

Applications of Phase Change Materials (PCMs) in Occupational Clothing Textiles (A review study)

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ABSTRACT

Phase change materials (PCMs) are increasingly proposed for occupational clothing, either to delay heat transfer to the skin during thermal hazard exposure or to relieve heat strain during work in hot environments. This critical review examines PCMs incorporated through three distinct routes: fiber, yarn, or fabric incorporation; coatings and laminated structures; and removable packs or modules and follows each from material properties through garment construction and heat and moisture transfer to wearer outcomes and maintenance. The evidence comes mainly from firefighting and includes numerical models, bench tests, full-scale room fires, and a small number of human trials. In fire-protective layers, PCM generally slowed heat transfer during exposure, yet part of the reported gain reflected added mass or thermal resistance rather than latent heat. Models of wetted fire-protective clothing from one research group predicted that heat released on re-solidification can cause burns that a PCM-free garment would not, particularly after brief, intense exposures or with melting points above 50 °C, and glove-sample tests showed prolonged post-exposure temperature rises. Removable PCM vests produced marked local cooling, but beneath heavy firefighting clothing did not lower core temperature, heart rate, or thermal sensation during exercise in the heat. Fiber-route evidence for occupational textiles stops at fabric characterization; laundering has not been linked to burn-protection or comfort outcomes, and no PCM-specific studies were found for arc flash, molten-metal, or welding clothing. Joint testing of exposure and cooling phases against thickness- and mass-matched controls should precede wider use.

Keywords: Phase Change Materials, Occupational Protective Clothing, PCM, Thermal performance, Thermal Comfort, Microencapsulation.



1. Introduction

Heat exposure at work is a health problem of global scale: International Labour Organization estimates reported by the World Health Organization (WHO) and the World Meteorological Organization (WMO) indicate that more than 2.4 billion workers are exposed to workplace heat stress, and that 22.85 million occupational injuries and 18,970 deaths each year are directly linked to excessive heat at work[1]. The same guidance lists the requirement to wear impermeable or insulating protective clothing among the three determinants of workplace heat stress, because multilayer, laminated, or impermeable garments restrict the sweat evaporation on which heat balance during work depends[1]. Protective clothing therefore embodies a protection–comfort trade-off. At fabric level, thermal protective and thermo-physiological comfort performance are generally inversely related, and product standards weight protective performance more heavily in certification[2]; at garment level, studies reviewed by Song et al. found thermal protective clothing less comfortable than regular clothing, and impermeable protective clothing less comfortable than permeable clothing, because it impedes the escape of sweat vapor and metabolic heat [3]. Similar trade-offs have been described for firefighters and oilfield workers [2] and for live-line electrical workers, whose enclosed conductive shielding suits severely limit heat and moisture exchange[4].

PCMs have been studied as a means of improving the heat protection of firefighter clothing for about two decades [5]. Because they absorb heat as they melt and release it as they re-solidify, PCMs can in principle buffer short thermal transients. Early work found that a paraffin PCM layer had a positive but small effect on the heat protection of firefighter clothing combinations, with an efficiency that depended on the location of the layer and the incident heat intensity and proposed that PCMs could thereby contribute to lighter equipment [5]. Modelling suggested that the gear could be made thinner for similar thermal performance [6]. PCMs have since been examined in firefighter turnout fabrics and ensembles [5, 7], firefighting gloves [8], outer-layer heat-shielding vests [9], and cooling vests worn beneath firefighting clothing [10], with materials ranging from paraffin microcapsules to salt hydrates and incorporation methods ranging from fiber spinning to coatings and removable pouches [11, 12].

Two features of the literature motivate this review. First, PCM textiles are often discussed collectively as “PCM clothing”, although the incorporation routes differ in the PCM dose they can carry, their durability, their effect on permeability, and their regeneration needs [10, 13]; this review argues that the routes should not be pooled. Second, the value of a PCM layer depends on the phase of exposure at which it is judged. Numerical studies of wetted fire-protective clothing from one research group have predicted that heat stored in a PCM layer can be released toward the skin after the heat source is removed, producing burns that a PCM-free garment would not have caused under some exposure conditions [14], and that PCMs melting above 50 °C can cause re-solidification burns when the garment is wetted after a flash fire unless the thermal liner is modified [15]; glove-sample tests by another group recorded longer

post-exposure temperature rises with PCM than without it [8]. A review that judges fire-protective PCM layers only during exposure therefore risks endorsing configurations whose net effect in realistic use is unfavorable.

This review addresses the question: under what material, textile-design, and occupational-use conditions do PCMs provide meaningful and durable thermal benefits without compromising clothing comfort, protection, or practicality? Two functions are distinguished throughout because different outcomes judge them: PCM layers intended to delay heat transfer to the skin during thermal hazard exposure, evaluated by burn-injury criteria, and PCM garments intended to relieve heat strain during work in hot environments, evaluated by physiological and perceptual outcomes. Three incorporation routes are also distinguished: PCMs incorporated into fibers, yarns, or fabrics; PCM-containing coatings, finishes, and laminated structures; and removable PCM packs or modules incorporated into garments. Evidence from non-occupational PCM textiles (e.g., sportswear, bedding) is used only to illustrate incorporation mechanisms, and its transferability to occupational protective contexts is flagged as limited because flammability, certification, and exposure-severity requirements differ.

Earlier experimental and modelling work established the basic premise. McCarthy and di Marzo combined bench-scale tests of PCM-embedded firefighter clothing specimens with a finite-difference heat transfer model and attributed the temperature reduction behind the face cloth largely to the added material, with a smaller contribution from latent heat[6]. Reviews have since addressed PCM-integrated textiles in general, mainly for consumer, medical, building, and automotive uses [11, 16], spinning routes for phase change fibers [12], smart coatings for firefighter clothing in which PCMs are one of several material families [2], personal cooling garments with an emphasis on PCM garments [13], and the thermal protective performance of firefighter clothing, including PCMs, moisture barriers, and air gaps [17]. The last of these concludes that PCM-integrated systems appear among the most feasible candidates for near-term implementation [17]. Still, it is confined to firefighting, does not report its search procedure, does not distinguish incorporation routes or consider removable PCM cooling vests, and does not examine re-solidification heat release as a burn hazard. The present review integrates the three incorporation routes across the occupational settings in which PCM clothing has been studied, treats exposure-phase and post-exposure outcomes as jointly decisive for fire-protective layers, separates burn-protection from heat-strain outcomes, and examines durability and sustainability alongside thermal performance. No claim is made that it is the first review of PCM textiles in any respect; its contribution lies in this specific integration.

2. Thermal Comfort in Occupational Clothing

Heat balance in a clothed worker depends on metabolic heat production and on heat exchange with the environment by conduction, convection, radiation, and

evaporation, all of which the clothing system modifies. Evaporative heat loss is particularly sensitive to clothing design: layers added for thermal protection typically increase evaporative resistance, and multilayer, laminated, or impermeable garments restrict evaporative cooling [1-3]. although some knitted heat-protective base-layer fabrics combine high air permeability with effective moisture management[18]. The clothing microclimate, the temperature and humidity of the layer between the skin and the innermost fabric, is therefore shaped jointly by workload (metabolic rate), ambient environment, garment fit, the number of clothing layers, and exposure duration. Occupational guidance sets a core temperature of 38 °C as the limit for sustaining an eight-hour shift and recognizes that work requiring protective clothing is likely to induce greater physiological heat strain[1].

Moisture accumulation within occupational protective clothing is substantial and slow to clear: beneath a firefighting ensemble in 55 °C air, evaporated sweat amounted to only about 10% of total sweat production [10]. Moisture also alters heat transfer in ways that depend on its source and on the exposure. In bench tests of four two-layer wildland firefighter fabric systems, external moisture (outer layer saturated) tended to decrease, and internal moisture (underwear layer saturated to simulate perspiration) to increase, heat transfer under an 83 kW/m² flame exposure, whereas under a 10 kW/m² radiant exposure internal moisture decreased heat transfer and the effect of external moisture was inconclusive; all effects were fabric-dependent [19]. Under 6.3 kW/m² radiant exposure of turnout systems, absorbed moisture reduced protective performance most at comparatively low add-on levels (15-20% of system weight) [20]. Moisture therefore complicates the prediction of heat transfer through protective clothing independently of any PCM.

Subjective thermal comfort and physiological heat strain are related but distinct constructs. Heat strain is indexed by core and skin temperature and heart rate, whereas comfort is a perceptual judgement that can diverge from strain, particularly with respect to skin wetness; wet skin is associated with greater thermal discomfort for a given skin temperature[1]. Local sensations from the back and chest dominate overall thermal sensation, whereas those from the hand and foot carry less weight [21]. Local comfort also depends on the thermal state of the body: in transient conditions, studies summarized by Zhang et al. found cold stimuli to the hand, forehead, and neck very pleasant during hyperthermia, with local comfort higher than under uniform conditions, and in their own tests foot cooling was perceived as very comfortable when the whole body was warm [21]. Uniformity of skin temperature is therefore not in itself a design target. The gap between local and whole-body responses is also evident in PCM garments: beneath firefighting clothing, vests that lowered torso temperature by 3- 4 °C left thermal sensation and core temperature statistically unchanged during exercise [10]. This body-region dependence bears directly on where PCM mass is placed within a garment, a point taken up in Sections 6 and 7.

3. Fundamentals and Classification of PCMs

PCMs store and release thermal energy primarily as latent heat during a solid–liquid phase transition, allowing a much larger energy exchange per unit mass, over a narrow temperature range, than sensible (temperature-change) heat storage alone. Performance-relevant properties for textile use include the phase-transition temperature range, latent heat (enthalpy) of fusion, degree of supercooling (the extent to which a PCM must cool below its nominal freezing point before crystallizing), thermal hysteresis between melting and freezing, thermal conductivity, and stability over repeated melt–freeze cycles [16, 22].

PCMs used in textiles are broadly organic (paraffins and non-paraffin organics such as fatty acids, esters, and polyethylene glycols), inorganic (principally salt hydrates such as sodium sulphate decahydrate, or Glauber's salt), or eutectic mixtures [11, 16]. Organic PCMs show negligible supercooling and are chemically stable and non-corrosive, but their thermal conductivity is low (about 0.2 W/(m·K)) and their flammability is detrimental in firefighting clothing [16]; an early study of paraffin-based PCM layers for firefighter clothing concluded that their burning behavior had to be improved before commercial use [5]. Salt hydrates offer high latent heat per unit volume, higher thermal conductivity (about 0.5 W/(m·K)), and non-combustibility, but are prone to supercooling, corrosion, and phase separation, which require thickening and nucleating agents [16]. Together with deliquescence, these drawbacks explain why salt hydrates are rarely used within textile structures [12]; in the occupational studies reviewed here, they appear only as macro-encapsulated packs, such as Glauber's salt-based packs with latent heats of 108.0 and 126.0 J/g [10]. Eutectic PCMs are blends formulated to produce a particular melting point [22], but thermophysical property data for them remain insufficient [16]. Bio-based PCMs (for example, fatty acids or esters derived from plant sources) represent a sourcing distinction rather than a separate thermodynamic class: a bio-based fatty acid is still an organic PCM, and its renewable origin should not be conflated with superior thermal or textile performance.

Selecting a melting point for occupational protective clothing is not simply a matter of matching skin temperature; the reported optimum depends on where the PCM sits in the clothing system, on exposure intensity, and on the burn criterion used. For comfort-oriented garments, the PCM is chosen to change phase near skin temperature, and in a human trial beneath firefighting clothing a vest melting at 24 °C cooled the torso more strongly than one melting at 28 °C [10]. For fire-protective layers placed within the ensemble to intercept heat before it reaches the skin, higher melting points have been favored. In glove-material samples, a 1 mm layer of a 68 °C bio-based PCM gave the longest time to a 60 °C hand-surface temperature in direct-contact tests, whereas the 68 and 108 °C PCMs performed similarly in furnace tests and a 151 °C PCM did not melt [8]. A three-dimensional bioheat model of turnout gear predicted optimum melting points of 40 -90 °C at 83 kW/m² and 50 -80 °C at 8.3 kW/m², with protection declining at higher melting points because the PCM melted

less efficiently [23]. A one-dimensional model of a dry ensemble found that time to second-degree burn decreased as melting temperature increased and recommended a melting point high enough that melting does not begin before the exposure but low enough to allow full melting [24]. By contrast, a bench study of PCM-coated fabrics deliberately used nominal 25 and 42 °C PCMs, reasoning that skin may burn before a PCM with a phase change temperature above 44 °C melts; it reported no statistically significant effect of phase change temperature on second-degree burn time in most configurations, although 25 °C coatings gave longer burn times in some positions, and the authors concluded that protective performance depended on phase change temperature, FR type, and position [25]. Two further constraints apply. First, high melting points can increase post-exposure hazard: in a model of fire-protective clothing wetted by a post-fire water splash after an approximately 3 s, 80 kW/m² flash exposure, PCMs melting above 50 °C were predicted to cause second-degree burns during re-solidification with the baseline thermal liner [15]. Second, burn criteria differ across studies: the Henriques damage integral, in which injury accumulates only above a basal-layer temperature of 44 °C [14, 15, 24], a fixed 60 °C skin-surface temperature [8, 23], and copper-calorimeter second-degree burn time [25], so optimum melting points from different studies cannot be compared directly. Figure 1 and Table 1 summarize PCM classes against these occupational textile selection considerations.

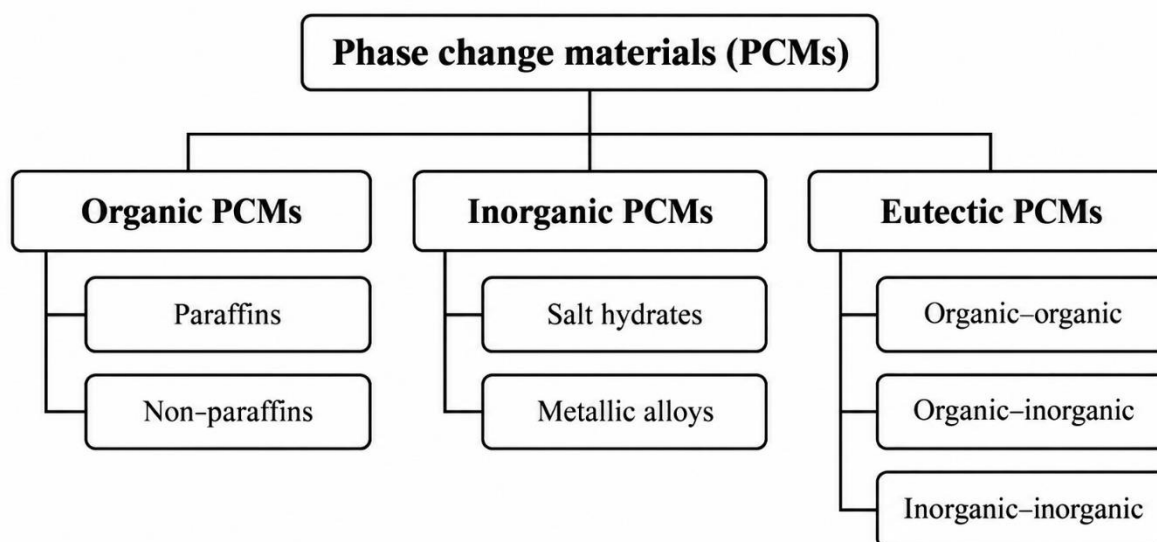


Figure 1: Classification of phase change materials (PCMs) into organic, inorganic, and eutectic categories [16].

Table 1: PCM classes, values reported in previous studies, and suitability considerations for occupational textile use.

N O	PCM class	Latent heat	Melting points used or modelled	Key advantages	Key limitations
1	Organic - paraffins	105 kJ/kg (Rubitherm PX52) [6]; 105 kJ/kg (PX82, microencapsulated , ~60% PCM) [9]; 135 and 120 J/g (nominal 25 and 42 °C products; basis not stated) [25]	Nominal 25 and 42 °C (comfort- layer coating) [25]; 44-55 °C [6, 26]; 50 °C [5]; 71-86 and 77-85 °C [6, 9].	Negligible supercooling ; chemically stable; non- corrosive [16].	Low thermal conductivity (~0.2 W/(m·K)); flammable, detrimental in firefighting clothing [5, 16]; petroleum- derived [16]. Flammable, as other organic PCMs [16]; the 151 °C PCM did not melt under the test exposures [8]; occupational durability data not reported
2	Organic fatty acids/ester s incl. bio- based)	Not reported for the PCMs tested in [8]; 213.0 kJ/kg assumed in models[7, 23].	68, 108, and 151 °C tested [8]; 40-200 °C modelled, optimum 50-80 °C [23].	Renewable sourcing possible; described as non-toxic and thermally and chemically stable [23]	Supercooling; corrosion; phase separation requiring thickening and nucleating agents [16]; deliquescence; rarely used within textile structures[12]
3	Inorganic salt hydrates (e.g., Glauber's salt)	108.0 and 126.0 J/g (Glauber's-salt- based packs) [10]	24 and 28 °C [10]	High latent heat per unit volume; conductivity ~0.5 W/(m·K); non- combustible [16]	

4	Eutectic mixtures	Depends on components not reported in the occupational studies reviewed	Set by composition [22]	High heat storage per unit volume [16]	Complex formulation; higher cost; limited occupational-specific data. Insufficient thermophysical property data [16]; no occupational data identified
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4. Methods of Incorporating PCMs into Textiles

PCM incorporation methods are not interchangeable [11, 12], and this review treats them as three distinct routes: (a) PCM incorporated into fibers, yarns, or fabrics at the material level; (b) PCM-containing coatings, finishes, or laminated structures applied to a finished textile; and (c) removable PCM packs or modules inserted into or attached to a garment. Some configurations fall between these routes, notably macro-encapsulated PCM layers sealed into a bag and inserted between garment layers [8] and discrete PCM segments replacing part of a thermal liner [7, 23]; these are identified as such rather than forced into one route.

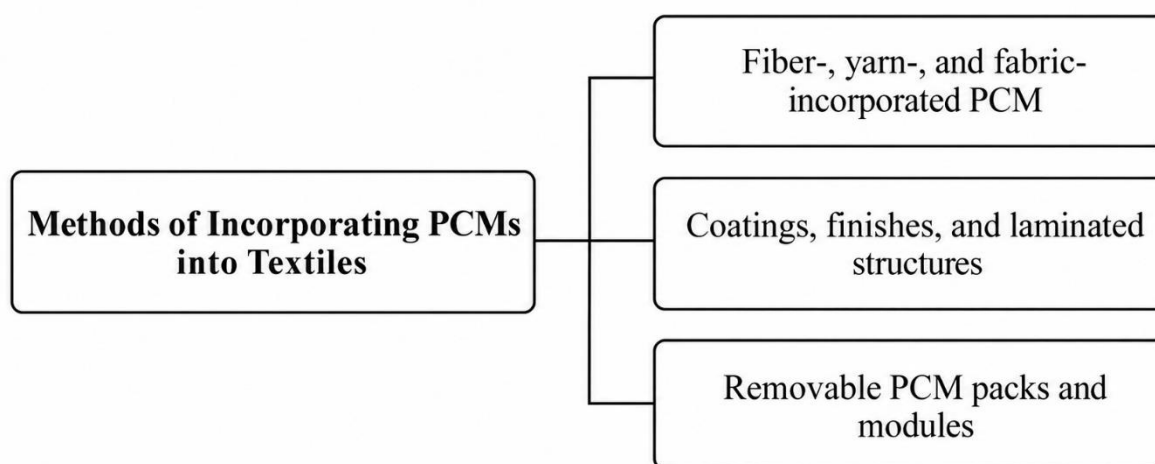


Figure 2: Main Approaches for Incorporating Phase Change Materials (PCMs) into Textile Structures



4.1. Fiber-, yarn-, and fabric-incorporated PCM

This route embeds PCM, usually as microcapsules or form-stabilized composites, within the fiber by wet, melt, electro-, or centrifugal spinning, or places PCM-containing yarns within the fabric structure [11, 12]. Microcapsules used in textiles are typically 1-30 μm in diameter [16]. At fiber level, the spinning method imposes a trade-off between PCM content and mechanical integrity: wet-spun phase change fibers commonly carry more than 70 wt % PCM, with latent heat up to about 190 kJ/kg, but breaking strengths no higher than 2.12 cN/dtex, whereas melt-spun fibers are stronger but their latent heat is usually limited to about 30 kJ/kg because PCM loading remains below 45 wt % [12]. Primary data illustrate the same constraint: polyethylene glycol (PEG) form-stabilized at 70 wt % on silica (composite enthalpy about 101 J/g) and melt-spun into polyamide 6 at 20 wt % composite gave fibers with melting and crystallization enthalpies of only 17.14 and 13.15 J/g; aggregates formed at this loading that can impair spinnability, and breaking strength fell from 2.58 cN/dtex (neat polyamide 6) to 1.22 cN/dtex at a draw ratio of 2, rising to 1.97 cN/dtex at a draw ratio of 2.8 [27]. Enthalpy was unchanged over 100 heating-cooling cycles, but laundering, abrasion, flammability, and fabric-level comfort were not tested [27]. Coatings are described as vulnerable to abrasion and washing because capsules that are not firmly bonded may detach [12, 27], and the fiber route is often presumed to be more durable; the supporting evidence is construction-specific, however, with leakage reported for PCM-filled hollow fibers and poor durability for water-soluble PEG-based fibers [12], and no laundering data were identified for an occupational fiber-route textile. Wash durability should therefore be demonstrated for each construction rather than assumed for the route.

The only fiber-route study identified with an occupational end use stopped at fabric level. Commercial paraffin-based PCM yarns woven as the skin-side weft of a polyester double cloth for merchant maritime uniforms gave a fabric latent heat of only 0.354 -0.420 J/g (80 -96 J/m²); air and water permeability did not differ significantly from a conventional-yarn control, thermal conductivity was significantly lower, and tensile strength and ultraviolet protection were reduced [28]. No laundering, thermal-cycling, transient thermal, manikin, or wearer testing was reported, and the phase-change temperature range was not stated [28]. No manikin, wearer, or burn-time evidence for fiber-incorporated PCM in an occupational garment was found among the sources reviewed; this is treated as an evidence gap rather than inferred to be favorable or unfavorable.

4.2. Coatings, finishes, and laminated structures

Coating applies a paste or slurry containing PCM to one side of a finished fabric by knife (dry) coating, padding, or lamination. In a study of PCM-coated fabrics for firefighting clothing, a slurry containing 45% PCM suspension together with adhesive, thickener, and defoamer was knife-coated in three passes onto flame-resistant substrates; the resulting PCM add-on was not reported, and the authors acknowledged that the coated fabrics were thick and stiff, with poor breathability and

elasticity, and that durability and possible PCM leakage in long-term use had not been examined [25]. The same study showed that flame-retardant (FR) co-formulation, not the PCM alone, shapes the fire behavior of coated systems: in cone-calorimeter tests at 15 kW/m², a phosphorus nitrogen FR lengthened time to ignition by up to 16 s relative to an FR-free coated control, whereas an organic-silicone FR reduced total heat release by up to 3.44 MJ/m²; neither FR type nor FR content significantly changed second-degree burn time in the thermal protective performance (TPP) test at 84 kW/m² [25]. Quantified wash data exist for a covalently grafted PEG finish, but only on non-flame-resistant cotton: melting and crystallization enthalpies of 37 and 36 J/g per gram of treated fabric fell to 28 and 26 J/g after 20 washes [29], a reduction of about one quarter in melting enthalpy (calculated here). Flammability, permeability, and wearer response were not assessed in that study, so it demonstrates a durability test pathway rather than suitability for occupational garments.

4.3. Removable PCM packs and modules

This route places PCM, typically macro-encapsulated salt-hydrate elements or pouches of microencapsulated PCM in pockets or a removable matrix, so that it can be removed, replaced, or re-solidified independently of the garment. Because the PCM is not bonded to the textile, dose is reported as element or pack mass rather than as a weight percentage: vests worn beneath firefighting clothing held 1,734 and 1,743 g of salt-hydrate PCM in 21 packs [10], and a firefighter heat-shielding vest worn over turnout gear used pouches containing 6 g of microencapsulated PCM per 7 × 7 cm in Laboratory assemblies, with the total PCM mass per vest not reported [9]. Across the personal cooling literature, PCM vests weigh up to about 3 kg in most cases [13]. The latent heat per charge is finite: the authors of the firefighting-vest trial estimated that complete melting would absorb only about 13.5-20.3% of the metabolic heat produced over the first 45.5 min of the protocol (20 min of cycling at room temperature followed by walking in the heat), assuming no heat gain from the environment [10]. Regeneration is therefore a practical requirement specific to this route; in that trial, vests were kept at 20 °C overnight to re-solidify before reuse [10]. For high-melting fire-protective pouches, regeneration means cooling rather than refreezing, and the authors of the heat-shielding vest study recommended that the vest be cooled after use, preferably in a ventilated place [9].

Adding PCM coverage does not translate directly into better wearer comfort. PCM packs hinder the transport of sweat and can make the garment surface less smooth and comfortable [12], and a review of cooling garments lists restricted moisture transfer, with the resulting wetness sensations and skin irritation, among the challenges of PCM vests [13]. Beneath a firefighting ensemble, only about 10% of sweat production evaporated [10]; in this review's interpretation, the moisture penalty of additional pack coverage is therefore likely to be greatest where evaporation is already restricted, although this has not been tested directly. Figure 3 compares the three incorporation routes on the dimensions most relevant to occupational garment design.

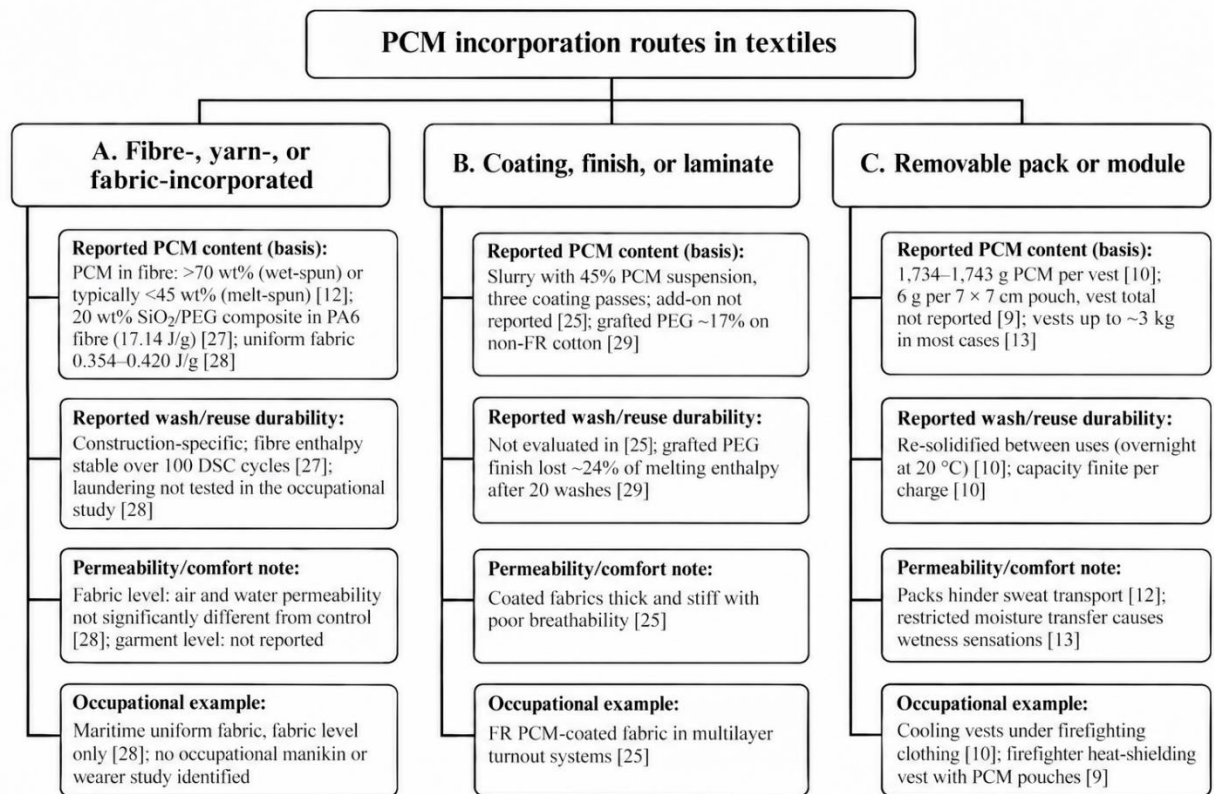


Figure 3. Incorporation routes and their occupational textile performance trade-offs. Values are on different bases and are not directly comparable.

5. Applications in Occupational Clothing

5.1 Firefighting turnout gear, gloves, and vests

Firefighting is the most extensively studied occupational application of PCM clothing in this review's evidence base, spanning numerical modelling, bench scale fabric testing, and prototype garment evaluation, and the interaction between PCM and moisture already present in fire protective clothing has been a specific focus of this literature [23, 30, 31]. A one dimensional heat and mass transport model of wet fire protective clothing, built on Gibson's hygroscopic porous medium formulation and the Henriques burn injury criterion, found that PCM incorporated into the thermal inner layer prevented the skin temperature spikes caused by water vapor condensation during exposure, because condensation occurred preferentially at the PCM rather than at the skin [3, 10, 11, 32]. However, the same study found that for a short, high intensity exposure (80 kW/m² for 8 s), the PCM containing configuration produced a second degree burn that did not occur without PCM, because the PCM's stored sensible and latent heat was released toward the skin as it re solidified in the post



exposure phase [32]. For longer exposures at the same intensity (9-12 s), PCM inclusion instead delayed second degree burn time relative to a PCM free baseline, but re solidification latent heat release remained the dominant cause of the eventual burn in these delayed cases [32]. This post exposure finding echoes an earlier report from the same research group, which explicitly framed delayed PCM heat release as “the other side of the story” for PCM firefighting garments [15], and is consistent with the broader observation that water in firefighter protective clothing is itself a major cause of steam burn injury independent of any PCM present [7]. PCM incorporation in structural firefighting ensembles has been investigated in full scale room fire exposures as well as at bench and numerical scale, with early full scale work already flagging the need to characterize post exposure behavior rather than exposure phase performance alone [9].

Bench scale testing of a PCM coated comfort layer within a full turnout fabric system (outer shell, waterproof/breathable membrane, insulation layer, PCM coated comfort layer) under a standardized low level radiant heat exposure found that PCM incorporation extended second degree burn time by up to 15.3 s on average and lowered peak simulated skin surface temperature by up to 4.51 °C, with a 6.4 mm clothing air layer extending burn time a further 52–63.7% relative to no air layer[33]. During the post exposure cooling phase, however, cumulative heat released toward the simulated skin was greater for the PCM systems than for the PCM free baseline, and increased further with higher PCM loading; the fraction of stored heat actually released during cooling (heat storage release efficiency) fell from 62.4–79.7% without an air layer to 42.5–54.9% with the 6.4 mm air layer, indicating that the air layer mitigates, but does not eliminate, the post exposure hazard [33].

PCM integrated firefighting gloves, evaluated under high heat direct contact and radiant/convective exposures, showed protection time extensions of roughly two to five fold for direct contact and about 1.5 fold for radiant/convective exposure using a 1 mm PCM layer with a melting point around 68 °C, but also exhibited a longer post exposure temperature rise attributable to stored latent heat, consistent with the turnout fabric and wet clothing findings above [13]. A firefighter PPE vest incorporating removable PCM pouches, evaluated through bench scale multilayer testing, heat/flame requirement testing, and a simulated urban fire exposure, showed that a higher latent heat PCM roughly doubled a heat transfer index metric in some conditions while also increasing the time required for the garment to cool afterward [12]. A PCM coated fabric formulated with a phosphorus-nitrogen flame retardant showed higher fire resistance than an otherwise comparable silicone based formulation, which instead reduced peak heat release rate, indicating that flame retardant chemistry choice materially affects fire safety outcomes independent of the PCM itself [16].

5.2 Surgical and general occupational cooling vests

In real operating theatre trials and matched laboratory tests with a single surgeon subject, cooling vests using Glauber's salt elements improved subjective thermal

comfort, thermal sensation, and perceived skin wetness relative to regular clothing, with the largest improvement seen in an iteratively redesigned vest that reduced total mass slightly (1.8 kg versus a 2.0 kg commercial vest) while spacing cooling elements to preserve sweat evaporation [5, 34]. In a separate six subject climatic chamber trial of a well insulated protective suit matched for total insulation (3.30 clo) with and without 450 g of microencapsulated PCM, the PCM suit produced significantly lower back skin temperature between 20 and 40 minutes and significantly better thermal sensation ratings between 60 and 80 minutes of a 120 minute seated exposure, but the benefit was not sustained for the full exposure duration as the PCM's latent heat capacity was exhausted [5].

Beyond firefighting and the surgical/insulated suit studies with full wearer level data available to this review, PCM based personal cooling garments, predominantly removable pack vests, have been reported for other occupationally hot environments. For live line electrical maintenance specifically, a phase change cooling garment evaluated in a climatic chamber (38 °C, 75% RH) with 15 participants achieved a maximum observed cooling duration of 116 minutes, significantly reduced mean skin temperature by 2.6 ± 0.8 °C and core temperature by 0.7 ± 0.2 °C, and decreased sweat volume from 0.83 ± 0.13 kg to 0.55 ± 0.10 kg, moving a composite heat stress index from the severe to the mild category, with improved subjective comfort and no cold discomfort reported[4]. Broader narrative and critical reviews of personal cooling garments more generally covering mining, construction, explosive ordnance disposal, and other occupational settings corroborate this pattern of reduced physiological strain and improved comfort with PCM pack garments, while also cataloguing the same finite capacity, weight, and humidity buildup limitations documented for firefighting and surgical applications in Sections 5–7[13]. These broader reviews were used here for corroboration and context rather than as a source of new precise figures; readers requiring exact sector-specific outcomes beyond the live line electrical example above should consult the primary studies cited within them directly.

5.3 Sectors with no identified PCM-specific evidence

No peer-reviewed, PCM-specific study of occupational clothing for electrical arc flash protection, foundry or molten metal contact, or welding was identified in this review's search. Protective clothing for these hazards is governed by established test standards, for example, ASTM F1959/F1506 for arc rating and ASTM F955 for molten substance heat transfer, but none of the retrieved literature reported PCM incorporation evaluated against these standards. This is reported as an explicit gap (see Section 11) rather than inferred either way.

Table 2. Study evidence summary for the principal quantitative sources reviewed.

Source	Application/con- figuration	Test method	Key outcomes	Noted limitations
[3]Wet FPC, numerical model	PCM in thermal inner; melting temp. 50–90 °C; 0 or 170 J/g; heat flux 80/20/5 kW/m ²	1D heat/mass transport model; Henriques burn criterion	Prevents condensation-driven skin spikes; but 8 s/80 kW/m ² case produces a burn absent without PCM	Numerical only; not validated against a matched human/manikin trial in this paper
[33] Multilayer turnout fabric, bench test	PCM 25/PCM 42 coated comfort layer, 34–55 wt%; ± 6.4 mm air layer	Stored energy test, 8.5 kW/m ² , 360 s exposure + 240 s cooling	Burn time +≤ 15.3 s avg.; peak skin temp. –4.51 °C; but cooling phase heat release greater with PCM	Simulated skin sensor, not human trial; single radiant flux level tested
[5] Surgical cooling vest	Glauber's salt elements, 1.8– 2.0 kg, 4 configurations	Real operating theatre + lab trials, n = 1	Comfort/sensation/w etness ratings improved with optimized spaced element vest	Single-subject design; no statistical testing possible
[5] Insulated protective suit	Outlast® microcapsules, 450 g, matched 3.30 clo	Climatic chamber, n = 6, 120 min seated, 27 °C/50% RH	Lower back skin temp. 20–40 min (p<.04); better sensation 60–80 min (p<.05); effect not sustained to 120 min	n = 6; single condition; low activity (seated) protocol
[13] Firefightin g gloves	1 mm PCM layer, ~68 °C melting point	Bench high heat direct contact and radiant/convectiv e tests	Protection time ×2– ×5 (contact), ~×1.5 (radiant/convective); longer post exposure rise	Bench scale; optimum drawn partly from related modelling work
[12] Firefighter PPE PCM vest	Removable PCM pouches	Lab multilayer + heat/flame requirement + simulated urban fire tests	Higher latent heat PCM ~doubled a heat transfer index metric in some conditions; longer cooling time	Secondary characterization; original tables not independently re-verified here

6. Effects on Thermal Comfort and Wearer Performance

According to the reviewed studies, PCM incorporation consistently improved outcomes measured during the heat exposure phase: lower peak or delayed onset skin temperature, longer time to second-degree burn, and (where measured) better subjective thermal sensation and comfort ratings [5, 32]. This pattern held across very different evidence types: a numerical model of wet fire protective clothing [32], bench scale stored energy testing of coated turnout fabric [33], and human wearer climatic chamber and operating theatre trials of cooling vests [5], which strengthens confidence that the exposure phase benefit is real rather than an artefact of any single methodology. The reviewed studies agree more closely on exposure-phase outcomes for fire-protective layers than on wearer outcomes for cooling garments. In fire-protective configurations, PCM delayed heat transfer to the skin or skin simulant during exposure in numerical models [9, 14, 23], in bench tests of coated fabrics and glove samples [25, 13], and in laboratory assemblies of clothing layers [5, 14], although in several studies part of the effect reflected added mass or thermal resistance rather than latent heat [6, 14], and at flashover a PCM-modified sample gave no significant benefit [26]. For heat-strain relief, a review of cooling garments summarizes PCM garments as improving physiological and perceptual responses, although heart rate or core temperature did not change in several of the studies it tabulates [13], and beneath a firefighting ensemble in extreme heat, marked local torso cooling produced no significant change in core temperature, heart rate, or thermal sensation during exercise [10]. Evidence for the exposure-phase benefit of fire-protective layers is therefore reasonably convergent across evidence types, whereas the translation of local cooling into whole-body benefit depends strongly on the clothing ensemble and the heat load.

For fire-protective layers, the same body of evidence, however, documents a consistent second-stage effect that qualifies this benefit. Once the external heat source is removed, PCM that has melted during exposure re-solidifies, releasing stored sensible and latent heat. In the wet -clothing model, this reversed the apparent benefit entirely for a brief, high -intensity exposure, producing a burn that would not otherwise have occurred [32]. In the coated turnout fabric bench test, cumulative [20], and a later model of garments wetted by a post-fire water splash predicted re-solidification burns for melting points above 50 °C with the baseline thermal liner, which a 4% increase in liner fiber fraction prevented [15]; both come from the same research group and are numerical. Glove samples showed longer post-exposure heat release to the simulated skin; temperature rises with PCM were consistently higher than without it, and rose further with increasing PCM content, even though exposure phase outcomes improved over the same range [8]; laboratory assemblies with PCM pouches cooled more slowly [9]; in an earlier bench study, PCM specimens often still felt warm after cooling [6], and a full-scale study suggested that the added PCM mass may have retained thermal energy [26]. The effect is not a general property of PCM content; with low-melting cooling vests worn beneath firefighting clothing, core

temperature peaked lower after exposure than without a vest [10]. Figure 1 summarizes this two-stage behavior of fire-protective PCM layers schematically.

Wearer-level comfort outcomes depend on more than PCM quantity. Restricted moisture transfer beneath PCM packs is a recognized source of discomfort in cooling vests [12, 13], consistent with the association between skin wetness and thermal discomfort [1]; designs optimized for skin-temperature reduction alone may therefore fail to deliver the intended comfort benefit if they compromise moisture-vapor transport. Air permeability may matter more than static resistances suggest in 12 heat-acclimated men exercising at 35 °C in encapsulating protective suits without PCM, during 3 h of 45/15 min work–rest cycles; physiological strain correlated with fabric air permeability but only poorly with static thermal and evaporative resistance or weight [35].

Divergent findings across studies can be traced to differences in PCM melting point relative to the exposure profile, PCM mass and position, garment fit, workload, the severity of evaporative restriction, and whether the outcome measure captured the cooling phase as well as the exposure phase. Position illustrates the problem: a one-dimensional model found that a PCM layer performed best closest to the external heat source [24], a whole-body model found an inner position slightly but not significantly better [23], and glove tests found that the preferred position depended on melting point [8]. Air gaps are a further, largely untested variable: the one-dimensional model assumed perfect contact between garment layers and with the skin as a worst case, noted that its skin-temperature predictions are therefore slight overestimations where air gaps exist, and called for study of the effect of air gaps on heat transfer across firefighting garments [24]. For cooling vests, the lower-melting vest cooled the torso more strongly despite a lower reported total latent heat, consistent with the skin-to-PCM temperature gradient governing cooling rate, and only about 10% of sweat evaporated through the ensemble [10]. Burn endpoints also differ (Section 4), and much of the evidence on post-exposure harm comes from a single modelling group [14, 15]. Studies that measured only exposure-phase outcomes would systematically under-report the post-exposure release documented in [8, 14].

7. Testing and Performance Evaluation

Evaluation of PCM occupational textiles spans three levels. At the material level, differential scanning calorimetry (DSC) characterizes the phase-change temperature range, enthalpy, and cycling stability. Nominal and actual transition ranges can differ widely: DSC of two paraffin PCMs with nominal phase change temperatures of 25 and 42 °C gave actual ranges of 9.4–34.1 °C and 34.0–55.5 °C, with stated enthalpies of 135 and 120 J/g, and part of the lower-melting PCM had already changed phase before testing began [25]. DSC enthalpies depend on scan rate and are overestimated at high heating or cooling rates [12], so report the scan rate with any enthalpy used to estimate buffering capacity. Material-level values are also reported on different mass bases per gram of pure PCM, PCM product, composite, fiber, or treated fabric. They

cannot be converted to a garment-level benefit without the PCM mass fraction and the area or mass of the finished textile. For example, a SiO₂/PEG composite of about 101 J/g yielded fibers of about 17 J/g [27]. A grafted cotton fabric gave 37 J/g per gram of treated fabric [29], and a PCM-yarn uniform fabric gave 0.35 - 0.42 J/g [28].

At the textile level, steady-state methods such as the sweating guarded hot plate quantify thermal and evaporative resistance but are inadequate for transient thermal behavior [2] so they cannot by themselves characterize a PCM textile. Bench methods for thermal protection, such as TPP and radiant protective performance tests, rate protection over the exposure period; at radiant fluxes of 6.3–8.3 kW/m², protection times estimated at 1–5 min by these methods have been reported to fall to 0.5–3 min when stored thermal energy is considered, as summarized in a recent review [17]. ASTM F2731-24 addresses this by measuring transmitted energy and, in a second procedure, the stored energy released when the exposed specimen is compressed. Post-exposure heat release in the PCM studies reviewed here was captured only by study-specific protocols, such as continued temperature logging after glove and assembly tests [8, 16], Wash, abrasion, and thermal-cycling durability were rarely linked to these thermal measurements. Most thermal evaluations of phase change fibers have been performed on small fabric pieces under static conditions that exclude sweating and movement-induced convection [12].

At the garment and wearer level, instrumented-manikin burn-injury prediction (ISO 13506-1:2024 and ISO 13506-2:2024; ASTM F1930-23) and climatic-chamber or field human trials provide the most directly occupationally relevant outcomes: second-degree burn time, skin and core temperature, subjective ratings, and physiological strain. No instrumented-manikin flame test of a complete PCM garment was found among the sources reviewed. Sample sizes in the wearer-level studies were small: one surgeon in the operating theatre and two subjects in the laboratory, and six in the insulated-suit trial [34]; six in the firefighting cooling-vest trial [10]; 15 in the live-line cooling-garment trial [4]; and 12 in a non-PCM protective-suit trial [35]. Environmental conditions, garment fit, and exposure protocols also varied too widely to allow direct numerical comparison. Standards relevant to PCM-incorporated firefighter and industrial protective clothing have changed since much of the earlier literature was published, and this review uses current designations: ISO 13506-1:2024 and ISO 13506-2:2024 (transferred-energy measurement with an instrumented manikin and skin-burn prediction, respectively; second editions replacing the 2017 parts, which had superseded the single-part ISO 13506:2008); ASTM F1930-23 (manikin fire simulation test); ASTM F2731-24 (transmitted and stored energy of firefighter protective clothing systems); and NFPA 1970 (2025 edition), which consolidated NFPA 1971 (structural and proximity ensembles), NFPA 1975 (work apparel), NFPA 1981 (open-circuit self-contained breathing apparatus), and NFPA 1982 (personal alert safety systems). Several of the studies reviewed describe gear or layer systems specified under the earlier NFPA 1971 [8, 23, 25], and that designation is retained when describing them. Table 3 summarizes the comparability constraints across the three evaluation levels.

Table 3. Evaluation levels and comparability constraints for PCM occupational textiles.

NO	Level	Representative method(s)	What measures Comparability	Constraint
1	Material	Differential scanning calorimetry (DSC), with scan rate reported	Phase-change range, enthalpy of fusion, cycling stability [12, 25, 27]	Mass basis differs (pure PCM, product, composite, fiber, fabric) [27, 29]; nominal and actual transition ranges can differ [25]; not convertible to garment-level benefit without PCM mass fraction and textile area
2	Textile	ASTM F2731-24 stored-energy test; TPP/RPP; sweating guarded hot plate	Transmitted and stored energy; thermal and evaporative resistance; wash/abrasion durability (rarely linked)	Steady-state methods miss transient behavior [2]; exposure-period ratings overstate protection when stored energy is ignored [17]; post-exposure release captured only by study-specific protocols [8, 16]
3	Garment/wearer	ISO 13506-1/-2:2024 and ASTM F1930-23 manikin tests; climatic-chamber and field human trials	Second-degree burn time; skin/core temperature; subjective comfort; physiological strain	Small samples (n = 6-12) [4,15,[35]; burn endpoints differ (Henriques integral, 60 °C skin surface, TPP criterion) [14, 15, 25] Constant-temperature manikins are not comparable with human responses [10]

8. Advantages, Limitations, and Practical Implementation

Where melting point, mass, and position are matched to the exposure profile, the reviewed evidence supports several benefits of PCM incorporation: delayed onset of second-degree burn or of a critical skin-surface temperature within specific exposure windows [11, 13-15]; lower skin or skin-simulant temperatures during exposure [8, 17], and improved thermal sensation with PCM vests in several of the studies summarized in a review of cooling garments [13]. These benefits are best evidenced at bench or model scale for firefighting turnout fabrics and glove samples, whereas wearer-scale evidence is limited to cooling vests, in which local cooling has not consistently translated into whole-body benefit [10, 13].

Set against these benefits are several practical limitations. PCM latent heat capacity is finite and, once exhausted, provides no further buffering: complete melting of the approximately 1.7 kg of PCM in the firefighting cooling vests was estimated to absorb only 13.5–20.3% of the metabolic heat produced over the first 45.5 min of the protocol [10], and field cooling with PCM vests typically lasts about 2 h or less [13].

Regeneration between uses is an operational requirement for removable pack systems (re-solidification overnight at 20 °C in one trial [10]; cooling in a ventilated place for high-melting pouches [9] and was not addressed by the coating or fiber studies reviewed, none of which tested repeated use in an occupational context. Added weight is most evident for removable pack systems (about 1.7 kg of PCM in the firefighting cooling vests and up to about 3 kg for most personal cooling vests) [10, 13]. Coated and fiber-incorporated PCMs instead risk reducing air and moisture-vapor permeability and increasing stiffness: dry-coated PCM fabrics were described as thick and stiff with poor breathability [25], whereas a PCM-yarn uniform fabric showed no significant permeability penalty but stored very little heat [28]. For fire-protective layers, the most serious limitation is the post-exposure heat release described in Sections 6 and 7: a configuration optimized only for exposure-phase performance could, according to a numerical study of wet clothing, be more hazardous than an equivalent PCM-free garment for short, high-intensity exposures [14], and in a model of garments wetted after a flash fire, melting points above 50 °C added a re-solidification hazard with the baseline thermal liner, which a 4% increase in liner fiber fraction removed [15].

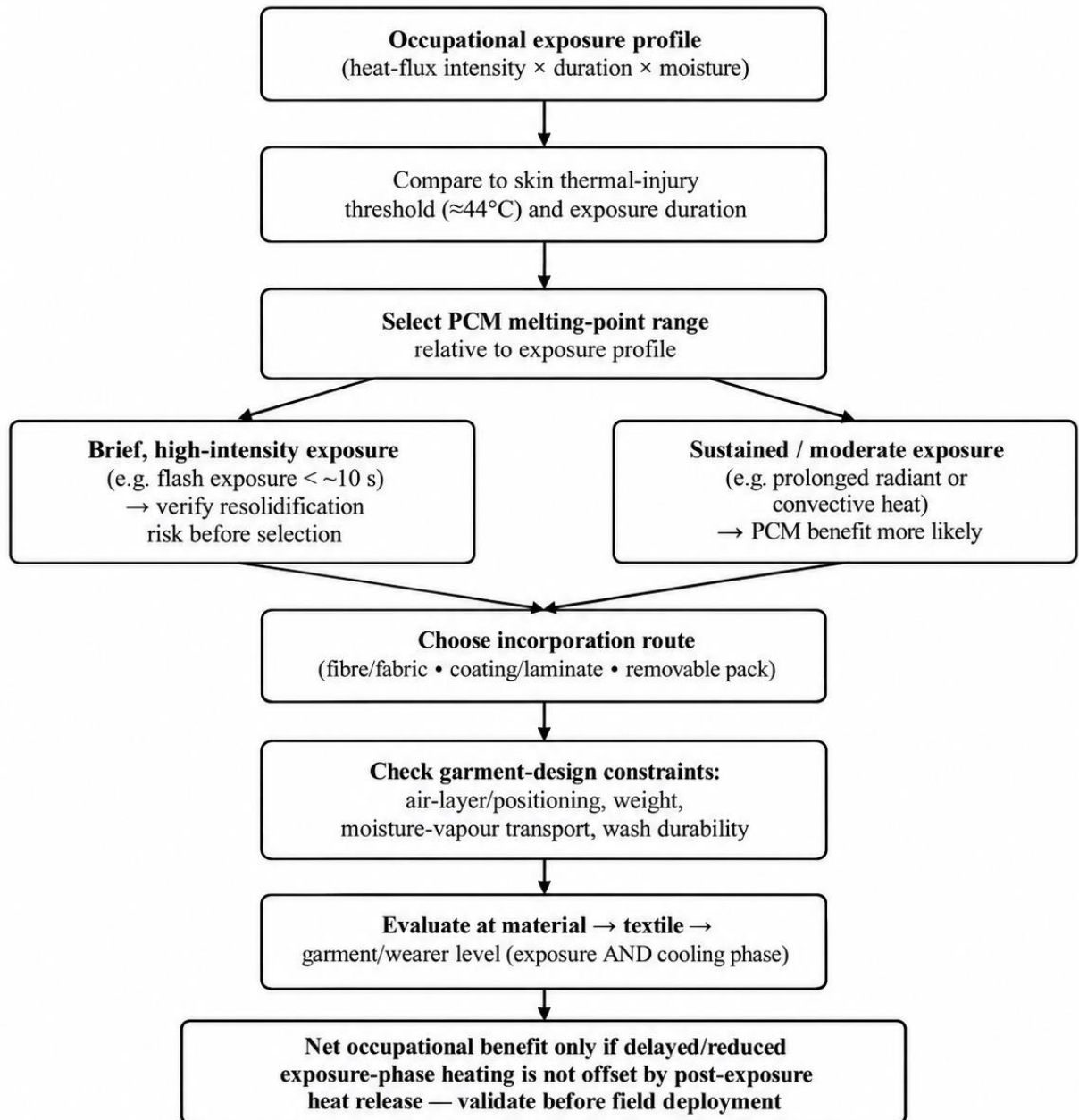
Translating material-level PCM performance into demonstrated occupational protection or comfort is limited by three structural factors evident across the reviewed literature: the absence of a standardized mass-normalization convention (per gram of PCM, per unit textile area, or per garment, none of which converts directly to another; Section 8); the fact that certification-relevant bench tests rate protection over the exposure period, so a garment can perform well in them while carrying a post-exposure risk that they do not evaluate [17]; and the small sample sizes and short exposure and recovery windows of wearer-level studies (Table 3), which fall well short of a full occupational shift. Occupational guidance also places personal cooling after engineering and administrative controls and notes that cooling equipment can restrict heat loss and increase work effort depending on its mass[1]; PCM garments should therefore be evaluated as one component of a heat-management plan rather than as a substitute for exposure control. Figure 4 sets out a selection framework, synthesized from this evidence rather than independently validated, for working through these considerations when specifying a PCM layer for an occupational garment.

9. Sustainability Considerations

Sustainability data specific to occupational PCM clothing are sparse in the literature retrieved for this review; most of the following draws on the broader PCM textile literature and should be read as indicative rather than occupational-garment-specific. The organic PCMs used in the coated and fiber-incorporated systems reviewed here are mostly paraffins [25, 28], which are petroleum-derived [16] and flammable [5, 16]. This creates a conflict in fire-protective applications, where a flammable thermal-management additive must be flame-retarded or otherwise protected (Section 5.2) to



avoid compromising the garment's primary protective function [25]. Some flame retardants used with PCMs, such as polybrominated diphenyl ethers and hexabromocyclododecane, raise concerns about leaching and environmental accumulation [16]. Encapsulation and finishing chemistries also carry health and environmental considerations. Melamine–formaldehyde has been proposed as a PCM finish to improve flame retardancy, but concerns that it could cause skin allergy and reduce fabric strength have kept it out of direct use in thermal protective clothing [25] and urea–melamine–formaldehyde copolymers have been used as.



Conceptual framework synthesised from the reviewed evidence; not a validated design algorithm.

Figure 4. Suggestion for an application-based selection framework for PCM-incorporated occupational protective clothing.

microcapsule shells for PCM fibers [29]. None of the occupational studies reviewed here reported formaldehyde release from PCM microcapsules. Bio-based fatty-acid PCMs are already used in glove and turnout-gear studies [8, 23]], but this review

identified no occupational durability, wash-cycle, or life-cycle data for bio-based PCMs or biopolymer shells; any sustainability advantage should not be assumed to extend automatically to textile processing compatibility, occupational durability, or certified thermal protective performance, none of which is established by bio-based sourcing alone.

Manufacturing burden, regeneration energy (for systems requiring repeated melt-freeze cycling or active recharging), in-service repair, and end-of-life recycling or disposal of PCM textile composites were not reported in occupational-clothing-specific form by any source retained in this review. General reviews of PCM textiles attribute a likely increase in manufacturing energy use and emissions to the additional processing stages (PCM selection, microencapsulation, formulation, and application), note that non-recyclable, non-biodegradable PCM additions may add to waste, and conclude that life-cycle assessment is needed for each new material; these assessments are qualitative and include no inventory data [16]. The life-cycle section of a broader review likewise contains no assessment of a PCM textile [11]. Claims of environmental benefit in this literature energy savings extrapolated from building applications, or longer product life attributed to user comfort are not supported by textile-specific measurements and are not adopted here [16]. No formal life-cycle assessment specific to occupational PCM protective clothing was identified; this remains an open question rather than a settled negative or positive finding.

10. Future Perspectives

Five priorities follow directly from the evidence gaps identified in this review, rather than from a general survey of emerging PCM technologies. First, combined washing and thermal-cycling durability protocols are needed that link standardized laundering or abrasion cycling to repeat burn-time and comfort testing on the same garments. At present, durability evidence consists of DSC cycling of fibers [27] and enthalpy after 20 washes of a non-flame-resistant grafted fabric [29], whereas occupational outcome data (Table 3) come from entirely separate studies, none of which laundered the test materials. Laundering procedures already specified for flame-, thermal-, and arc-resistant clothing could provide the conditioning step [36]. Second, a comparable reporting protocol requires PCM performance to be expressed on stated mass bases (per gram of PCM, per unit textile area, per garment), together with the DSC scan rate, the burn criterion, and the presence of a thickness- and mass-matched PCM-free control.

Third, body-region placement deserves systematic study, building on the finding that the influence of local sensation on overall thermal sensation varies by body region [21]. A whole-body model suggests that PCM protects only the skin beneath it, so that gaps between segments should not exceed about 5 mm [7]; this has not been tested on instrumented manikins or across occupational garment types, and a recent firefighter-



clothing review lists optimal placement, loading, and durability of PCM systems in high-risk body regions among its own priorities [17].

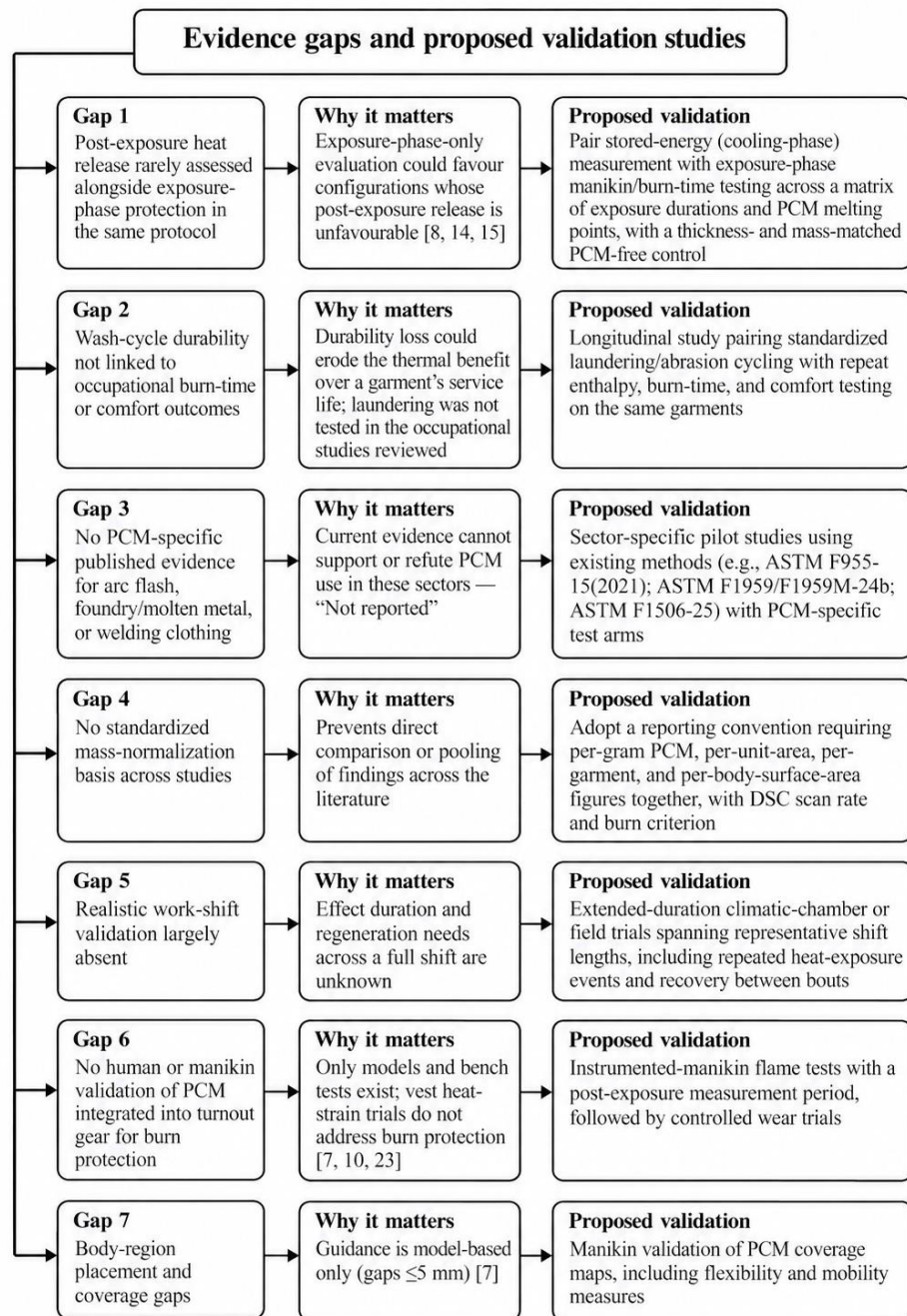


Figure 5. Evidence gaps and proposed validation studies

11. Conclusions

The evidence reviewed here does not support a general claim that PCMs improve occupational clothing. It supports a conditional claim, and the conditions differ between the two functions that PCMs are asked to perform.

In fire-protective layers, PCMs delay heat transfer to the skin during exposure in models, coated fabrics, glove samples, and laboratory assemblies. Part of this gain, however, came from the mass and thickness that the PCM added, and one full-scale test found no benefit at flashover. The heat stored during exposure is released as the PCM re-solidifies. Models of wet clothing from a single research group predict that this release can cause burns after brief, intense exposures or when melting points are high, although a small increase in the fiber fraction of the thermal liner removed the effect in those models; glove tests from another group showed prolonged heating after exposure. A fire-protective PCM layer should therefore be judged over the whole exposure–recovery cycle, which no instrumented-manikin study among the sources reviewed has yet measured.

In cooling garments, removable packs produced large local cooling, but in a trial at 55 °C beneath a heavy firefighting ensemble they did not reduce core temperature, heart rate, or thermal sensation during exercise. Their usefulness is further limited by finite latent capacity, the need to regenerate the PCM between uses, added mass, and restricted moisture transfer beneath the packs.

The incorporation routes are not interchangeable. Packs carry a substantial PCM mass but add weight and obstruct evaporation. PCM-coated firefighting fabrics were thick, stiff, and poorly breathable. The one occupational fabric made with PCM yarns kept its permeability but stored little heat, and it was not tested beyond fabric level. Meaningful benefit is therefore most likely where the melting point and PCM mass are matched to the expected exposure, the cooling phase is evaluated as well as the exposure phase, and the chosen route preserves moisture transfer.

Durability, the second half of the review question, remains unanswered. Laundering has not been linked to protective or comfort outcomes, life-cycle data for occupational PCM garments are absent, and no PCM-specific evidence exists for arc flash, molten-metal, or welding clothing. Before wider occupational use, PCM garments should be tested for both exposure-phase and cooling-phase performance against PCM-free controls matched for thickness and mass, with results reported per garment as well as per gram of PCM.

References

1. World Health, O. and O. World Meteorological, Climate change and workplace heat stress: technical report and guidance. NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy, 2026. **35**(4): p. 468-470.
2. Shakeriaski, F., et al., Smart coating in protective clothing for firefighters: An overview and recent improvements. Journal of Industrial Textiles, 2022. **51**(5_suppl): p. 7428S-7454S.



3. Song, G., S. Mandal, and R.M. Rossi, 5-Performance evaluation of thermal protective clothing. *Thermal Protective Clothing for Firefighters*. Duxford, UK: Woodhead Publishing, 2017: p. 57-144.
4. Wang, S., et al., Phase change cooling garment for thermal stress reduction: experimental evaluation and predictive modeling. *Ergonomics*, 2026: p. 1-20.
5. Rossi, R.M. and W.P. Bolli, Phase Change Materials for the Improvement of Heat Protection. *Advanced Engineering Materials*, 2005. **7**(5): p. 368-373.
6. McCarthy, L.K. and M. Di Marzo, The application of phase change material in fire fighter protective clothing. *Fire Technology*, 2012. **48**(4): p. 841-864.
7. Xu, S., Pollard, J., Zhao, W. , Optimization of the Size and Distribution of Phase Change Material (PCM) in Firefighters' Turnout Gear. In: Tareq Ahram and Waldemar Karwowski (eds) *Human Factors in Design, Engineering, and Computing*. AHFE in International Conference. 2024, AHFE Open Access: AHFE International, USA.
8. Wang, X., et al., Experimental study on the thermal protection enhancement of novel phase change material integrated structural firefighting gloves under high-heat exposures. *Case Studies in Thermal Engineering*, 2024. **56**: p. 104286.
9. Santos, G., et al., Smart firefighters PPE: impact of phase change materials. *Applied Sciences*, 2023. **13**(18): p. 10318.
10. Gao, C., K. Kuklane, and I. Holmér, Cooling vests with phase change materials: the effects of melting temperature on heat strain alleviation in an extremely hot environment. *European Journal of Applied Physiology*, 2011. **111**(6): p. 1207-1216.
11. Shahid, M.A., et al., Research and development on phase change material-integrated cloth: A review. *Journal of Industrial Textiles*, 2024. **54**: p. 15280837241262518.
12. Xiao, X., et al., Research progress of thermoregulating textiles based on spinning of organic phase change fiber of energy storage. *Textile Research Journal*, 2024. **94**(11-12): p. 1388-1419.
13. Rahimi, E., et al., Personal cooling garments and phase change materials: A review. *Renewable and Sustainable Energy Reviews*, 2024. **190**: p. 114063.
14. Malaquias, A.F. and J. Campos. Influence of PCMs on thermal performance of wet fire protective clothing. IOP Publishing.
15. Malaquias, A.F. and J. Campos, Influence of PCM incorporation on thermal performance of fire protective clothing subject to wet exposures. *International Communications in Heat and Mass Transfer*, 2026. **175**: p. 111043.
16. Hossain, M.T., et al., Fabrications, Classifications, and Environmental Impact of PCM-Incorporated Textiles: Current State and Future Outlook. *ACS Omega*, 2023. **8**(48): p. 45164-45176.
17. Kumar, V., J. Acharya, and D. Bhanja, Thermal Protective Performance of Firefighter Clothing: A Review of Advances in Heat, Moisture, Materials, and Physiological Safety. *Fire Technology*, 2026. **62**(6): p. 140.
18. Vasile, S., et al., Thermal and moisture management properties of knitted fabrics for skin-contact workwear. *Materials*, 2025. **18**(8): p. 1859.



19. Lawson, L.K., et al., Moisture effects in heat transfer through clothing systems for wildland firefighters. *International journal of occupational safety and ergonomics*, 2004. **10**(3): p. 227-238.
20. Barker, R.L., et al., Effects of moisture on the thermal protective performance of firefighter protective clothing in low-level radiant heat exposures. *Textile Research Journal*, 2006. **76**(1): p. 27-31.
21. Zhang, H., et al., Thermal sensation and comfort in transient non-uniform thermal environments. *European journal of applied physiology*, 2004. **92**(6): p. 728-733.
22. Bizuallem, Y.D., et al., Phase change materials for thermal energy storage: classification, challenges, and advances. *Navigating a Sustainable Future with Phase Change Materials for Energy Storage*, 2026: p. 19-54.
23. Xu, S.S., J.P. Pollard, and W. Zhao, Effect of Phase Change Material Melting Points on Thermal Protection Behavior of Firefighters' Turnout Gear. 2025.
24. Fonseca, A., T.S. Mayor, and J. Campos, Guidelines for the specification of a PCM layer in firefighting protective clothing ensembles. *Applied thermal engineering*, 2018. **133**: p. 81-96.
25. Su, Y., et al., Flame-retardant phase change material (PCM) for thermal protective application in firefighting protective clothing. *International Journal of Thermal Sciences*, 2023. **185**: p. 108075.
26. Barowy, A.M. and D.M. Madrzykowski, Thermal Behavior of Structural Fire Fighting Protective Ensemble Samples Modified with Phase Change Material and Exposed in Full-Scale Room Fires. 2012.
27. Chen, Z., et al., Preparation of form-stable silica/polyethylene glycol composites using flash-drying for large-scale melt-spun fibers with thermal management property. *Polymer Engineering & Science*, 2023. **63**(2): p. 454-466.
28. Seddik, K.M., et al., Examine integrating PCM yarns for enhancing merchant maritime uniform fabricated by polyester double cloth fabric. *Scientific Reports*, 2025. **15**(1): p. 32551.
29. Kumar, A., et al., Cotton functionalized with polyethylene glycol and graphene oxide for dual thermoregulating and UV-protection applications. *Scientific Reports*, 2023. **13**(1): p. 5923.
30. Malaquias, A.F., S.F. Neves, and J. Campos, Incorporation of phase change materials in fire protective clothing considering the presence of water. *International Journal of Thermal Sciences*, 2023. **183**: p. 107870.
31. Pennes, H.H., Analysis of tissue and arterial blood temperatures in the resting human forearm. *Journal of applied physiology*, 1948. **1**(2): p. 93-122.
32. Song, G., S. Mandal, and R.M. Rossi, Thermal protective clothing for firefighters. 2017: Elsevier.
33. Ge, X., et al., Thermal management strategies for thermal protective clothing containing phase change material (PCM): A focus on heat storage and release. *International Communications in Heat and Mass Transfer*, 2026. **179**: p. 112386.



34. Reinertsen, R.E., et al., Optimizing the performance of phase-change materials in personal protective clothing systems. International Journal of Occupational Safety and Ergonomics, 2008. **14**(1): p. 43-53.
35. Epstein, Y., et al., The Effect of Air Permeability Characteristics of Protective Garments on the Induced Physiological Strain under Exercise-Heat Stress. The Annals of Occupational Hygiene, 2013. **57**(7): p. 866-874.
36. Haase, J., 14 - Flame resistant clothing standards and regulations, in Handbook of Fire Resistant Textiles, F.S. Kilinc, Editor. 2013, Woodhead Publishing. p. 364-414.