Within the organic-PCM category discussed in Section 4.1, specific n-alkane (paraffin) compounds offer melting points spanning the range relevant to this application: n-octadecane melts near 28 °C, n-eicosane near 37 °C, and higher-carbon-number paraffins and paraffin blends extend into the 50–70 °C range required for the fire-protection use case discussed in Section 4.6. Non-paraffin organic alternatives in a comparable melting-point range include certain fatty-acid esters and polyethylene-glycol (PEG) formulations, which offer differing viscosity, odour, and biodegradability trade-offs relative to paraffin blends, consistent with the sustainability discussion of Section 14.3. The specific commercial gel PCM used in the present prototype was selected primarily on the basis of its stated  $\approx 68$  °C melting point and gel (rather than solid-wax) physical form, which simplified the flexible-bag encapsulation process described in Section 7.2; a full chemical characterisation of the exact formulation was outside the scope of this study, consistent with the material-characterisation limitation noted in Section 15.

### 7.7 Ergonomic and Comfort Considerations

Beyond the raw thermal-protection metrics reported in Section 11, wearer comfort and ergonomic acceptance are practical determinants of whether a PCM-integrated glove would see real-world adoption. Three qualitative factors were considered during prototype fabrication: first, the added mass of the gel PCM insert relative to a conventional glove, which affects perceived hand fatigue over an extended wear period; second, the local stiffness introduced at the seams of the encapsulating bag, which can create pressure points or restrict finger-joint flexion if not carefully moulded to the hand's natural creases; and third, the potential for condensation or a perceived clammy sensation at the inner base layer as the PCM approaches its melting point, since a gel-phase PCM layer beneath a moisture barrier can feel different underhand from a purely dry textile insulation stack even when no actual moisture transfer occurs across the barrier. None of these ergonomic factors was formally quantified in this study- for instance, through standardized grip-strength or pinch-force testing- and their systematic evaluation is included among the future-work priorities of Section 16.

### 7.8 Sensitivity to Environmental Humidity and Moisture

As highlighted by Song et al. [5] in the context of flash-fire thermal protective clothing, moisture present within a garment assembly- whether from ambient humidity, prior perspiration, or firefighting water spray- can substantially alter the effective thermal response of a layered textile

system, both by adding a sensible- and latent-heat sink of its own (through evaporation) and by locally increasing thermal conductivity where fibres become saturated. The convection-oven test protocol used in Section 9 was conducted under ambient laboratory humidity without any deliberate pre-wetting of the glove samples, and the moisture barrier layer shown in Fig. 2 is intended, in a production design, to limit liquid-water ingress toward the PCM and base layers. However, the interaction between the PCM's own latent-heat buffering and any co-occurring moisture-driven evaporative cooling was not isolated or independently characterised in this study, and represents a meaningful source of divergence between the present laboratory results and performance under genuinely wet structural-firefighting conditions.

## 7.9 Manufacturing Process Flow

Translating the hand-fabrication steps described in Sections 7.2 and 7.3 into a repeatable manufacturing process flow would proceed through the following stages: (i) metering and degassing of the gel PCM to a target mass; (ii) forming the encapsulation film to the glove-palm and finger contours, using a heated die or vacuum-forming step to achieve the moulded shape shown in Fig. 4 at production scale; (iii) filling and heat-sealing the encapsulated PCM insert, with in-line thickness and seal-integrity inspection; (iv) laminating the insert between the outer-shell and moisture-barrier textile layers per the architecture of Fig. 2; and (v) final glove assembly, incorporating the base layer and any remaining glove construction (cuff, stitching, closures) common to conventional glove manufacturing. Stages (i)–(iii) are the process steps most specific to the PCM-integration aspect of this design and are therefore the steps most in need of the automated, purpose-built equipment discussed in Section 13.2 to achieve consistent quality at production volume.

## 8. Governing Calculations and Formulas

### 8.1 Algorithm for Calculating the Specific Heat Capacity

Determination of the heat required to raise the temperature of the PCM:

$$Q_r = m_s \cdot c_s \cdot \Delta T \quad (6)$$

Calculation of the electrical heating power supplied to the system:

$$Q_{el} = \dot{Q}_{el} \cdot \Delta t \quad (7)$$

Determination of the heat absorbed by the tested PCM, from the overall heat balance:

$$Q_{el} = Q_{PCM} + Q_r \quad (8)$$

$$Q_{PCM} = Q_{el} - Q_r \quad (9)$$

Determination of the specific heat of the solid-state PCM:

$$c_v = Q_{PCM} / (m \cdot \Delta T) \quad (10)$$

### 8.2 Algorithm for Calculating the Heat of Fusion

Calculation of the electrical heating power supplied to the system during the phase-change plateau, and determination of the corresponding heat absorbed by the PCM from the heat balance:

$$Q_{el} = Q_{PCM} \quad (11)$$

Calculation of the specific heat of fusion of the PCM:

$$Q_{fusion} = Q_{PCM} / m \quad (12)$$

### 8.3 Interpretation of the Heat-Balance Approach

The two algorithms above are complementary halves of a single calorimetric procedure. Outside the phase-change plateau, the temperature of the PCM rises or falls sensibly with time, and the heat-balance equations of Section 8.1 allow the sensible specific heat to be back-calculated from the measured heating power and temperature rise once the parasitic heat absorbed by the sample holder,  $Q_r$ , has been subtracted. Within the plateau itself, the PCM temperature remains essentially flat despite continued heat input, and because there is no  $\Delta T$  to divide by- the appropriate quantity to extract is instead the specific heat of fusion, obtained by dividing the heat absorbed during the plateau by the sample mass, as in Section 8.2. Applying both algorithms to a single heating run therefore yields a full characterisation of the PCM's thermal response:  $c_s$  (or  $c_v$ ) below and above the plateau, and  $Q_{fusion}$  across it.

### 8.4 Uncertainty and Error Analysis

Three principal sources of uncertainty affect the calorimetric quantities derived above. First, thermometer placement uncertainty: because a single meat thermometer probe was used to characterise the glove surface temperature, small variations in probe contact and position between the PCM and control samples introduce a temperature-reading uncertainty estimated at  $\pm 1-2^\circ\text{C}$ . Second, timing resolution: temperature was logged at 10–20 second intervals, which bounds the resolution with which the onset and duration of the phase-change plateau can be identified, and introduces a corresponding uncertainty in  $\Delta t$ -dependent quantities. Third, sample-to-sample variability in PCM mass and layer thickness during hand fabrication of the encapsulated gel inserts contributes an uncertainty in  $m$  and, through  $m$ , in both  $c_v$  and  $Q_{fusion}$ . The three-trial repeatability protocol described in Section 9.4 was adopted specifically to bound this combined uncertainty empirically, via the spread of repeated trials, rather than relying solely on instrument-specification error propagation.

### 8.5 Dimensionless Groups Relevant to the Analysis

In addition to the Biot number introduced in Section 3.5, the Fourier number,  $Fo = \alpha \cdot t / \delta^2$ , provides a useful dimensionless measure of the extent to which a transient thermal disturbance has penetrated a layer of thickness  $\delta$  and thermal diffusivity  $\alpha$  within a given exposure time  $t$ . For  $Fo \ll 1$ , the far (inner) face of a layer remains largely unaffected by a heat pulse applied at the near (outer) face- the semi-infinite-solid regime- whereas for  $Fo$  of order unity or greater, the full layer thickness participates meaningfully in the transient response. The oven-exposure durations used in Section 9 (of order  $10^2-10^3$  s) and the PCM layer thickness ( $\approx 1$  cm) place the system in an intermediate  $Fo$  regime in which neither a semi-infinite-solid nor a fully lumped approximation is strictly appropriate, reinforcing the choice of a full finite-element treatment (Section 10) for the spatial temperature field, while the

lumped heat-balance equations of Sections 8.1 and 8.2 remain valid as an integral, whole-sample energy accounting method independent of the internal spatial distribution.

### 8.6 Worked Numerical Consistency Check

The worked Biot- and Fourier-number estimates developed in Appendix F ( $Bi \approx 1.0$ ,  $Fo \approx 0.09$  for representative PCM properties and an 80 s exposure) are internally consistent with the qualitative description of the PCM glove's thermal response given throughout Sections 3, 8, and 11: a Biot number near unity supports the decision to model the assembly with a full spatial (finite-element) method rather than a lumped-capacitance approximation, while a Fourier number well below unity supports the observation of a sustained, incompletely-through-penetrated thermal plateau in the experimental trace of Fig. 7(b) rather than a rapid, uniform temperature rise across the PCM layer. Readers are directed to Appendix F for the full numerical working underlying this consistency check.

## 9. Experimental Methodology

### 9.1 Test Apparatus and Instrumentation

The experimental apparatus consisted of a domestic convection oven, used as a controllable and repeatable convective/radiative heat source; a meat thermometer probe, used to record surface and internal glove temperatures; and a stopwatch/timer used to log elapsed time at each reading. The convection oven was selected over an open flame both for laboratory safety and because it provides a more repeatable and controllable thermal environment than a live fire, at the cost of not reproducing the very high radiative flux and turbulent flame-contact conditions of an actual structural fire — a trade-off discussed further as a limitation in Section 15.

### 9.2 Glove Testing Setup

The prototype glove was placed inside a convection oven preheated to 180 °C. The meat thermometer probe was inserted through a small guide slit in the outer shell and secured with tape so that its tip sat against the inner (base-layer) surface of the glove, at the location directly beneath the PCM insert in the palm region for the PCM samples and at the corresponding palm location for the control samples; this inner-surface position, rather than the oven-facing outer shell, was the position used for all threshold and plateau readings reported in this study. Temperature measurements were recorded at 10–20 second intervals from this fixed probe position. Temperature monitoring continued until the inner-layer reading reached 60 °C- the accepted threshold for second-degree burns- which was adopted as the sole test-termination criterion for every trial.

At this point, the glove sample was removed from the oven and allowed to cool naturally at room temperature, while continuous temperature data were collected from the same fixed inner-layer probe position throughout the cooling phase.

A control setup using a standard glove without PCM was also tested under identical conditions, with the probe fixed at the equivalent inner-layer location. This control enabled a direct

comparison with the PCM-embedded glove, allowing the effectiveness of the PCM layer in delaying thermal breakthrough and improving thermal protection to be evaluated. This method was designed to simulate real-world convective heat-exposure scenarios relevant to firefighting environments.



**Figure 3:** Convection-oven based heat-exposure testing setup used to evaluate the glove samples.

### 9.3 Calibration Procedure

Prior to each test series, the oven's set-point temperature was allowed to stabilise for a minimum preheating period, and the thermometer probe was checked against a room-temperature and boiling-water reference point to confirm reading consistency between trials. This two-point calibration check was intended to catch any drift in the probe's response rather than to serve as a full metrological calibration, which was outside the scope of the resources available for this project-level study.

### 9.4 Test Matrix and Repeatability

To ensure the reproducibility and reliability of the experimental results, each test was conducted three times under identical conditions, both with and without the PCM. This repeated testing helped minimise random errors and confirm the consistency of the observed outcomes. The resulting test matrix comprised six total heating-cooling cycles: three replicate trials of the control (non-PCM) glove and three replicate trials of the PCM-integrated glove, all conducted at the same 180 °C oven set-point and terminated at the same 60 °C inner-layer threshold criterion.



**Figure 5:** Glove testing setup: (a) glove and PCM insert inside the convection oven during heating, and (b) the convection oven running with the glove inside

### 9.5 Data Acquisition and Processing

Recorded temperature-time pairs for the oven, ambient, glove-surface, and inside-glove locations were transcribed and plotted, as shown in Fig. 7, to allow visual comparison of

the heating and cooling trajectories between the control and PCM samples. The presence, extent, and approximate duration of a thermal plateau in the inside-glove trace was used as the primary qualitative indicator of PCM activity, while the time to reach the 60 °C inner-layer threshold was used as the primary quantitative metric of thermal protection performance, consistent with the results reported in Section 11.

## 9.6 Health and Safety During Testing

All heating trials were conducted with appropriate precautions for handling a convection oven at 180 °C, including heat-resistant gloves for sample insertion and removal (distinct from the test specimens themselves), and clearance of flammable material from the immediate test area given the combustibility of the organic PCM discussed in Section 14.2. Samples were monitored continuously during heating rather than left unattended, both to permit timely temperature logging and as a safety precaution against unexpected thermal behaviour, such as encapsulation seal failure or excessive smoking, neither of which was observed during the trials conducted for this study.

## 9.7 Statistical Treatment of Repeated Trials

With three replicate trials per configuration, the sample size is too small to support formal inferential statistics such as a t-test with meaningful power; instead, the repeated trials were used descriptively, to establish the qualitative consistency of the thermal-plateau signature and to bound the reported protection-time range (60–100 s for the PCM configuration versus approximately 30 s for the control) as an empirical spread across trials rather than a single point estimate. This descriptive approach is consistent with the exploratory, prototype-stage character of the study, and a larger trial count is recommended for future work (Section 16) for any effort seeking a formally powered statistical comparison or a certification-grade performance claim.

# 10. Numerical Simulation Methodology

## 10.1 CAD Modelling

A simplified computer-aided design (CAD) representation of the layered glove cross-section was constructed to support finite-element thermal analysis. Rather than modelling the full anatomical glove geometry, a representative flat multilayer coupon- comprising the outer shell, PCM thermal-barrier layer, moisture barrier, and base layer stacked in sequence- was used, consistent with the layer schematic of Fig. 2. This simplification is standard practice for early-stage thermal-barrier evaluation, since the through-thickness heat-transfer path dominates the response for a thin, large-area layered assembly, and it substantially reduces the computational cost relative to an anatomically accurate mesh of the hand and glove.

## 10.2 Mesh and Boundary Conditions

The simulation was performed using CAD modelling and the SimScale cloud-based finite-element platform. A convective boundary condition, representative of the 180 °C convection-

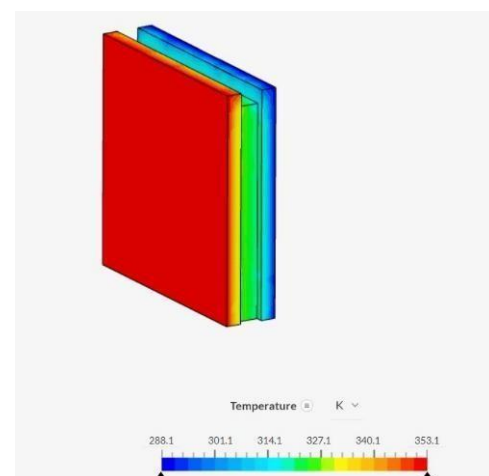
oven environment, was applied to the outer-shell face, and a second convective boundary condition, representative of ambient room conditions, was applied to the inner base-layer face. Layer material properties- thermal conductivity, density, and specific heat, with the enthalpy-method latent-heat treatment of Section 3.4 applied to the PCM layer- were assigned per layer based on typical values for the constituent materials described in Section 7.1.

## 10.3 Material Properties Used in Simulation

The PCM layer was assigned a melting point of approximately 68 °C (341 K) and a latent heat of fusion consistent with a gel-based organic PCM formulation, in line with the classification and typical property ranges summarised in Table II and with the representative organic-PCM datasheet values reported by the manufacturer [16]. The textile layers were assigned standard cotton-polyester and carbon-fabric conductivity and specific-heat values drawn from generic material property libraries within the simulation platform.

## 10.4 Simulation Results

The resulting finite-element temperature field, shown in Fig. 6, illustrates the heat distribution and phase-transition behaviour of the prototype glove under convective thermal exposure. The simulation displays a pronounced temperature gradient across the thickness of the assembly, with the outer layers approaching the applied boundary temperature while the inner layers remain substantially cooler, consistent with the thermal-buffering role expected of the embedded PCM layer. The colour-banded temperature field, spanning approximately 288 K to 353 K across the visualised range, corresponds qualitatively to the wide separation between oven and inside-glove temperatures observed experimentally in Fig. 7, providing a consistency check between the numerical and experimental portions of the study, even though the two were not formally cross-calibrated against a common set of material properties in this preliminary analysis.



**Figure 6:** Finite-element simulation of the prototype glove incorporating PCM, performed using CAD modelling and SimScale. The analysis illustrates heat distribution and phase-transition behaviour under convective thermal exposure, highlighting the glove's thermal-buffering capability

## 10.5 Mesh Independence and Validation Considerations

A rigorous finite-element study would ordinarily include a mesh-independence check, in which the simulation is re-run at progressively finer mesh resolutions until the predicted temperature field no longer changes appreciably, together with a formal validation step comparing simulated and experimentally measured temperatures at matched locations and times. Within the scope and computational resources available for this project-level study, a single representative mesh resolution, as provided by the SimScale platform's default automatic meshing for the simplified layered-coupon geometry, was used, and the comparison with experiment in Section 11.4 is therefore qualitative rather than a quantitatively validated match. Establishing a fully validated, mesh-independent numerical model- ideally using thermal properties measured directly from the fabricated PCM and textile samples rather than generic literature values- is identified as a priority direction for future work in Section 16.

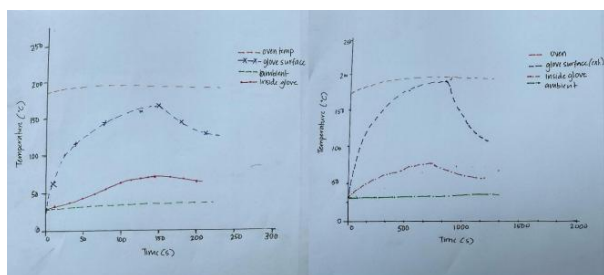
## 11. Results and Discussion

### 11.1 Heating-Phase Temperature Profiles

The experimental data clearly demonstrate the benefits of PCM integration:

- Conventional gloves (without PCM) allowed the hand-surface temperature to rise to 65–75 °C within 30 seconds of exposure, leading to a rapid risk of burns.
- PCM-integrated gloves significantly delayed this rise, extending the safe time window to 60–100 seconds before dangerous skin temperatures were reached.

The PCM effectively absorbed latent heat during its solid-to-liquid phase change, thereby maintaining lower internal glove temperatures. Upon cooling, the PCM gradually released the absorbed energy as it solidified, providing prolonged thermal comfort and delaying the rapid cooling that can otherwise cause discomfort. Temperature profiles recorded during the experiments indicate that PCM gloves reduced the rate of temperature increase and stabilised the surface temperature during both the heating and cooling phases. This dual heat absorption-release functionality reduces the risk of thermal injury during both active exposure and post-exposure periods.



**Figure 7:** Temperature profiles recorded for the glove sample: (a) without the PCM layer, and (b) with the PCM layer embedded

### 11.2 Summary of Protection-Time Results

Table V summarises the qualitative comparison between the control and PCM-integrated glove samples across the metrics recorded during testing. The ranges reflect the spread

observed across the three repeat trials described in Section 9.4.

**Table V:** Summary of protection-time results

| Metric                              | Control Glove (no PCM)         | PCM-Integrated Glove                                     |
|-------------------------------------|--------------------------------|----------------------------------------------------------|
| Time to 60 °C inner-layer threshold | ≈30 s                          | 60–100 s                                                 |
| Hand-surface temperature at 30 s    | 65–75 °C                       | Below control at equivalent time                         |
| Presence of thermal plateau         | Not observed                   | Observed, coincident with PCM melting                    |
| Cooling-phase rate                  | Rapid, closely follows ambient | Moderated, gradual latent-heat release                   |
| Qualitative post-test PCM state     | Not applicable                 | Fully melted at threshold, then re-solidified on cooling |

### 11.3 Comparison Between Control and PCM Glove

The extension of the safe exposure window from approximately 30 seconds for the control glove to 60–100 seconds for the PCM-integrated glove represents a two- to threefold improvement in the time available before the inner-layer temperature reaches the second-degree-burn threshold. In an operational firefighting or rescue context, an additional 30–70 seconds of safe hand-contact time can be the difference between completing a critical task- operating a valve, freeing a trapped limb, releasing a coupling- and having to withdraw. This magnitude of improvement is broadly consistent with the trends reported by Wang et al. [1] for PCM-integrated structural firefighting gloves under high-heat exposure, and with the transient thermal-buffering behaviour modelled by Fonseca et al. [6] for PCM firefighting suits.

### 11.4 Comparison with Literature Values

The observed thermal plateau in the PCM-glove inside-temperature trace of Fig. 7(b) is qualitatively consistent with the idealised heating profile of Fig. 1, in which the temperature rise stalls near  $T_{pc}$  while the material absorbs latent heat. The magnitude of the delay achieved here- roughly doubling to tripling the safe exposure time with only a 1-cm-thick PCM insert - is consistent with the general finding across the PCM-textile literature [1], [3], [5]–[7] that a modest PCM addition can deliver a thermal benefit disproportionate to its added thickness, in contrast to simply adding an equivalent thickness of conventional insulating textile.

### 11.5 Repeatability and Trial-to-Trial Consistency

Across the three repeat trials conducted for each configuration, the qualitative shape of the heating and cooling curves- including the presence and approximate duration of the plateau for the PCM samples- was consistent, supporting the reliability of the observed thermal-buffering effect. Minor trial-to-trial variation in the precise time to reach the 60 °C threshold is attributed to the uncertainty sources discussed in Section 8.4, particularly probe-placement variability and small differences in PCM layer thickness introduced during hand fabrication of each sample.

### 11.6 Effect of PCM Layer Thickness

Although only a single nominal thickness ( $\approx 1$  cm) was tested experimentally, the underlying heat-balance relationships of Section 8 imply that the total latent-heat reservoir available to buffer an incoming heat flux scales directly with PCM mass and hence, for a fixed encapsulation area, with layer thickness. A thicker PCM layer would therefore be expected to further extend the protection time, at the cost of additional glove bulk and reduced dexterity- reintroducing, in a more favourable ratio, the same trade-off that motivated moving away from purely sensible-heat insulation in the first place. Identifying the thickness at which this trade-off is optimised for a given occupational task is identified as a direction for future parametric study in Section 16.

### 11.7 Effect of Melting-Point Selection

The choice of a PCM melting point close to, but below, the skin-damage threshold is deliberate: a lower melting point would cause the PCM to begin melting- and therefore to begin exhausting its finite latent-heat reservoir- prematurely during normal wear or mild heat exposure, reducing the reservoir available when a genuine high-heat event occurs. Conversely, a melting point set too close to or above the burn threshold would delay the onset of latent-heat absorption until skin damage risk has already become significant. The 68 °C melting point used in this study represents a reasoned compromise within this design space, consistent with the reasoning in Section 1.2, though a more systematic sensitivity study across a range of melting points was outside the scope of the present single-formulation prototype.

### 11.8 Comparison Between Experimental and Simulated Results

The finite-element temperature field of Fig. 6 and the experimentally recorded temperature-time histories of Fig. 7 were obtained through independent methods- a steady applied boundary-condition simulation versus a transient oven-exposure measurement- and were not formally cross-calibrated to a shared set of measured material properties, as noted in Section 10.5. Qualitatively, however, both point to the same physical picture: a pronounced temperature drop across the PCM thermal-barrier layer, consistent with its function as the dominant thermal resistance and latent-heat sink within the assembly. This qualitative agreement supports the physical plausibility of the simulation without constituting a quantitative validation, a distinction maintained deliberately throughout this discussion to avoid over-stating the numerical model's predictive precision.

### 11.9 Comparative Positioning Relative to Prior PCM Glove Studies

Positioned against the closely related work of Wang et al. [1] on PCM-integrated structural firefighting gloves, the present study contributes a low-cost, laboratory-accessible convection-oven test protocol and an accompanying finite-element cross-check, rather than a specialised fire-testing-facility evaluation. This positions the present work as a complementary, reproducible starting point suited to academic project settings, while the more specialised prior

literature [1], [6] remains the appropriate reference for certification-grade performance claims. The consistent qualitative finding across both this study and the prior literature- that a thin PCM layer can extend safe exposure time by a factor of two or more relative to a non-PCM control- strengthens confidence in the underlying thermal-buffering mechanism even though the absolute magnitudes are not directly comparable across differing test apparatus and PCM formulations.

### 11.10 Model-Based Parametric Sensitivity Estimates

While a full experimental parametric sweep across PCM thickness and melting point was outside the scope of this study (Section 15), the governing heat-balance relationships of Section 8 and the scaling arguments of Section 11.6 can be used to generate illustrative, model-based estimates of how the protection time might vary with these design parameters, to guide the future parametric testing recommended in Section 16. Table VI presents such illustrative estimates, obtained by scaling the observed 60–100 s experimental protection-time range in proportion to the assumed PCM mass (and hence latent-heat reservoir) at each thickness, holding all other layer properties fixed at their as-tested values. These figures are explicitly model-based projections rather than additional experimental measurements, and should be interpreted as planning estimates only.

**Table VI: Model-based parametric sensitivity estimates**

| PCM Thickness      | Relative Latent-Heat Reservoir | Estimated Protection Time                    |
|--------------------|--------------------------------|----------------------------------------------|
| 0.5 cm             | 0.5×                           | $\approx 30\text{--}50$ s (model estimate)   |
| 1.0 cm (as tested) | 1.0×                           | 60–100 s (measured)                          |
| 1.5 cm             | 1.5×                           | $\approx 90\text{--}150$ s (model estimate)  |
| 2.0 cm             | 2.0×                           | $\approx 120\text{--}200$ s (model estimate) |

The near-linear scaling assumed in Table VI is a first-order approximation consistent with the dominant role of the latent-heat reservoir term in the overall heat balance; in practice, the relationship would be expected to depart from strict linearity at larger thicknesses as the internal conduction resistance of the PCM layer itself (captured by the Biot number of Section 3.5) becomes non-negligible, slowing the rate at which heat reaches and melts the more distal PCM material. Confirming or refining this scaling relationship experimentally is listed among the future-work priorities of Section 16.

### 11.11 Implications for Glove Certification

Relative to the standards landscape discussed in Section 3.9, the present results should be understood as a proof-of-concept demonstration of the PCM thermal-buffering mechanism rather than as evidence of compliance with any specific certification standard. The convection-oven protocol used here differs from standardized convective and radiant heat-resistance test methods in apparatus, boundary conditions, and pass/fail criteria, and a glove intended for actual structural-firefighting deployment would need to be evaluated under the relevant full standardized test battery- including radiant heat, convective heat, flame contact, and mechanical performance requirements- before any certification or operational-use claim could be responsibly made.

## 12. Applications

### 12.1 Structural Firefighting and Fire Rescue

The primary application context motivating this study is structural firefighting, where hands are exposed to intense, transient heat during forcible entry, hose handling near a fire front, and victim extraction. A PCM-integrated glove offers the potential to extend the safe-contact window during these high-intensity, short-duration exposures without the mobility penalty of thicker conventional insulation, directly supporting tasks that require fine motor control under time pressure.

Beyond structural firefighting proper, wildland-urban-interface firefighters face a related but distinct thermal profile characterised by longer-duration, lower-peak radiant exposure punctuated by brief intense flare-ups as fuel loads ignite nearby; the melting-point-tuning discussion of Section 11.7 suggests that a wildland-oriented PCM glove variant might reasonably adopt a different target melting point than the structural-fire-oriented 68 °C formulation used in this study, an application-specific tuning question left for future work.

### 12.2 Arctic and Cold-Weather Operations

The same PCM layer that absorbs heat during a fire event can, if pre-melted before deployment, subsequently release stored latent heat as it re-solidifies in a cold environment, providing a period of active warming during winter rescue, polar expedition, or cold-chain logistics work. This dual-mode capability is a distinguishing advantage of a latent-heat-based approach over a purely resistive insulation strategy, which offers no comparable active warming function.

For cold-weather deployment specifically, the PCM would typically need to be pre-conditioned (melted, via a body-worn warming pouch or external heat source) prior to the start of an operation, since — unlike the fire-protection use case, where ambient/body heat naturally drives melting during the hazard event itself — a cold environment provides no comparable trigger to bring the PCM into its heat-storing liquid state. This operational pre-conditioning requirement is a practical consideration distinct from, and in addition to, the passive activation that characterises the heat-protection application.

### 12.3 Industrial and Foundry Applications

Workers handling hot equipment, castings, or process piping in foundries, glassworks, and steel mills face intermittent, localized high-heat contact broadly analogous to the transient exposure profile modelled in this study's oven-based test protocol. A PCM insert tuned to a melting point appropriate for the specific process temperature could offer similar transient protection benefits in these industrial contexts.

Because industrial contact heat sources are often more spatially localized than the whole-glove convective exposure modelled in Section 9 (for example, gripping a single hot handle or component rather than immersing the whole hand in a heated environment), an industrial variant of the design might favour a regionally concentrated PCM insert over the full-palm layer used in this prototype, trading overall latent-

heat reservoir for a thinner, more targeted profile at the specific high-contact zones of the glove- the palm and fingertips.

### 12.4 Medical, Sports, and Consumer Applications

Beyond high-hazard occupational settings, PCM-integrated gloves and related garments have potential application in sports requiring hand protection from cold or friction-generated heat, in medical settings where localized thermal therapy or protection is required, and in consumer cold-weather apparel, where the same latent-heat-buffering principle can improve comfort during transitions between indoor and outdoor thermal environments.

### 12.5 Physiological Basis for Extremity Thermal Protection

The hands are physiologically distinctive as thermoregulatory organs: a high surface-area-to-volume ratio and a dense, superficial vascular network (including arteriovenous anastomoses concentrated in the fingers) make the hands both especially prone to rapid heat gain or loss and important contributors to whole-body thermoregulation. This physiology cuts both ways for the present application- it is precisely why hands are so vulnerable to rapid burn injury during fire exposure, motivating the burn-injury framing of Section 3.7, and it is also why effective hand warming during cold exposure (Section 12.2) can measurably improve whole-body thermal comfort and manual task performance, since cold, vasoconstricted fingers rapidly lose the fine tactile sensitivity and dexterity that PPE designers are simultaneously trying to preserve through thin-profile designs such as the one presented in this study.

### 12.6 Cross-Application Design Commonalities

Across the diverse application contexts surveyed in Sections 12.1 through 12.4, a common design pattern emerges: each application benefits from a thin, latent-heat-based thermal-barrier layer whose melting point is deliberately tuned to sit just below that application's specific injury or discomfort threshold, following the general reasoning developed for the firefighting case in Section 11.7. This suggests that the layer architecture, encapsulation strategy, and fabrication process validated for the structural-firefighting prototype in this study (Sections 7 and 9) could, in principle, be reused largely unchanged across the other application domains, with the primary design variable requiring re-optimisation for each new context being the PCM melting point and, secondarily, the layer thickness — rather than a wholesale redesign of the underlying glove architecture. This portability is a practical advantage of the latent-heat-based approach relative to application-specific insulation solutions that must typically be redesigned from first principles for each new operating environment.

This commonality also has a practical implication for manufacturing economics (Section 13.2): a single production line and encapsulation process, per the process flow of Section 7.9, could plausibly serve multiple application markets- structural firefighting, cold-weather, and industrial variants alike- differentiated primarily by the PCM

formulation loaded at the filling stage rather than by distinct tooling or assembly processes, which would be expected to improve the achievable production volume and unit economics relative to designing and tooling each application variant independently.

### 13. Economic and Practical Considerations

#### 13.1 Cost Analysis

Gel-based organic PCMs of the type used in this study are commercially available at relatively modest cost per unit mass compared with specialised flame-resistant textiles, suggesting that the incremental material cost of adding a PCM thermal-barrier layer to an existing glove design need not be prohibitive. A full cost-benefit analysis would additionally need to account for encapsulation material costs, assembly labour, and the cost of any additional quality-control steps required to verify layer thickness uniformity and seal integrity, none of which were formally costed in this project-scale study.

Table VII presents a qualitative, relative cost breakdown across the main components of a PCM-integrated glove, expressed as a proportion of the illustrative total incremental cost added over a comparable non-PCM base glove, intended to indicate where cost-reduction efforts would have the greatest leverage rather than as an absolute costed bill of materials.

**Table VII:** Relative cost breakdown of PCM glove components.

| Cost Component            | Relative Share | Primary Cost Driver                 |
|---------------------------|----------------|-------------------------------------|
| Gel PCM material          | Low–Moderate   | PCM mass and chemistry grade        |
| Encapsulation film        | Low            | Film type (Table IV) and area       |
| Assembly / sealing labour | Moderate–High  | Manual vs. automated sealing        |
| Quality control / testing | Moderate       | Thickness and seal-integrity checks |

This breakdown suggests that assembly labour and quality-control overhead, rather than the PCM material itself, are likely to dominate the incremental cost of a hand-fabricated prototype such as the one described in Section 7, and that transitioning to the automated forming and sealing equipment discussed in Section 13.2 would be expected to shift the cost balance further toward material cost as production volume increases.

#### 13.2 Manufacturing Scalability

The encapsulation approach used here- sealing gel PCM within flexible bags and moulding the resulting insert into the glove shape- is conceptually compatible with existing textile and flexible-packaging manufacturing processes, suggesting a plausible path to scaled production. Achieving consistent layer thickness and seal integrity at production volumes, however, would likely require purpose-built forming and sealing equipment rather than the manual fabrication process used for this prototype.

#### 13.3 Durability and Maintenance

Long-term durability considerations for a PCM-integrated glove include the mechanical fatigue resistance of the encapsulation film under repeated flexing, resistance to puncture or abrasion during operational use, and the effect of repeated melt–freeze cycling on the PCM's latent-heat capacity over the glove's service life. None of these long-term durability factors were evaluated in the present single-cycle-per-trial testing protocol and are identified as priorities for future work in Section 16.

A related maintenance consideration is field serviceability: a glove with a discrete, replaceable PCM insert- rather than a permanently bonded or microencapsulated PCM finish- could in principle allow a damaged or thermally degraded insert to be swapped out without discarding the entire glove, extending the useful service life of the more expensive outer-shell and barrier-layer components. Whether such a modular design is mechanically and ergonomically practical for a close-fitting glove was not evaluated in this study but is a natural extension of the layer-architecture discussion in Section 7.1.

#### 13.4 Market and Research Trends

Interest in PCM-based thermal management has grown steadily across building energy storage, cold-chain logistics, electronics thermal management, and, increasingly, wearable and protective-textile applications, a trend reflected in the breadth of the review literature summarised in Table I. As encapsulation technologies mature and per-unit PCM costs decline with wider industrial adoption across these adjacent markets, the incremental cost barrier to incorporating a PCM thermal-barrier layer into protective gloves and other PPE can reasonably be expected to fall, strengthening the economic case discussed in Section 13.1 over time even without further breakthroughs in the underlying PCM chemistry itself.

#### 13.5 Insurance and Liability Considerations

For occupational PPE, insurers and employers typically require evidence of standardized certification (Section 3.9) before a new protective-equipment design can be adopted for operational use, both to manage liability exposure and to satisfy occupational health and safety obligations. A demonstrated, certified extension in safe thermal-exposure time could, in principle, support a favourable risk case for insurers and fire departments considering adoption of PCM-integrated gloves, but- consistent with the certification discussion of Section 11.11- this study's laboratory-scale convection-oven results do not by themselves constitute the standardized evidence base such a risk case would require.

### 14. Safety, Environmental, and Sustainability Considerations

#### 14.1 Encapsulation Failure and Skin Contact

Because the PCM layer sits close to the wearer's skin, encapsulation failure- whether from puncture, seal failure, or thermal degradation- represents the primary safety concern specific to this design approach. The non-toxic, low-irritancy profile prioritised in the selection criteria of Section 4.6 is

intended to limit the consequences of an inadvertent release, but a full safety qualification would require dedicated skin-contact and leak-testing protocols beyond the scope of this study.

## 14.2 Flammability

Organic PCMs, including paraffin-based gels, are combustible, which is a material consideration for any application involving proximity to open flame. In a production glove design, the PCM layer would need to be fully enclosed within non-combustible or self-extinguishing outer and barrier layers, consistent with the outer-shell and moisture-barrier layers already present in the multilayer architecture of Fig. 2, to prevent the PCM itself from becoming a fuel source in the event of outer-layer burn-through.

## 14.3 Environmental and End-of-Life Considerations

The environmental footprint of a PCM-integrated glove depends on the source and biodegradability of the PCM chemistry, the recyclability of the encapsulation film, and the overall service life achieved before replacement is required. Bio-based organic PCMs derived from plant oils and fatty acids offer a more favourable sustainability profile than petroleum-derived paraffin, at potentially higher cost, and represent a reasonable substitution to evaluate in future formulation work.

## 14.4 Regulatory Compliance Pathway

Bringing a PCM-integrated glove to market for occupational safety use would require navigating the applicable regulatory pathway for personal protective equipment in the target jurisdiction- for example, alignment with the relevant national or regional PPE regulation framework, followed by third-party certification testing against the specific standards identified in Section 3.9. This regulatory pathway is distinct from, and considerably more demanding than, the exploratory laboratory testing described in Section 9, and would typically require engagement with an accredited testing laboratory well before any market launch, a step outside the scope and resources of the present academic project.

## 14.5 Circular-Economy and Repairability Considerations

The modular, replaceable-insert concept introduced in Section 13.3 also carries circular-economy implications: a glove design that allows the PCM insert to be recovered, reconditioned, or recycled independently of the outer textile shell could reduce the overall material footprint of the product over repeated replacement cycles, relative to a fully bonded, non-separable construction that must be discarded in its entirety once any single layer degrades.

## 15. Limitations of the Study

- The convection-oven test protocol approximates but does not replicate the radiative flux, flame-contact, and turbulent convective conditions of an actual structural fire.

- A single meat thermometer probe, rather than a distributed thermocouple array, was used to characterise the temperature field, limiting spatial resolution of the measured thermal response.
- Only a single PCM formulation, melting point, and layer thickness were tested; no parametric sweep of these design variables was performed experimentally.
- Mechanical durability under repeated flexing, laundering, and long-term thermal cycling was not evaluated.
- Moisture transport effects, shown by Song et al. [5] to influence thermal protective clothing performance under flash-fire conditions, were not directly measured in this study.
- The finite-element simulation used generic literature-typical material properties rather than properties measured directly from the specific PCM and textile samples used in fabrication, limiting quantitative cross-validation between simulation and experiment.

Taken together, these limitations characterise the present study as a proof-of-concept demonstration of the PCM thermal-buffering mechanism at prototype scale, rather than a certification-grade performance evaluation. None of the identified limitations undermines the core qualitative finding- that a thin PCM layer measurably extends safe exposure time relative to a matched control- but each bounds the confidence with which the specific quantitative magnitudes reported in Section 11 should be generalised beyond the tested conditions.

## 16. Future Work

- Conduct radiant-heat or live-flame testing under standardised protective-equipment test methods to complement the convection-oven protocol used here.
- Perform a parametric study varying PCM layer thickness and melting point to identify an optimum trade-off between protection time and dexterity.
- Instrument future prototypes with a distributed thermocouple or infrared thermal-imaging array to capture spatial, not just point, temperature data.
- Evaluate mechanical fatigue, puncture resistance, and melt-freeze cycling durability of the PCM encapsulation over simulated multi-year service life.
- Directly measure the thermal properties ( $k$ ,  $c_p$ ,  $Q_{\text{fusion}}$ ) of the specific PCM and textile samples used, to enable quantitative validation of the finite-element model against experiment.
- Investigate bio-based or non-flammable PCM formulations to address the sustainability and flammability considerations raised in Section 14.
- Extend the dexterity assessment beyond qualitative discussion to standardized grip-strength and fine-motor-task testing with the prototype glove worn.

Among these directions, radiant/live-flame testing (to close the largest fidelity gap identified in Section 15) and direct material-property characterisation of the specific PCM and textile samples used (to enable genuine quantitative validation of the finite-element model against experiment) are considered the highest-priority next steps, since both directly address the two limitations most likely to affect the generalisability of the core protection-time finding reported

in Section 11.1. The remaining directions- durability cycling, formulation optimisation, and standardized dexterity testing- are correspondingly framed as the subsequent stage of the development pathway summarised in Appendix G.

## 17. Conclusions

The integration of a gel-based phase change material into the prototype glove improved thermal buffering under the controlled convection-oven conditions used in this study. An approximately 1 cm PCM layer with a melting point near 68 °C extended the observed time to the defined 60 °C inner-layer threshold from approximately 30 s for the control to approximately 60 to 100 s for the PCM configuration. The theoretical analysis and finite-element simulation qualitatively support the latent-heat mechanism responsible for this delay. These findings demonstrate the feasibility of PCM integration as a potential approach to improving glove thermal protection without relying solely on increased passive insulation. Further work should include standardized radiant or flame exposure, direct measurement of material properties, durability assessment, and quantitative dexterity testing before operational performance can be established.

The theoretical treatment developed in Section 3, the heat-balance calculations of Section 8, the convection-oven experimental protocol of Section 9, and the finite-element simulation of Section 10 together provide a coherent, if preliminary, evidence base for the thermal-buffering mechanism underlying the observed two- to threefold extension in safe exposure time. Realising this benefit in a production-ready garment will require the additional durability, safety, and manufacturing-scale work outlined in Sections 13–16.

In summary, this work has (i) situated PCM-based glove design within the broader thermal energy storage and protective-textile literature; (ii) developed the governing conductive, latent-heat, and moving-boundary theory relevant to a layered PCM garment; (iii) classified candidate PCM chemistries and justified the selection of a 68 °C gel-based organic PCM; (iv) fabricated and tested a 1-cm-thick PCM-integrated glove prototype against a matched control under a repeatable convection-oven protocol, observing a 60–100 s safe-exposure window versus approximately 30 s for the control; (v) cross-checked the observed thermal-buffering behaviour against a finite-element simulation of the layered assembly; and (vi) discussed the applications, economics, safety, and limitations relevant to translating this prototype toward operational use. Collectively, these contributions support the central claim that a thin, latent-heat-based thermal-barrier layer can meaningfully extend glove thermal protection time without the added bulk associated with thicker conventional insulation, though the anticipated dexterity benefit remains a design objective to be confirmed through the standardized testing recommended in Section 16 rather than a directly measured outcome of this study.

Further research can focus on optimising PCM compositions and glove designs to tailor phase-change characteristics to a wider range of operational needs.

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### Appendix A: Derivation of the Enthalpy Method

Beginning from the transient conduction equation for a single-phase material,  $\rho \cdot c_p \cdot (\partial T / \partial t) = \nabla \cdot (k \nabla T)$ , the enthalpy method replaces the temperature-based storage term with an enthalpy-based storage term by defining  $h(T)$  such that  $dh = c_p \cdot dT$  away from the phase-change temperature, and such that  $h$  includes an additional jump of magnitude  $Q_{\text{fusion}}$  as  $T$  crosses  $T_{\text{pc}}$ . Substituting  $\partial h / \partial t = c_p \cdot (\partial T / \partial t)$  (away from the transition) into the conduction equation and generalising to include the transition itself yields the enthalpy-form governing equation used in Section 3.4,  $\rho \cdot (\partial h / \partial t) = \nabla \cdot (k \nabla T)$ . Because  $h(T)$  is a known, prescribed function of  $T$  for a given material (Fig. 1), this reformulation allows a single field equation to be solved across a domain containing both PCM and non-phase-changing textile layers without needing to explicitly track an internal moving boundary, which is the key numerical convenience exploited by the finite-element simulation of Section 10.

### Appendix B: Sample Calculation

As an illustrative application of the algorithm in Section 8.2, consider a PCM sample of mass  $m$  undergoing complete melting under a constant applied electrical heating power  $Q_{\text{el}}$  over a measured plateau duration  $\Delta t_{\text{plateau}}$ . The total heat supplied during the plateau is  $Q_{\text{el}} = Q_{\text{el}} \cdot \Delta t_{\text{plateau}}$ . Because heat losses to the surroundings during the short plateau interval are assumed small relative to  $Q_{\text{el}}$  in this simplified illustration, the full heat input is attributed to the PCM, giving  $Q_{\text{PCM}} \approx Q_{\text{el}}$ , and the specific heat of fusion follows directly as  $Q_{\text{fusion}} = Q_{\text{PCM}} / m$ . Applying the same bookkeeping to the pre- and post-plateau heating segments, together with the corresponding measured  $\Delta T$  over each segment and the reference-loss correction  $Q_r$  introduced in Section 8.1, yields the sensible specific heat  $c_v = (Q_{\text{el}} - Q_r) / (m \cdot \Delta T)$  for the solid and liquid phases respectively. This worked procedure is the same one applied, trial by trial, to reduce the raw oven temperature-time data of Section 9 into the summary comparison presented in Table V.

It is worth emphasising the internal consistency check this procedure affords: because  $Q_{\text{fusion}}$  and  $c_v$  are derived from independent segments of the same heating run (the plateau versus the pre/post-plateau ramps respectively), agreement

between the resulting  $Q_{\text{fusion}}$  value and literature-typical values for the PCM's chemical family (Table II) provides a useful sanity check on the overall calorimetric procedure, including the reference-loss correction  $Q_r$ , independent of any single measurement in isolation.

### Appendix C: Representative PCM Property Ranges

Table VIII lists representative, literature-typical property ranges for gel-based organic PCM formulations of the general type used in this study, compiled from the classification discussion of Section 4 and the underlying review literature [8]–[10]. These are presented as indicative ranges for context rather than as measured properties of the specific commercial PCM gel used in fabrication, consistent with the material-characterisation limitation noted in Section 15.

**Table VIII:** Representative PCM property ranges

| Property                         | Typical Range             | Relevance                                                    |
|----------------------------------|---------------------------|--------------------------------------------------------------|
| Melting point, $T_{\text{pc}}$   | 20–70 $^\circ\text{C}$    | Sets the activation temperature of the buffering effect      |
| Latent heat, $Q_{\text{fusion}}$ | 150–250 J/g               | Governs the total thermal-storage reservoir per unit mass    |
| Thermal conductivity, $k$        | 0.15–0.3 W/(m·K)          | Governs internal conduction resistance ( $Bi$ , Section 3.5) |
| Density, $\rho$ (solid)          | 800–950 kg/m <sup>3</sup> | Relates layer thickness to PCM mass                          |
| Specific heat, $c_p$             | 1.8–2.5 J/(g·K)           | Governs sensible-heat behaviour outside the plateau          |

### Appendix D: One-Dimensional Finite-Difference Illustration

This appendix illustrates, in simplified one-dimensional form, how the enthalpy-method governing equation of Section 3.4 can be discretised and stepped forward in time using an explicit finite-difference scheme, providing the numerical-methods context underlying the finite-element simulation of Section 10. Consider a slab of thickness  $\delta$ , discretised into  $N$  equally spaced nodes with spacing  $\Delta x = \delta / (N - 1)$ , subjected to a fixed outer-face temperature  $T_\infty$  (approximating the well-mixed oven environment) and an insulated or convective inner face.

The explicit update for an interior node  $i$ , expressed in enthalpy form, is:

$$h_i^{n+1} = h_i^n + (k \cdot \Delta t / (\rho \cdot \Delta x^2)) \cdot (T_{i-1}^n - 2T_i^n + T_{i+1}^n) \quad (13)$$

where the superscript  $n$  denotes the time step. Given the updated enthalpy  $h_i^{n+1}$ , the corresponding temperature  $T_i^{n+1}$  is recovered by inverting the prescribed  $h(T)$  relationship for the local material (PCM or textile), which is piecewise-linear in the sensible-heat regions and includes the latent-heat plateau of magnitude  $Q_{\text{fusion}}$  at  $T = T_{\text{pc}}$ , as illustrated in Fig. 1. Physically, a node whose enthalpy falls within the latent-heat band remains pinned at  $T = T_{\text{pc}}$  regardless of further enthalpy input, until its enthalpy exceeds the band and it transitions fully to the liquid-phase branch of  $h(T)$  — this is the discrete, nodal analogue of the continuous moving-boundary interface condition of Section 3.3.

Numerical stability of the explicit scheme requires the time step to satisfy the standard parabolic stability criterion,

$$\Delta t \leq \rho \cdot c_p \cdot \Delta x^2 / (2k) \quad (14)$$

evaluated using the more restrictive (typically lower-conductivity, and hence more restrictive on this bound only through the ratio  $cp/k$ , since a lower  $k$  tightens the bound while a lower  $cp$  loosens it) of the PCM or textile properties at each interface, since the layered assembly contains materials of differing  $k$ ,  $\rho$ , and  $cp$ . In practice, commercial finite-element platforms such as the one used in Section 10 employ implicit or semi-implicit time integration precisely to avoid this restrictive explicit stability bound, allowing larger time steps at the cost of solving a linear system at each step rather than the simple explicit update shown above; the explicit scheme is presented here for its pedagogical transparency in illustrating how the enthalpy method embeds the phase-change plateau directly into an otherwise standard transient-conduction numerical framework.

Applied qualitatively to the present glove geometry, this scheme predicts- consistent with the finite-element result of Fig. 6 and the experimental trace of Fig. 7(b)- that nodes within the PCM layer remain clustered near  $T_{pc}$  for an extended number of time steps once the melting front reaches them, producing the flattened, plateau-like segment of the inner-glove temperature history, before resuming a more rapid sensible-heat-driven temperature rise once the local PCM enthalpy has fully crossed the latent-heat band.

#### Appendix E: Glossary of Terms

- Latent heat- Energy absorbed or released by a material during a phase change at constant temperature, as distinct from sensible heat.
- Phase-change plateau- The interval during which a PCM's temperature remains nearly constant while it absorbs or releases latent heat.
- Supercooling- The tendency of a PCM to remain liquid below its nominal freezing point before crystallisation initiates, delaying heat release.
- Enthalpy method- A numerical technique for modelling phase change that solves a single enthalpy field rather than explicitly tracking a moving solid-liquid interface.
- Biot number ( $Bi$ )- A dimensionless ratio of surface convective resistance to internal conductive resistance within a body.
- Fourier number ( $Fo$ )- A dimensionless measure of the extent to which a transient thermal disturbance has diffused through a layer over a given time.
- Thermal protective performance (TPP)- A standardized rating of a fabric assembly's resistance to combined convective and radiant heat exposure.
- Microencapsulation- Enclosure of a PCM within micron-scale polymeric shells, enabling its incorporation into coatings or fibres.

#### Appendix F: Worked Biot and Fourier Number Estimate

To illustrate the dimensionless-group reasoning introduced in Section 3.5, consider representative values for the PCM layer used in this study: thickness  $\delta \approx 0.01$  m, thermal conductivity  $k \approx 0.2$  W/(m·K) (within the organic-PCM range of Table VIII), and an assumed effective convective coefficient at the glove's outer surface within a convection oven of  $h \approx 15$ – $25$  W/(m<sup>2</sup>·K), typical of moderate forced-convection conditions. Substituting representative values into the Biot number definition of Section 3.5 gives:

$$Bi = h \cdot \delta / k \approx (20 \times 0.01) / 0.2 = 1.0 \quad (15)$$

A Biot number of approximately unity confirms the qualitative statement in Section 3.5 that the PCM layer's internal conduction resistance is comparable in magnitude to its surface convective resistance — neither negligible nor overwhelmingly dominant — which is precisely the regime in which a full spatial (finite-element or finite-difference) treatment, rather than a simple lumped-capacitance approximation, is warranted for accurate prediction of the internal temperature field, justifying the modelling approach adopted in Sections 8 through 10.

For the Fourier number, taking a representative thermal diffusivity  $\alpha = k/(\rho \cdot cp) \approx 0.2 / (900 \times 2000) \approx 1.1 \times 10^{-7}$  m<sup>2</sup>/s (using representative organic-PCM density and specific heat from Table VIII) and an exposure duration of  $t \approx 80$  s (near the midpoint of the observed 60–100 s protection window) gives:

$$Fo = \alpha \cdot t / \delta^2 \approx (1.1 \times 10^{-7} \times 80) / (0.01)^2 \approx 0.09 \quad (16)$$

A Fourier number well below unity indicates that, over the observed protection-time window, the thermal disturbance has not yet fully penetrated and equilibrated across the PCM layer thickness — consistent with the persistence of a distinct, incompletely melted thermal plateau throughout most of the recorded exposure duration in Fig. 7(b), rather than a rapid, layer-wide temperature rise. This worked estimate is offered as an illustrative order-of-magnitude check using representative literature property values rather than properties measured directly from the tested samples, consistent with the material-characterisation limitation noted in Section 15.

#### Appendix G: Checklist for Future Standardized Testing

To support the transition from the exploratory prototype testing described in this paper toward the certification pathway discussed in Sections 3.9 and 11.11, Appendix G lists the principal test and evaluation activities that a future, standards-aligned evaluation of a PCM-integrated glove would need to address, organized by category.

- Thermal performance: radiant heat resistance, convective heat resistance, and flame-contact testing per the relevant national/regional standard (Section 3.9).
- Mechanical performance: puncture resistance, cut resistance, tensile/tear strength, and seam strength of both the outer glove and the PCM encapsulation.
- Durability: multi-cycle melt-freeze thermal cycling of the PCM insert, and repeated flex/abrasion testing of the encapsulation film (Section 13.3).
- Dexterity and ergonomics: standardized grip-strength, pinch-force, and fine-motor-task testing with the glove worn (Sections 7.4 and 16).
- Chemical/toxicological safety: skin-contact irritancy and leachate testing of the PCM chemistry in the event of encapsulation failure (Section 14.1).
- Flammability and combustibility: assessment of the PCM's contribution to fuel load and flame spread if the outer layers are breached (Section 14.2).

- Environmental and end-of-life: recyclability and biodegradability assessment of both the PCM chemistry and the encapsulation film (Section 14.3).

Completing this checklist in full, ideally through an accredited third-party testing laboratory, is presented here as the concrete, actionable bridge between the proof-of-concept results reported in this paper and any responsible claim of operational readiness for PCM-integrated protective gloves.

#### Appendix H: Summary of Key Equations

For ease of reference, Table IX collects the principal governing equations developed across Sections 3 and 8, together with the section in which each is derived or applied.

**Table IX: Summary of key equations**

| Equation                                                           | Description                      | Section |
|--------------------------------------------------------------------|----------------------------------|---------|
| $Q_r = m_s \cdot c_s \cdot \Delta T$                               | Reference/holder sensible heat   | 8.1     |
| $Q_{el} = Q_{el} \cdot \Delta t$                                   | Electrical heat supplied         | 8.1     |
| $Q_{PCM} = Q_{el} - Q_r$                                           | Heat absorbed by PCM (sensible)  | 8.1     |
| $c_v = \frac{Q_{PCM}}{m \cdot \Delta T}$                           | Specific heat, solid-state PCM   | 8.1     |
| $\frac{Q_{fusion}}{Q_{PCM}/m}$                                     | Specific heat of fusion          | 8.2     |
| $Bi = h \cdot \delta / k$                                          | Biot number                      | 3.5     |
| $Fo = \alpha \cdot t / \delta^2$                                   | Fourier number                   | 8.5     |
| $\rho \cdot (\partial h / \partial t) = \nabla \cdot (k \nabla T)$ | Enthalpy-form governing equation | 3.4     |

Table IX is intended as a compact index rather than a substitute for the fuller derivations and physical interpretation given in the body of the paper; readers seeking the reasoning behind any individual relation should consult the referenced section directly.

#### Appendix I: Reproducibility Notes

In the interest of reproducibility, this appendix consolidates the key procedural parameters used throughout the study, drawn together from their respective sections, so that a future research group attempting to replicate or extend this work has a single reference point rather than needing to cross-search the full paper for each setting.

- Oven set-point temperature: 180 °C, allowed to stabilise before each trial (Sections 9.2, 9.3).
- Test-termination criterion: inner-glove-layer temperature of 60 °C (Sections 9.2, 3.7).
- Temperature logging interval: 10–20 s (Section 9.2).
- PCM layer nominal thickness:  $\approx 1$  cm, gel-based organic PCM, melting point  $\approx 68$  °C (Sections 7.1, 7.2).
- Outer/base textile layers: 35% cotton / 65% polyester interlock blend; outer protective layer: PANEX woven carbon fabric (Section 6.1).
- Trial count: three replicate trials per configuration (control and PCM), six trials total (Section 9.4).
- Simulation platform: CAD modelling with SimScale finite-element thermal analysis, simplified layered-coupon geometry (Sections 10.1, 10.2).

Researchers extending this work are encouraged to additionally record and report the specific commercial PCM product identifier, batch-level material property measurements ( $k$ ,  $c_p$ ,  $Q_{fusion}$ ,  $T_{pc}$ ), and ambient humidity at time of testing — none of which were captured in the present

study but all of which were identified in Section 15 as limiting the precision with which these results can be generalised or directly compared against future replications.

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