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PCM Thermal Storage Technology and its Military Applications: A Review

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Abstract: Phase Change Materials (PCM) are the most promising and budding technology in the field of Thermal Energy Storage (TES) and thermal comfort in buildings. PCMs are being extensively used and researched across the world for the improvement of thermal performance of buildings by smoothening temperature peaks as well as act as a power-saving tool in buildings where heating or cooling is required. PCMs can absorb and release heat or cold energy when it undergoes a phase change from solid to liquid and vice versa. This process takes place at a constant temperature absorbing a huge amount of energy in form of latent heat of fusion or vaporization in comparison to sensible heat which is absorbed with an increase of temperature. India's frontiers stretch across a few of the world's extreme terrains having extreme climatic conditions varying from extremely hot climates on western borders to extremely cold climates on its northern extremities. The unique characteristic of PCM based latent heat storage system can be utilized in lightweight prefabricated PUF insulated shelters used by security forces, to increase its thermal resistance or store excess heat from intermittent renewable sources during daytime for use during the night, thereby helping in maintaining a comfortable temperature inside the shelters. The PCMs characteristic of absorbing and releasing heat at a constant temperature can be effectively utilized in various other applications where thermal management or temperature control is of importance. It can also help in enhancing the mission reliability of its vehicles, equipment, plant, and electronic instruments when deployed in areas having extreme temperatures. In the present work, a broad study has been conducted based on recent progress and research across the world on PCM technology and its probable applications in the defense sector. The aim is to highlight the potential of PCMs to be utilized for the enhancement of the performance of manpower and critical equipment deployed under extreme climatic conditions encountered by the Security forces.

Keywords: Phase Change Material, Thermal Energy Storage, Latent Heat Storage, Military Applications, Security forces, Indian Armed forces.

I. INTRODUCTION

PCMs are excellent materials for thermal management solutions as they store and release thermal energy during the process of melting & freezing (changing from one phase to another). When PCM freezes, it releases heat energy in the form of latent heat or energy of crystallization, whereas when it is melted, same amount of energy is absorbed from the environment as its phase changes from solid to liquid. The study on phase change material (PCM) was started in the 1900s by Alan Tower Waterman at Yale University [1].

The first known application of PCM was by NASA in the aerospace field [2] since then a large no of materials have been investigated across the world for their use as PCMs suitable for various types of applications like Solar energy storage (SES), Thermal Energy Storage (TES), Waste Heat Recovery (WHR), Combined Heat and Power (CHP) systems, load shifting, power savings, wearable PCMs, Passive cooling and free cooling, HVAC systems, Net Zero Buildings, Cooling of electronics and batteries, Temperature controlled transportation and shipping of frozen foods, medicines and vaccines, human comfort, energy conservation and energy efficiency.

Indian Armed forces are deployed under very harsh conditions having extreme climates ranging from extremely hot deserts of Thar to extremely cold climates of great Himalayan Mountain ranges at high altitude areas. The performance of man, vehicles, equipment, and highly sophisticated weapon and surveillance systems deployed by Security forces in such areas is adversely affected due to extreme temperatures encountered. Especially the sensors, batteries and electronics starts malfunctioning in such conditions and many times it leads to their complete failure. Use of PCM is the most suitable and a practical solution to such problems.

Several R&D projects are being pursued in the field of PCM applications to address problems of extreme temperatures faced by Armed forces, like hot jackets for high altitude areas and high-capacity heat sinks for critical instruments.[3]

A. Thermal Energy Storage

With the increasing push for renewable energy sources for power generation to counter global warming, the importance of energy storage has increased manifolds to make it a viable and sustainable option for the future by overcoming its intermittent nature. Various types of energy storage are Battery Energy Storage, Thermal Energy Storage (TES), Mechanical Energy Storage, Pumped Hydro and Hydrogen Storage. Out of the above five categories one of the most versatile and flexible method of energy storage is TES which can be designed in various sizes and configurations specific to the application. TES systems have been used since ages when our ancestors designed their houses and used storage of ice for cooling purposes. TES technology is used to store energy in form of heat or cold in a medium to be used later for heating and cooling applications or even power generation. In buildings and industrial processes, approximately half of the energy consumed is in the form of heating or cooling requirements and the demand keeps varying during any given day. The use of TES systems can balance out variation in energy demand and supply over a day, week, and even seasons [4]. Use of TES system helps in increasing efficiency, ensuring better reliability and economics, reducing overall cost and reducing pollution & carbon emissions [5]. TES is being extensively researched and used in concentrated solar power (CSP) plants to store solar heat during the day which can be used for electricity production during night and peak demand periods ensuring round the clock production of power. The various types of thermal energy storage at temperatures ranging from 40°C to more than 400°C are classified as Sensible Heat Storage(SHS), Latent Heat Storage(LHS) and Thermo-Chemical Heat Storage(TCS) as shown in Fig 1 [6].

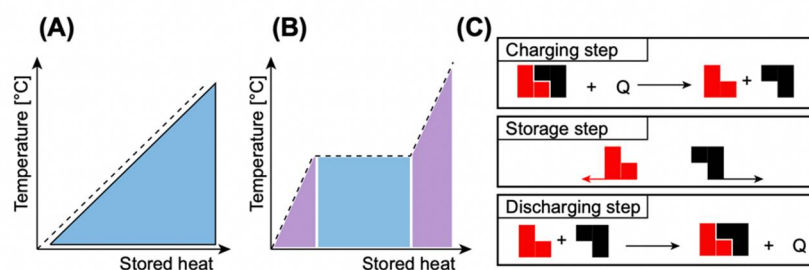


Fig 1. Methods of thermal energy storage (A) sensible heat; (B) latent heat; (C) thermochemical reactions.

Characteristics of a TES system can be described in following terms :-

- Capacity and size of the system.
- Rate of Charge and Discharge or Power.
- Efficiency of system to store and
- Storage period in terms of hours, days, weeks, and months).
- Charging and discharging period.
- Capital and Running Cost.
- Lifecycle.

1) *Sensible Heat Storage (SHS)*: SHS stores heat or cold energy by heating or cooling respectively, a liquid or solid material e.g., water, rocks, sand, molten salts etc [Fig 1(B)]. Water is most commonly SHS storage medium used in residential and industrial applications, being inexpensive, without any hazards and has high specific heat. The heat energy stored utilizes the specific heat capacity of the storage material, its mass and the change in the temperature for charging and discharging of TES [7]. The Water SHS system is either used as underground storage or stored in large insulated tanks, for applications above 100°C oils, molten salts, liquid metals, etc are used and even air heating is also used in rock-bed type storage.

$$Q_s = \int_{t_i}^{t_f} mc_p dt = mc_p(t_f - t_i)$$

Where,

Q_s = Quantity of heat stored in J;

m = Mass of heat storage medium in kg;

c_p = Specific heat in J/kg-K;

t_i = Initial temperature, in °C;

t_f = Final temperature, in °C.

- 2) **Thermochemical Heat Storage (TCS):** Thermochemical heat is the energy absorbed and released during the breaking and forming of molecular bonds [Fig 1(C)]. During charging, the molecular bonds are broken by endothermic reaction and heat is absorbed. While during discharge, two chemicals mix by exothermic reaction at a certain pressure and temperature and energy is released [8]. The TES working based on the above method is known as the thermochemical heat storage (TCS) system.
- 3) **Latent Heat Storage (LHS):** In the case of LHS, the energy stored as latent heat of fusion or solidification which is the enthalpy of material change is absorbed or released during the phase-change process [Fig 1(B)]. The heat is absorbed or released at quite a constant temperature (or a small change in temperature) during phase change from solid to liquid or liquid to gas or vice-versa and the latent heat energy is normally very high when compared to the sensible heat of the same material. Therefore, the LHS system results in increasing the energy density of the TES system and reducing its volume or size, therefore, resulting in a compact system [9].

The transformation of liquid to gas or solid to gas phase transitions are accompanied by a large volume change which is an unacceptable feature hence are inappropriate for application in LHS systems. An LHS system using PCMs undergoing solid to liquid and liquid to solid phase transition can effectively store thermal energy in form of heat during melting or cold during solidification accompanied by a minor change in volume usually below 10%. The advantage of an LHS method which makes it a better TES than SHS is its capacity to absorb more amount of heat with almost nil or very small change in temperature. The storage capacity of the LHS system (Q_s) using a PCM is given by

$$Q_s = \int_{t_i}^{t_m} mc_p dt + mf\Delta q + \int_{t_m}^{t_f} mc_p dt$$

$$Q_s = m[c_{ps}(t_m - t_i) + f\Delta q + c_{pl}(t_f - t_m)]$$

where,

- t_m = Melting temperature, in °C;
 m = Mass of PCM medium, in kg;
 c_{ps} = Average specific heat of the solid phase between t_i and t_m , in kJ/(kg-K);
 c_{pl} = Average specific heat of the liquid phase between t_m and t_f , in J/(kg K);
 f = Melt fraction; and
 Δq = Latent heat of fusion, in J/kg.

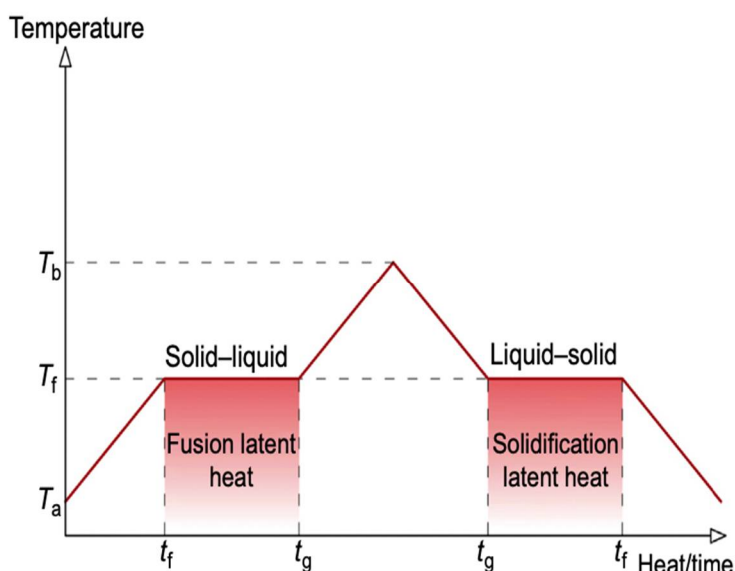


Fig 2 . The Phase Transition in LHS system.

II. PHASE CHANGE MATERIAL (PCM)

PCMs are the materials that follow the LHS principle and are one of the most efficient TES materials as a high amount of energy per unit mass is stored during melting i.e., the phase transition from solid to liquid, and released during freezing at a constant temperature [Fig 2]. The atomic bonds are loosened by increased lattice vibration when heat is absorbed by a material and consequently melting takes place when the material changes its state from solid to liquid. While, during solidification, the molecules release absorbed energy to their surroundings and results in a more ordered state is achieved by material i.e., the solid-state [10]. PCMs are available in any desired range of temperature starting from as low as -20°C to 1400°C.

Considering the example of a specific application of PCM for providing thermal comfort in buildings. PCMs have the ability to flatten the extremes of room temperature and shift the timing of air temperature fluctuations in a room. PCM can absorb latent heat energy in the range of 100 to 250 kJ/kg which is very large in comparison to sensible heats of other building materials like wood/plastics 1.5 -2 kJ/Kg or bricks/concrete 0.8-0.3 kJ/Kg only. Therefore, the total heat storage capacity (Q) of a PCM based TES is the sum of both the latent heat or enthalpy of phase transition and the sensible heat, expressed as:

$$Q = m[(c_p \Delta T)_{\text{sensible}} + (c_p \Delta T)_{\text{latent}}]$$

Considering applications in TES systems used for thermal management and human thermal comfort in buildings, the most commonly used PCMs are paraffin, hydrated salts and fatty acids. Table 1 lists some of the most commonly used PCMs with their thermal Properties including water which is used in cold storage applications as ice storage.

Table I
Some of the most Common PCMs and their Properties

PCM	Melting Pt (°C)	Latent Heat (kJ/Kg)	Density(g/cm ³)
Ice	0	333	0.92
Na-Acetate Tri-Hydrate	58	250	1.30
Paraffin	-5 to 120	150 to 240	0.77
Erythritol	118	340	1.30

A. Classification of PCMs

A variety of phase change material are available and depending on their chemical composition the PCMs can be grouped in three main categories: organic (paraffin and nonparaffin), inorganic (salt hydrates and metallic alloys), and eutectic (mixture of two or more PCM components: organic, inorganic, and both)[9].

- 1) *Organic PCMs*: Most common type of organic PCM are paraffin and fatty acids whereas some other types are HDPE or polymeric materials, poly-alcohols, palmitic acid, sugar alcohols and capric acid. Organic PCMs are characterised by their high latent heat storage, suitable range of melting points, and physical and chemical stability, additionally they are non-toxic, non-corrosive, exhibit no segregation and have negligible supercooling. Its shortcomings include low thermal conductivity, lower enthalpy and flammability. Supercooling is the decrease in temperature below its freezing or solidification point without having started the process of solidification, while segregation means separation of the components of a material over successive freeze/melt cycles both are usually more prominent in non-organic PCMs. Organic PCMs are generally used for low and intermediate temperature application within range of 100-200°C whereas the inorganic PCMs are used for high temperature applications. These can be divided into two major groups viz Paraffin based and Non-Paraffin based, also they can be further classified based on their melting temperature ranges as shown in Fig 3 a-c, which show melting points of some selected organic compounds [11]. The latest addition to organic PCMs are Plant based PCM derived from plant oil or animal fats which have higher latent heats and are available in temperature range between -30 °C and 150 °C, for example vegetable oil, corn fat oil, stearic acid etc.

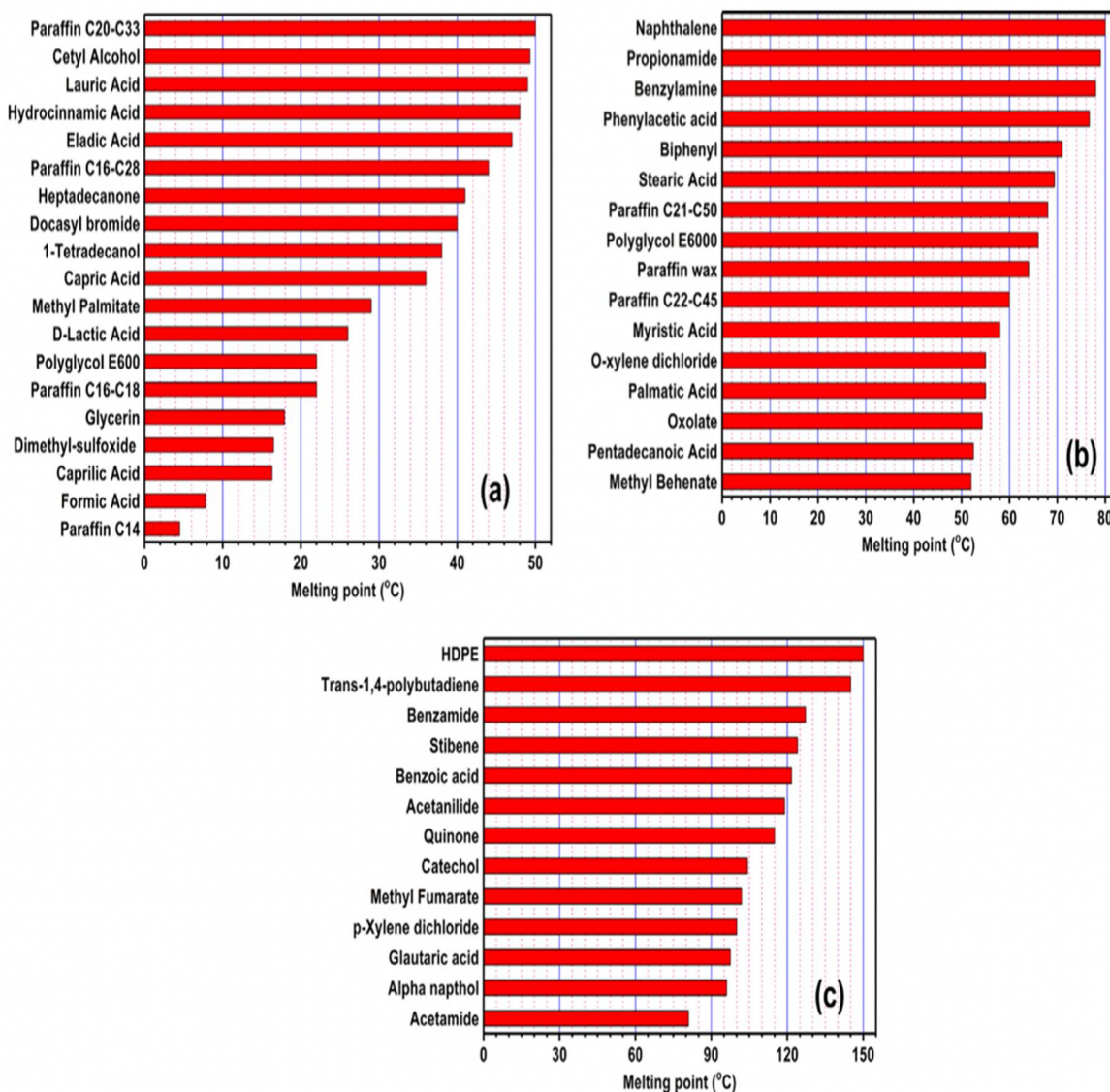


Fig 3. Melting points of selected Organic PCMs (a) below 50° C, (b) between 50° and 80° C and (c) over 80° C for thermal energy storage [11].

- 2) **Inorganic PCMs:** These PCMs have some advantages like high latent heat per unit volume, non-flammable, relatively high thermal conductivity, low vapour pressure, low super-cooling, non-degradation with cycling and compatibility with plastics. Further classified as salt hydrates and metallic salts. Salt hydrates are a typical crystalline solid formed by alloys of inorganic salts (AB) and n mol of water having general formula $AB \cdot nH_2O$. The solid-liquid transition takes place by dehydration and hydration of the salt when during melting the hydrated crystals disintegrate into anhydrous salt or its lower hydrate and water. Salt hydrates has few disadvantages like incongruent melting as water released during crystallization is not sufficient to dissolve all the solid and lower hydrates and supercooling. To overcome these problems thickening agents are used as additives in addition to stirring mechanism and encapsulation to reduce separation. Most salt hydrates have melting point below 200°C but some inorganic salts have very high melting points up to 1000°C, which are used widely in high temperature TES applications such as carbonates, chlorides, sulphates, fluorides and nitrates. Fig 4 a-c present melting points of few selected inorganic salts [11] Some of the most commonly used salt hydrates are $K_2H_2O_4 \cdot 6H_2O$, $KF \cdot 4H_2O$, $K_2H_2O_4 \cdot 4H_2O$, $LiBO_2 \cdot 8H_2O$, $FeBr_3 \cdot 6H_2O$, and $CaCl_2 \cdot 6H_2O$ [12].

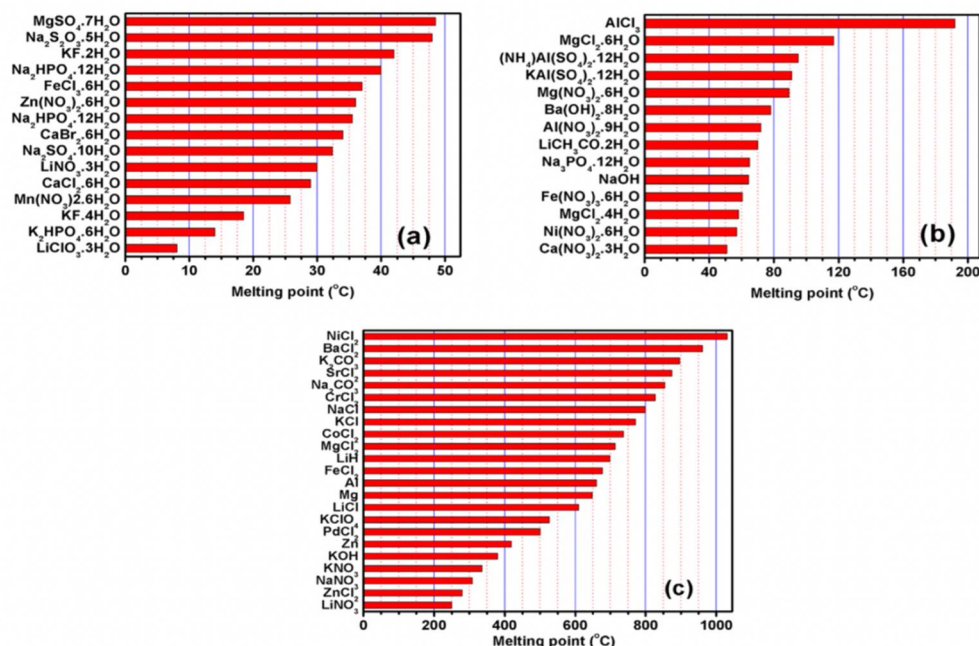


Fig 4. Melting Points of some Inorganic PCMs (a) Below 50°C, (b) between 50 – 200°C, and (c) Over 200°C.

Metallics are the category that includes low melting metals and metal eutectics like Gallium which is commonly used [12]. These PCMs are rarely used due to their low melting enthalpy per unit weight. Important features of metallic PCMs are higher heat of fusion per unit volume, lower heat of fusion per unit weight, higher thermal conductivity, low specific heat and relatively low vapor pressure.

- 3) *Eutectic PCMs*: Eutectic PCMs (EPCM) are a minimum melting combination of two or more components which melts or freeze congruently forming a mixture of the component crystals during crystallization. Some of the most common eutectic are Triethylolethane + water + urea, Triethylolethane + urea, Mg(NO₃)₃·6H₂O + NH₄NO₃, Mg(NO₃)₃·6H₂O + MgCl₂·6H₂O, and Mg(NO₃)₂·6H₂O + MgBr₂·6H₂O [12]. Advantages of eutectic material are high latent heat of fusion at lower melting point, always melt and freeze without segregation, high volumetric energy storage density and have the lowest melting temperature than the mixed material. EPCMs between temperature range of 25 to 180 C are most preferable for solar water heater, solar air heater and agriculture heating [9]. Metal alloys and inorganic eutectics have exceptionally high melting points most suitable for CSP applications. Similarly Eutectic Aluminium alloys are most suitable for high temperature TES for industrial applications[13]. EPCMs presently are under research and not in much use, but are promising PCM for the future. Fig 5 show melting points of some selected EPCMs [11].

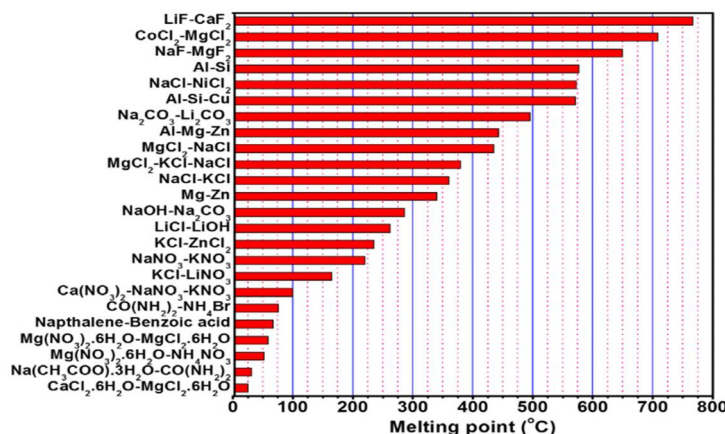


Fig 5. Melting Points of selected EPCMs.

B. Selection Criteria for PCMs

A PCM must possess certain desirable physical, thermal, chemical and kinetic properties to be used for a particular TES application. The selection of PCM also depends on its cost, availability, safety, adaptability and reliability in terms of repeated use [11]. All the above characteristics are key selection parameters for a PCM to be used in a particular TES application. Table 2; present a list of certain desirable properties of PCMs which are of importance for selection of PCM for a particular application [9]. Main properties of some commonly studied PCMs in various literatures is listed in Table 3 [14] for comparison purpose.

Table II
Desirable Properties of PCM [9]

S. No.	Property Classification	Desirable Properties
1	Thermodynamic Properties	<ul style="list-style-type: none"> PCM should have a suitable melting or freezing point in range of the intended application of TES. It is preferable to use a PCM having high latent heat, high specific heat capacity, high thermal conductivity for complete melting/solidification of PCM and should melt or freeze congruently.
2	Kinetic Properties	<ul style="list-style-type: none"> A major challenge faced by PCM in its application as TES is the supercooling which should be minimum for a PCM to be effective in its operating temperature range. Other desirable kinetic properties are high crystallization rate and high nucleation rate which assist in complete melting/solidification of PCM near its melting point.
3	Physical Properties	<ul style="list-style-type: none"> PCM should preferably have high density which helps in making a compact system and should exhibit no phase segregation during repeated cycles. For effective encapsulation and storage without leakage the material should melt/freeze with minimum volume change to be utilized as a PCM in addition to having minimum vapour pressure.
4	Chemical Properties	<ul style="list-style-type: none"> The PCM should be chemically stable, compatible with container and non-corrosive for its effective containment and from safety point of view it should be non-flammable, non-toxic and non-exploding. PCM should not degrade chemically after repeated use to be durable.
5	Economic Properties	<ul style="list-style-type: none"> PCM selected should be low cost, easily available and should exhibit good environmental performance to be acceptable for commercial application.

Table III
Comparison of Thermo-Physical Properties of Some PCMs [14]

PCM Type	Melting Point (°C)	Heat of Fusion (kJ/Kg)	Thermal Conductivity (W/m-K) (Liquid/Solid)	Density (Kg/m ³) (Liquid/Solid)	Specific Heat (kJ/Kg-K) (Liquid/Solid)
Paraffin	27-29	245	0.2 (liquid)	770/880	2 (liquid)
OM35	35	160	0.16/0.2	870/900	2.71/2.31
HS29 (Inorganic)	26-29	190	0.55/1.05	1530/1681	2.62 (liquid)
Paraffin wax	44	174.12	0.13 (liquid)	783/830	2.53/2.44
S 89	89	151	0.670	1550	2.480
Gallium (Metallics)	30	80.3	-	-	-

C. Containment of PCMs

PCM containment or encapsulation is required to contain the material in liquid and solid phases both without leakage or change in its thermo physical properties. PCM container should also ensure that its chemical composition is not changed by reacting with the container material or environment. The method used should make it more compatible with other materials used or make it suitable for its intended application in terms of shape, size and handling as well as efficient heat transfer. Two major types of encapsulation techniques used in various TES application are Macro-encapsulation and Micro-encapsulation.

The main characteristics desired from its containment system is more effective heat transfer as its heat storage density is higher compared to SHS systems. To enhance the heat transfer properties or thermal conductivity of PCMs different methods are used like inserting fins, mixing high conductivity particles, using metallic foams, carbonic foams, heat pipes inserted inside PCM and HTF, fibbers inside PCM, direct contact HX, rolling cylinders etc [15]. The most common strategy i.e., macro-encapsulation uses various geometries or shapes like tube, sphere, panels, cylinders or other shapes depending on its applications (Fig 5). Thermal performance of PCM also depends on the material selected for encapsulation like plastics or HDPE, aluminium, steel etc which also depends on chemical stability or compatibility of PCM and containment material. Whereas the Micro-encapsulation techniques are the latest trend which involve containment of PCM in microspheres of very thin and high molecular weight polymers of diameter less than 1mm. These spheres are then added to a compatible materials used in intended application like concrete, wall panels etc. For building applications, PCMs can be incorporated into its envelope by different methods which are listed in Table 4 [14].



Fig 5. Various methods of PCM containment.

Table IV
Methods of PCM Incorporation In Buildings

S No	Classification of Methods	Methods of Incorporation
1	Direct Incorporation	<ul style="list-style-type: none"> PCM added directly into construction materials like Gypsum mortar, cement mortar and concrete mix. Easiest and most economical. Leakage and weakening mechanical properties are major drawbacks.
2	Immersion	<ul style="list-style-type: none"> A porous construction material is immersed into liquid PCM. Leakage, incompatibility and corrosion are the problems faced.
3	Encapsulation	<ul style="list-style-type: none"> Most suitable and widely used method. Material used should prevent leakage, retain all thermal properties, do not react with PCM, provide structural stability and safe handling, protection from environmental degradation , provide good thermal conductivity and mechanical strength and should be compatible with intended application of PCM. Shells, tubes, channels, thin plates, pipes, panels and foils of aluminium, copper, HDPE and stainless steel. Micro-encapsulation of micro-sized PCMs in polymeric materials.
4	Shape-Stabilised	<ul style="list-style-type: none"> Contains PCM in a carrier matrix Provides better thermal conductivity, high specific heat and retain shape over many cycles. Expensive
5	Form-Stabilised	<ul style="list-style-type: none"> Advanced method of incorporation using composite materials. Could retain large amounts without leakage. Expensive and highly reliable.

D. Performance Enhancement Techniques

A large no of methods are being developed to improve the heat transfer characteristics of PCM based TES systems. Work is undergoing on methodologies like PCM-based thermal control units (TCUs), and concepts like inclusion of conducting paths or materials in the PCM storage volume such as metallic matrix or foams, micro- and nanosized metals, metallic fragments and metal oxide fillers, pins and fins, carbon nanotubes, carbon fibres, graphite and exfoliated graphite (graphene) [16].

The major drawback of many commonly used PCM materials is low thermal conductivity which effects it performance as it effects melting of PCM and thereby transfer of latent heat. It varies between 0.15 to 0.3 W/mK for organic PCMs and 0.4 to 0.7 W/mK for salt hydrates. A large no of methods of heat transfer enhancement have been studied for improving thermal properties of PCM materials. Two most common methods are application of finned surfaces and addition of porous matrix structures having higher conductivity into the heat storage medium or PCM material [42]. Fins used for improving thermal conductivity of PCM can be of metal like aluminium in case of organic PCMs having different configuration and shapes like rectangular or circular. Enhancement techniques using embedded high conductive structures include metallic slags or chips, stainless steel tube pieces, copper tube pieces, , matrix of expanded graphite(MEG), composite of exfoliated graphite (EG), carbon fibres brushes, compressed expanded natural graphite (CENG) etc. All the above latest techniques provide an opportunity to enhance heat transfer in TES systems if reliable contact between the composite materials and heat exchange surface.

III. POTENTIAL DEFENCE APPLICATIONS

A. General Application

The application of PCM has grown rapidly over recent years with increasing proliferation of renewables and its dependence on TES systems as well as growing trend for searching sustainable environment friendly solution to counter global warming. Some of the well-known applications of PCM are solar cooling and solar power plants, temperature control in PV solar systems, thermal management electronics and batteries, waste heat recovery, solar dryers, space heating and DHW, preservation of food and medicines and aero-space systems. PCM can be integrated into buildings for improvement in energy performance and thermal comfort or designing net zero energy buildings. [17].

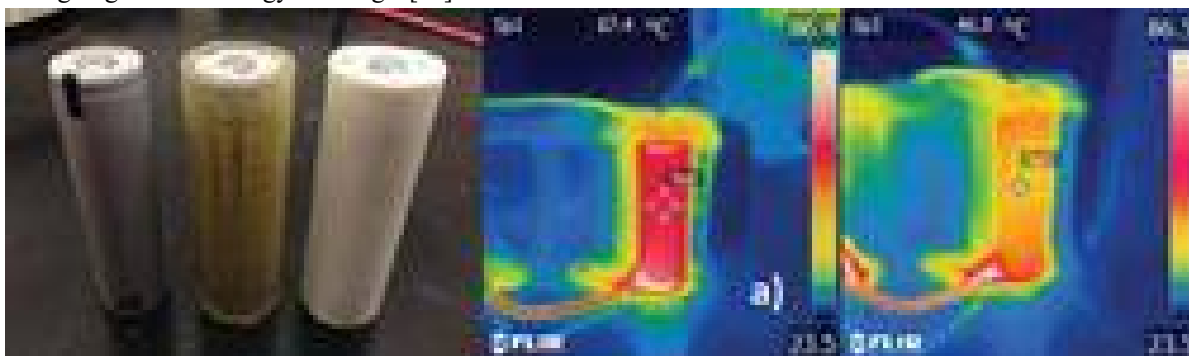


Fig 6. Passive Thermal Management of 18650 Li-ion Batteries using PCMs. IR images of (a) Batteries without PCM experiencing 67°C; and b) with PCM sleeve experiencing 47°C after a 17-minute discharge [42]



Fig 7. PCM Li-ion Battery Cooling Jackets for passive thermal management of the batteries between 20-40°C [24]

High Temperature Heat Storage Devices are being developed using silicon as PCM (melting temp 1414 °C) by for storing excess solar during daytime and use the same heat during night for electricity generation. It is the most promising type of ES system as it has an energy density higher than Li-ion batteries and can store much more energy in lesser space [18]. The major challenge in the adoption of this technology is handling of very high temperatures on which the work is going on with some success.



Fig 8. Thermal Barriers developed by PCM Products Ltd, UK for protection of heat

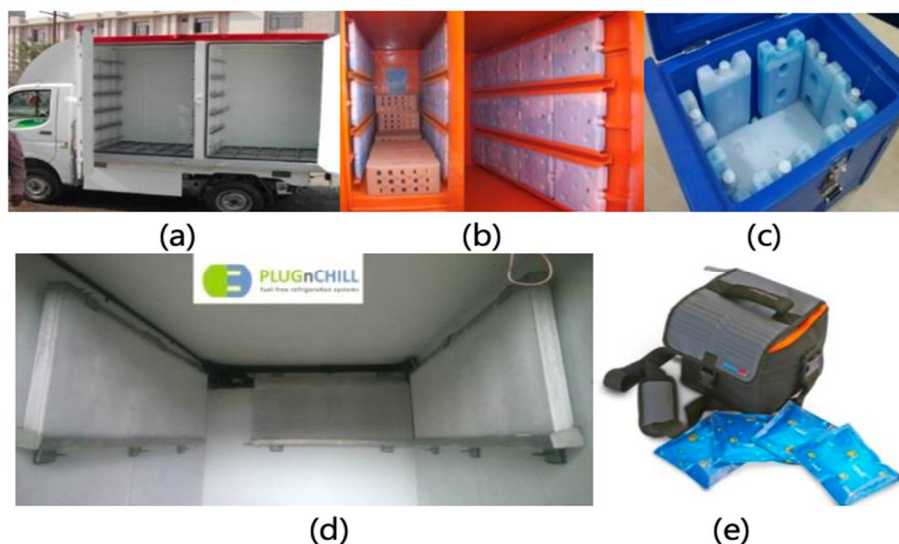


Fig 9. Commercially available PCM-based cold chain solutions for transportation and packaging by PLUS Advanced Technologies. (a) and (b) PCM panels installed in Reefer trucks for passive cooling; (c) Insulated box lined with PCM for delivery of frozen and refrigerated products; (d) PCM along the walls of a reefer truck charged for 5 hours before proceeding for temperature- controlled delivery for 20 hours; (e) PronGo – refrigerator on the go for transport of frozen and refrigerated goods for up to 5-10 hours [22]

Other major commercial applications of PCM based TES for provision of thermal comfort in buildings are absorption air conditioning, free cooling, passive cooling in light weight buildings or shelters, Fabricated TES like Gypsum sheets, PCM filled thermal blankets and solar heat storage for room heating. Another important application is in maintenance of cold chain during transportation and packaging for preservation of frozen food items, vaccines, and some critical medicines. PCMs are widely used for backup cooling in Cold storages, marine applications, display cooling and thermal management of telecom shelters (Fig 11) in remote locations [19]



Fig 11. Thermal management in telecom shelters using HDPE panels and aluminum pipes filled with PCM and stacked neatly.

B. Applicability of PCM for Military Requirements

As security forces carries out its operation in tough terrain having harsh weather conditions the thermal storage capacity of PCMs can be effectively utilised for protection of its critical equipment having sophisticated electronic circuits whose performance gets degraded under extreme temperatures. PCMs can be effectively utilised for heat management of advance war equipment like surveillance radar, latest weapon systems with sophisticated electronics, communication systems, aerospace systems and missile storage facilities having heat-sensitive electronics, microprocessors, sensors etc. [20]. Under extreme climatic conditions if PCMs are used for heat management it can help in improving the mission reliability of such sophisticated war equipment and aerospace systems. PCM can be used for thermal management of batteries in extreme cold climates where performance is degraded at low temperatures.

Extensive work has been done by Defence Lab, Jodhpur (DRDO) on R&D programme for developing PCM devices to counter extreme hot climates of desert sector on western frontiers and improving reliability of mission-critical defence components during operation. DRDO has developed metal eutectic alloys of Pb-Bi-Sn-In-Cd with melting points between 46 to 120°C along with a high capacity heat sink for heat management of critical electronic devices [21]. DRDO has developed a patented PCM which has better phase-reversal and stability problems in harsh desert climates compared to other commercially available PCMs which has been tested in a prototype cabin. This cabin was able to provide a relief of 8-15 °C when compared to unlined cabins. Additionally, it was observed and stated that, being a hydrogenous material this PCM is a good neutron absorber also, hence can be used to provide shielding against radiation in Armoured Personnel Carrier (APC) and Nuclear Bunkers[20]. DRDO has also developed PCM based Cool Vests and caps having a weight of 1.5 to 2 Kgs with removable PCM packs which can be charged by placing in refrigerator. These vests were able to provide thermal comfort to troop for up to 2 hours during extensive field trials have been conducted with Border Security Force (BSF) troops deployed on BOPs, inside cabin of AC (Russian BMP) and inside the Individual Protective Gear NBC-IPG. DRDO is further working on a futuristic technology of solar energy well to use waste energy/solar energy to partially meet energy requirements of Defence forces and has been able to develop a special PCM slurry having higher heat storage capacity than water [21].

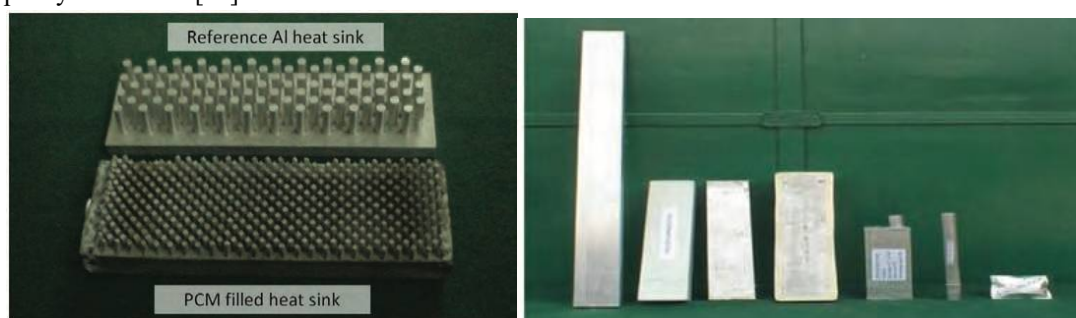


Fig 8. PCM based aluminium heat sink and PCM panels developed by Defence Lab, Jodhpur [21].

Another important application is wearable PCMs using for extreme climatic conditions like cool vests, jackets, helmets, underwear to reduce sweating, gloves, shoes etc. for hot climates and use of thermal barrier inside armored vehicles like tank where inside temperatures rise to extreme levels in such hot climatic conditions. PCM layer can be integrated with armored plate of bullet proof ballistic vests to provide thermal comfort to security personnel wearing thereby improve their effective deployment.



Fig 10. Commercially available PCM cool vests and pouches.

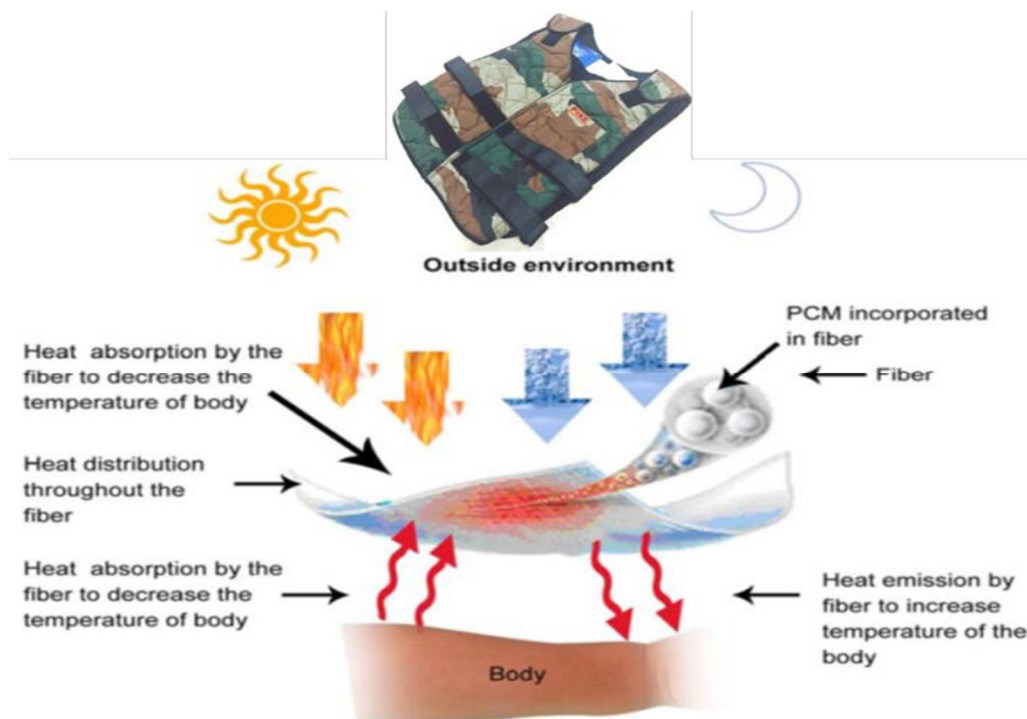


Fig 7. Thermodynamics of PCM Cooling Vest Jacket [22]

Tan & Fok [23] presented a conceptual design for PCM cooled helmet through simple calculations using thermal resistance networks. The proposed design can be implemented in military helmets to provide cooling of the head for about 2 h for security personnel deployed under extreme climatic conditions.

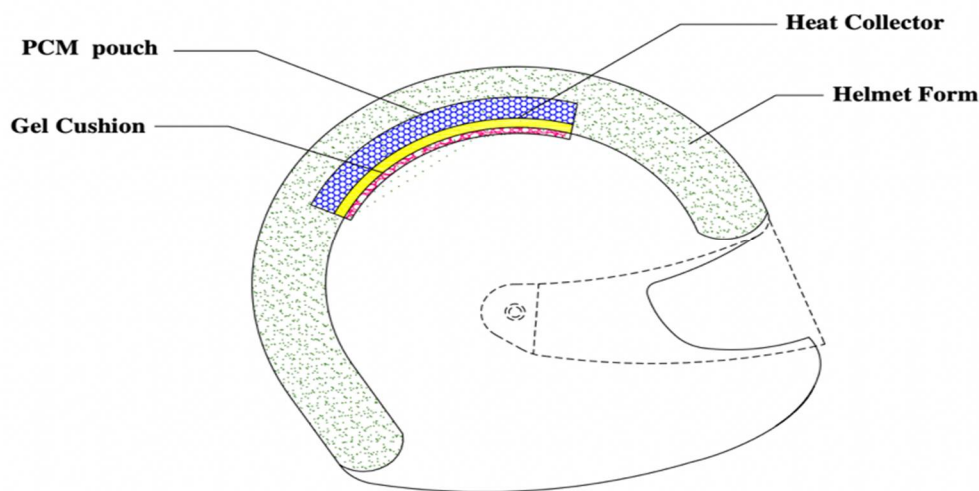


Fig 8. Concept design of a PCM integrated helmet [24].

PCMs can also be used to store heat generated in vehicles for utilizing it to counter cold starting problem. The heat stored can also be used for providing thermal comfort to the operator or drivers working in extreme cold conditions. In order to improve cold starting performance at very low temperatures have been proposed like glow plugs and air heaters in air intake lines. Kaya et al [24], proposed the design of an heat exchanger Fig [9], and tested the experimental setup using hot water to simulate various temperatures to increase the cold start performance and improve the exhaust emission characteristics of a two stroke diesel engine. It was reported that increase in temperature of intake air using PCM at 45-51 °C melting temperature assisted in improving the cold start performance, reducing the starting time as well as improved the emission characteristics.

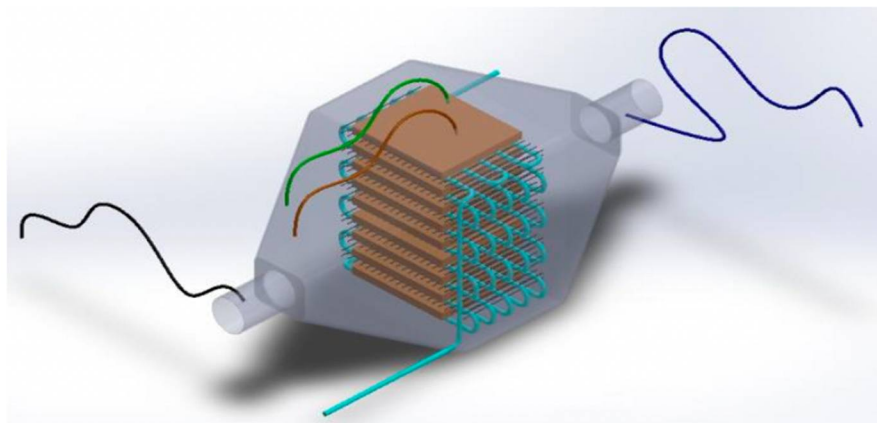


Fig 9. Heat Exchanger designed for cold starting of a two-stroke diesel engine. [24]

A report on Diesel Engine cold start improvement using thermal management techniques, was published on October 2000 by University of Dayton Research Institute prepared for U.S. Army Research Office [25]. The aim was to develop a passive thermal protection system based on PCM to reliably re-start the Diesel Engine of a US Army 5-ton tactical truck after exposure to cold weather for a period of at least 12 hours. The study was conducted with the PCM applied to the oil pan (maintained at $+50^{\circ}\text{F}$) and filter which resulted in a successful concept demonstration of thermal management systems capable of maintaining elevated temperatures of the oil pan or sump Fig 9. During cold start tests conducted after overnight cold exposure (13°F), the engine with the PCM applied to the oil system started faster and required much less cranking energy from the batteries than the baseline engine under similar conditions. Similar approach can be adopted to prevent overheating of engines when operating vehicle and plant in extremely hot climatic conditions.

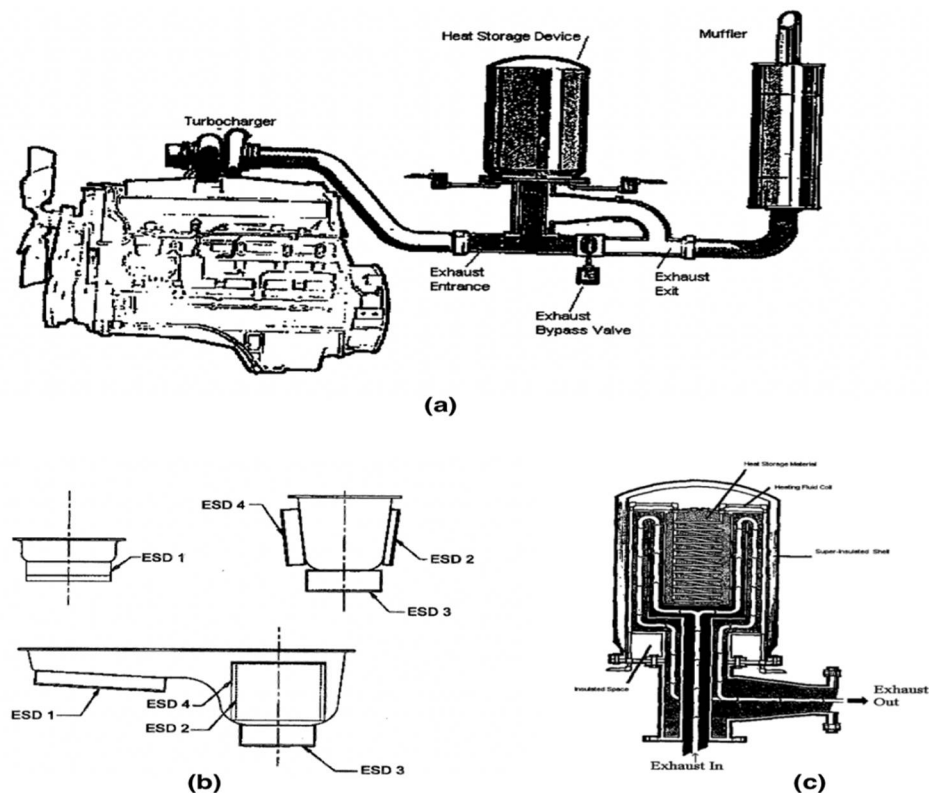


Fig 9. PCM based engine heating device for improving cold starting characteristics (a) Sander's engine Heating Device on Diesel Exhaust [26], (b) Layout of PCM energy storage device installed on oil pan [25], and (c) Sander's Engine heating Device (cut section) [26].

Another potential PCM applications in various military vehicles is its use for thermal buffering of heat generated by electronic devices as well as provision of thermal comfort to security personnel by providing thermal buffering for cabin climate system. Eduard Oró et al, [27] experimentally demonstrated the benefits of implementation of PCM inside cars and was able to maintain lower interior vehicle air and steering wheel surface temperatures by integrating PCM RT-27 (Rubitherm) in the roof. Fig 10 presents air map temperature of the vehicle at different times.

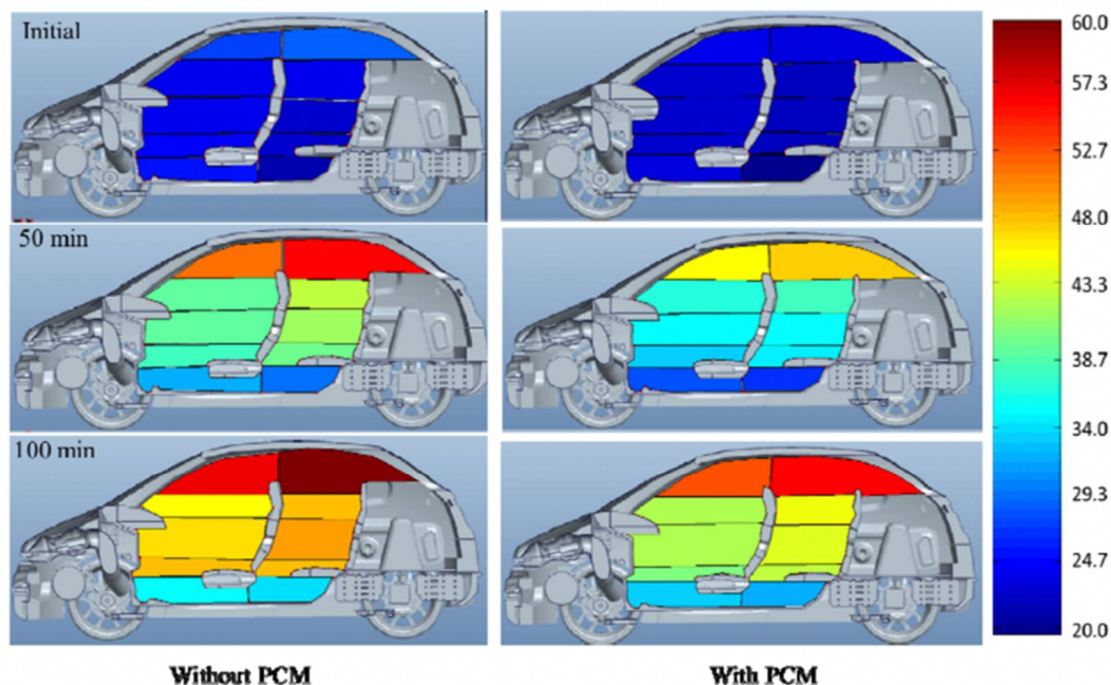


Fig 10. Air temperature map of car with and without PCM integrated in roof [27].

Thermal blankets and mattresses using PCM can be used in high altitude areas where temperature go as low as -20 to -40°C . PCM based cookers are also being developed to store heat generated by PV panels and use the same heat for cooking during periods without solar.

C. PCM Application in Military Buildings

As discussed, earlier Security forces are deployed at locations having extreme climates most of the times having no connectivity to grid being deployed at remote border areas of hot deserts in west or extremely cold high-altitude areas in north. Therefore, it becomes imperative to adopt alternative and sustainable methods like renewables for meeting the energy demand of military deployed at such locations. PCM integration in buildings provide a suitable method of providing thermal comfort and improving the thermal performance of light weight PUF (Poly-Urethane Foam) insulated shelters (used both in hot and cold climate) and dome type FRP (Fibreglass Reinforced Plastic) shelters (used in cold snow-bound areas) Fig 11.

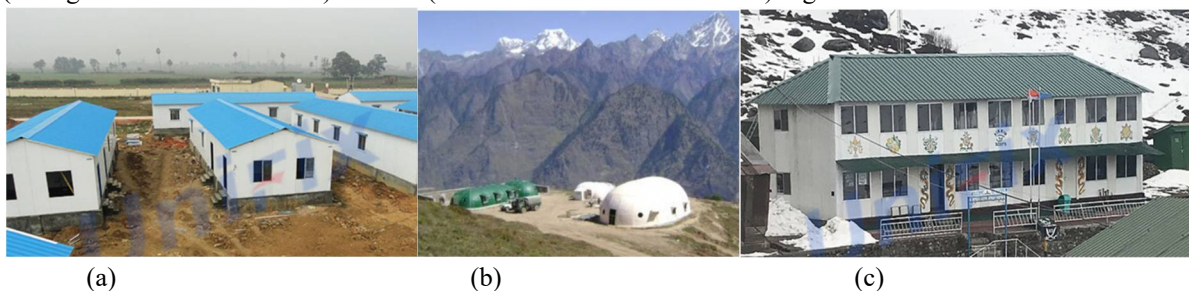


Fig 11. (a) Polyurethane Foam (PUF) Insulated shelters in plains, (b) Fibreglass Reinforced Plastic (FRP) shelters in high-altitude areas and (c) Double storeyed PUF shelters in snow bound high-altitude area. (Pictures taken from internet)

The traditional permanent building structures use thermal storage in form of high thermal mass which can store large sensible heat thereby providing thermal comfort to its occupants. This advantage is not available with prefabricated shelters used by security forces under extreme climatic conditions which are light weight as their thermal inertia is low [Fig 12]. As these shelters take minimum logistic effort and time for erection as compared to permanent structures hence are preferred over permanent structures for accommodating the security personnel. The thermal performance of these shelters is limited being light weight and is totally dependent on the artificial insulation provided like PUF insulated shelters. Another method to improve thermal performance of these shelters is integration of PCM with existing building envelope or improving the efficiency of the heating or cooling systems by integrating PCM thermal storage methods.

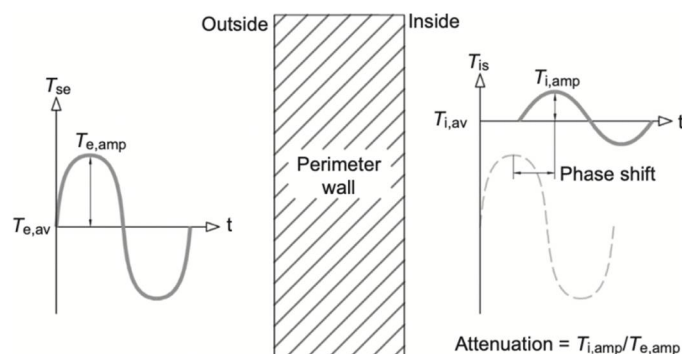


Fig 12. Thermal Inertia of a wall.

This work list some of the suitable methods for use of PCM for maintaining thermal comfort in military buildings. PCM integration not only improves the thermal efficiency, but it also helps in adopting renewable sources of energy by overcoming their biggest hurdle of being intermittent. The renewable energy available during the day can be easily stored in PCM based TES and can be utilised at a time in night or day when it is required. As the global energy demand is consistently increasing, it is a need of present times to adopt renewable energy and reduce energy consumption by adopting efficient methods of heating and cooling in the building energy sector. Over the years, the use of Thermal Energy Storage (TES) with solar energy systems has been verified to reduce efficiently the excessive usage of fossil fuels in building energy systems. Various advantages of using PCM in buildings has been listed in Fig 13.

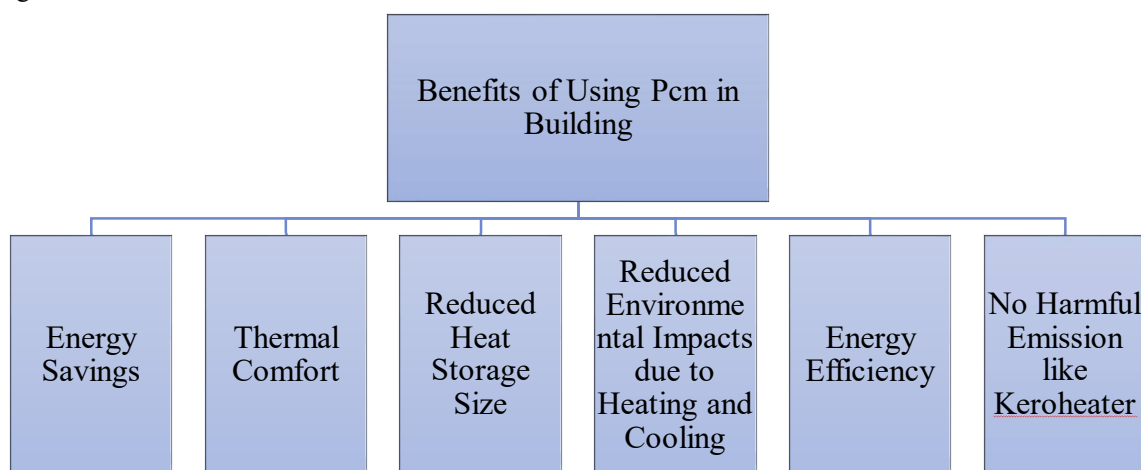


Fig 13. Benefits of PCM integration in buildings.

TES plays an important role in a wide range of industrial and residential applications to improve the efficiency of the power generation systems and to provide grid stability to power supply at a suitable cost. A vital purpose of TES can be found in its use to reduce peak loads in HVAC systems. PCM thermal storage could help in conserving energy and maintain thermal comfort for security personnel in extreme weather conditions in Pre-fabricated shelters. Integration of pcm in building walls/envelope for maintaining thermal comfort has certain benefits like energy savings, thermal comfort for security personnel, improved building life due to reduced thermal stress, reduced environmental impact and energy efficiency.

PCM can be used to increase thermal inertia or thermal mass of perimeter or partition wall panels of military light weight shelters using multiple methods like, using wall lining or false roofing of PCM impregnated Gypsum boards or encapsulated PCM panels fixed to inner lining of the shelters. PCM can be integrated with insulation material in form of micro encapsulated, form -stabilized or macro encapsulated form. Another method is to use PCM integrated with windowpanes or glass bricks, pouched mats, panels, rusticated mats, bags, and blocks. The PCM integrated in building envelope acts as a TES and helps in improving efficiency and effectiveness of HVAC systems and Renewable Energy systems.

The application of PCM TES for cooling application has limited applicability being either used in integration with HVAC systems or as passive application when integrated with building envelope. The use of passive method has been able to reduce the indoor temperatures by 4 to 5 °C [36] which is a considerable drop considering the high temperatures encountered in western front of the country. But the technology is in a very nascent stage and is barred by the inherent disadvantages of flammability of organic PCMs and incompatibility of hydrated salt PCMs with metals. Therefore, from military perspective there is no major advantage except for improving the efficiency of HVAC systems, that can be achieved at this stage of the technology. Hence the focus of this review will remain the potential heating applications based on PCM TES for shelters used under extremely cold climatic conditions.

- 1) *Methods for heating of shelters under Extreme Cold Climate:* Application of PCM TES in buildings for providing thermal comfort to occupants has been a widely researched topic in recent years. The integration of PCM can be in form of passive system which depends on weather condition or ambient temperature or an active system when PCM TES is used in integration with HVAC system to improve its efficiency. Faraj et al. [35] has listed various heating applications based on PCM TES which is listed below in Table 6.

Table VI
Methods of PCM TES Integration for Heating of Shelters.

S No	Classification	Methods of Integration in Buildings
1	Passive Methods	a. Integration in Building walls. (i) Bricks/Concrete/Stones (ii) PCM Wall Boards (iii) PCM plaster mortar (iv) Thermal Insulation b. Floor c. Ceiling d. Trombe Walls e. Solar Façade
2	Active Methods	a. Under Floor Radiant Heating Systems b. Solar Air Heaters c. Solar Water Heaters d. Solar Heat Pumps e. HVAC Systems f. Solar Domestic Hot Water Systems g. Ventilated Facades.

- 2) *Passive Methods for Heating of Shelter:* Looking at these applications with military perspective the gain in energy efficiency achieved by passive applications is not of importance as the results achieved can not be seen as a solution to the heating requirements for light weight shelters under extreme cold conditions. Therefore, we have listed certain methods of integration of PCM TES which are beneficial from military perspective. One of the most important characteristics of PCM TES is the peak shaving or overcome the problem of intermittency of renewable sources of energy like solar energy. Keeping these two properties certain PCM TES applications for heating of shelters under extreme cold weather are listed here.
- 3) *PCM TES integration with Existing Heating Mechanisms:* The armed forces personnel deployed under extreme cold climates are dependent on fossil fuels and wood burning to meet their warming and heating requirements including Daily Hot Water (DHW) requirements, as they are dependent on off-grid methods like, Kero-heaters, Bukhari or Wood stove or Oil-Bukharis with chimney and kerosene /LPG stoves. The use of fossil fuels and inefficient burning of wood not only results in GHG emission but also adversely effect the respiratory health of security personnel dependent on these methods of heating. Another major drawback of Keroheaters and Bukhari or wood stoves is that it cannot be used unattended or while sleeping as these methods are prone to fire- hazards and Carbon monoxide poisoning during sleep [Fig 12].

The use of keroheater has more severe effects on respiratory health as in absence of chimney, all the harmful gases generated during burning of kerosene stay inside the room, in absence of proper ventilation it may lead to carbon monoxide poisoning which can be fatal. However the most commonly used method for room heating adopted by armed forces is keroheater being cheap and need no additional logistic requirements.

James L Woodring et al, [28] measured and examined the combustion product emission from unvented keroheaters of both types convective and radiant using different types of fuels 1-K, 2-K (both kerosene) and Ether. It was observed that unvented keroheaters produce air contamination in excess of air quality standards. NO_x, Sox, CO₂, CO and Formaldehyde particulates levels exceeded recommended levels if ventilation is insufficient. It was also observed that ventilation can lower the concentration of emissions products by providing extra dilution air flow. But increasing ventilation air depends on the size and capacity of keroheater and beyond a point, the system will be uneconomical to use and will inefficient both in terms of fuel consumption and heat generated.

A similar study by Gregory W. Traynor et al, [29] examined that kerosene heaters can emit polycyclic aromatic hydro- carbons (PAHs); nitrated PAHs; alkylbenzenes, phthalates; hydro-naphthalene; aliphatic hydrocarbons, alcohols, and ketones; and other organic compounds, some of which are known mutagens. Exposure to these emissions for a long duration above the prescribed limits can be harmful, hence it is pertinent that we should look for cleaner alternatives for room heating for armed force personnel deployed in extreme cold conditions in high altitude areas where oxygen levels are below normal the effects of these harmful emissions get magnified.



Fig 12. Heating devices used by Armed Forces for off grid room heating, (a) Unvented Convective Keroheaters, (b) Unvented Radiant Keroheaters and (c) Hazard of unintentional Carbon Monoxide Poisoning [31].

Use of Bukharis or wood stove with a chimney is less harmful in terms of emission inside the shelters but the system is inefficient as excess heat generated initially (due to batch combustion is lost) to the environment and no control mechanism for controlling heat generation exist. The drawbacks of using wood which is non-renewable and uncontrolled burning can be partially overcome by use of biomass pellets which is a renewable source of energy and is manufactured using agricultural waste (crop stalk and straw material, rice husk, cotton stalk, coffee husk, alfalfa straw, coconut shell, palm shell, sugarcane bagasse, etc), forestry residue (sawmill residue, branches, bark, leaves, etc) and solid waste(junk paper, waste plastic, cardboard etc) [30].



Fig 13. (a) Bukhari or Wood-stove with chimney and (b) The advantages of Biomass pellets [30].

Use of PCM integrated with wood stoves to store additional heat generated during batch combustion of wood or biomass pellets has been studied in details and has shown promising results. The heat stored in PCM integrated not only improves the efficiency of system by storing excess heat but also overcomes its shortcoming of no unattended use or maintaining thermal comfort while sleeping as discussed above. The PCM is so placed around the wood stove that it gets charged during batch combustion of wood and discharges the same heat to maintain thermal comfort over a period of time when burning is stopped.. The batch combustion of wood/ biomass pellet (typical thermal efficiency of 70 to 80 %) yields a transient heat with a high peak heat release often exceeding the actual need, producing more heat than required [34]. As soon as the batch combustion reaches its end the heat released rapidly drops going below the required thermal comfort levels, leading to uncomfortable temperature inside the shelter or room [33].

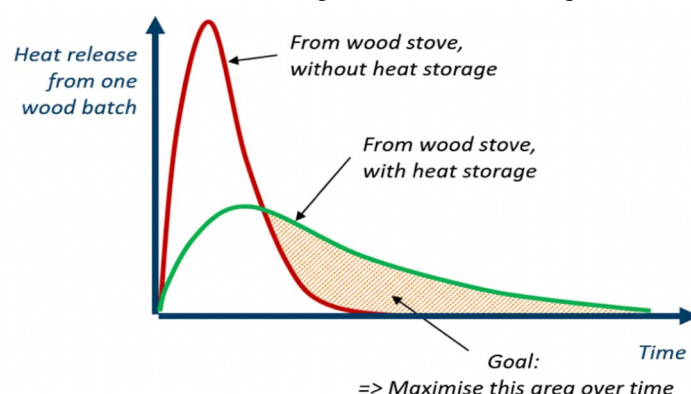


Fig 13. Heat release curve of a wood stove over time[32].

Sevault et al,[32] examined integration of PCM based TES on top of a Wood stove using CFD modelling with an aim of flattening the heat release curve over time by using a compact and durable system based on LHS. The results confirmed that LHS unit enhances thermal comfort as per design goals and observed the need for additional heat transfer features (HTF) to enhance the heat loss to the room. These results were under laboratory validation as of May 2019.

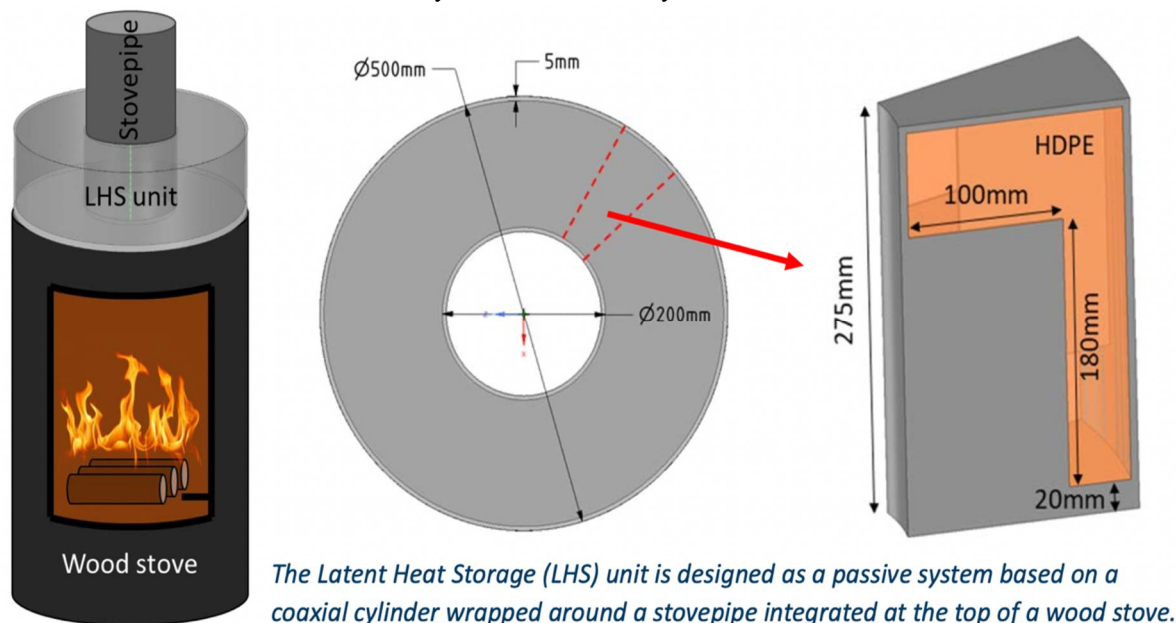


Fig 14. Concept design for integrating PCM based heat storage system or LHS on top of wood stove[32].

In another study, Sevault et al, [33] numerically studied an LHS system using Erythritol (PCM) with melting temperature within 100-150 °C based on a co-axial cylinder wrapped around a stovepipe located at top of wood stove using ANSYS FLUENT 17.2. Various fin lengths inside the PCM cylinder were simulated to keep PCM temperature within degradation range and improve thermal of wood stove by monitoring the slow release of latent heat over a period of 6.5 hrs.

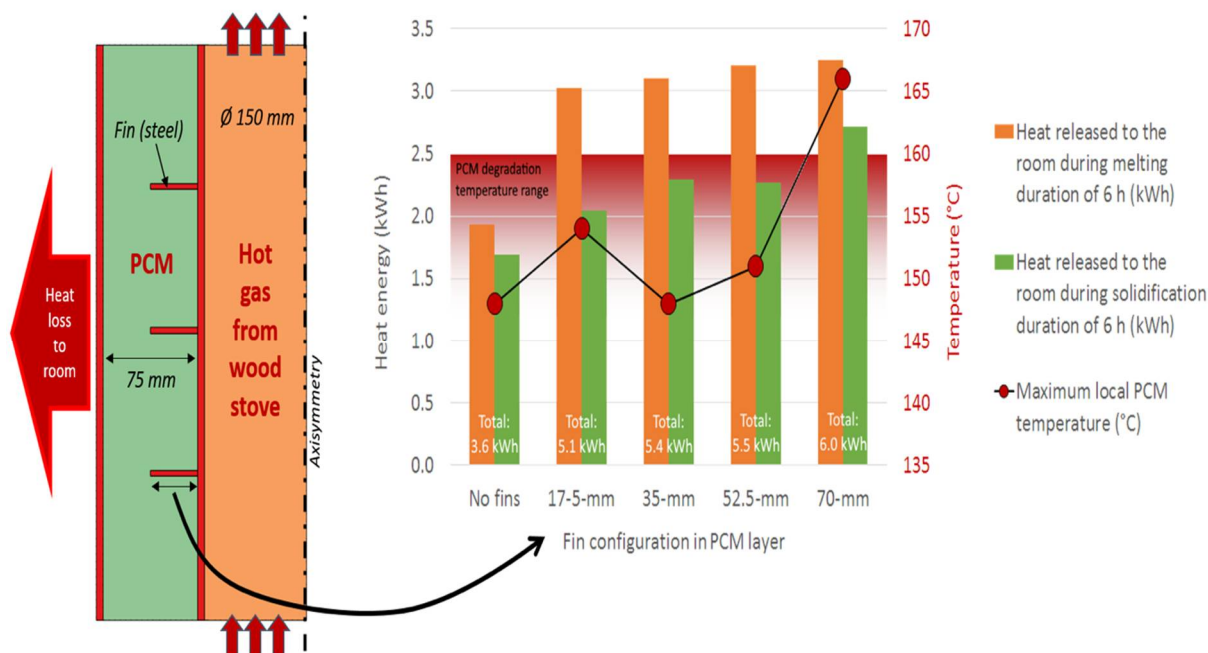


Fig 14. (a) Layout of PCM based LHS and (b) Graph depicting heat energy released using various fin dimensions during melting (left-y-axis) with corresponding maximum local PCM temperature during melting (right-y-axis) and the degradation temperature of PCM is also indicated [33].

4) *Active Methods for heating of shelters:* The PCM TES based active heating application which can be suitably used for heating of military buildings are underfloor radiant heating with PCM filled floor panels, solar water heaters and solar air heaters. The other methods include use of PCM TES for improving efficiency of HVAC systems and the solar domestic hot water systems for provision of hot water for security personnel deployed at high altitude areas having extreme cold weather. Underfloor PCM panels filled with PCM materials integrated either with electric heating coils or heating pipes circulated with hot water from a solar water heater can be used for maintaining thermal comfort temperature inside the shelters [36].

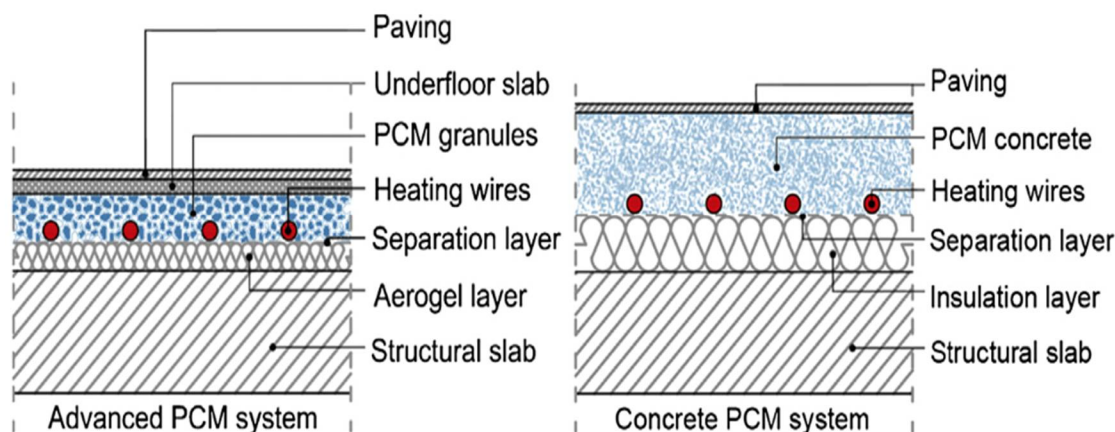


Fig 15. Underfloor radiant heating integrated with PCM TES [36].

Zhou et al. [37] compared different heat pipes and showed that capillary mat (CAP mat) provided better results than poly-ethylene pipes (PE pipes) in maintaining comfort indoor temperature and the discharge time for PCM TES was twice that of a sensible heat TES. Hence it can be said that PCM TES is a highly efficient thermal heat storage system when compared to sensible heat storage system.

The integration of PCM TES systems is effective to overcome the intermittency of solar energy, thereby making it a viable and effective option for HVAC systems and DHW systems. It also helps in rationalising the energy systems at microgrid established at

remote locations in Himalayan region as well as western desert sector. The TES systems based on paraffin based PCMs with phase change temperatures in the range of 40 to 60 °C is one of the most suitable option due to its inherent advantages like easy availability, low cost and high latent heat. Paraffin based TES system can be either used in integration with HVAC system to improve its efficiency or as an independent TES unit coupled with solar thermal collectors to provide continuous supply of heat or hot water as per demand. During day hours the paraffin PCM is melted or charged and the heat is recovered using a heat transfer fluid (HTF) for specific applications[39].

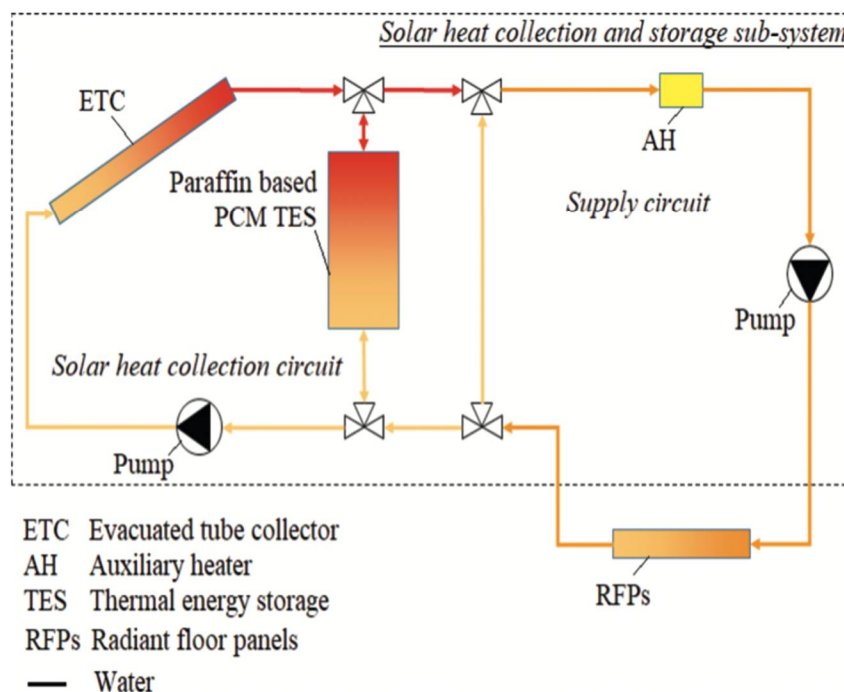


Fig 16. Solar integrated radiant heating system integrated with PCM TES[39].

Figure 16 shows a paraffin based PCM TES system which uses radiant floor panels for space heating and a PCM TES unit is used to store heat in for hot water. During day time TES unit is charged and heat is retrieved by circulating the hot water through radiant floor panels for space heating during night or whenever required. The hot water temperature to be circulated is controlled by controlling the fraction of mixing return water and space heating demand is met by varying the flow rate. It is also possible to achieve space heating using other types of radiators by circulating hot water as HTF as shown in fig 17.

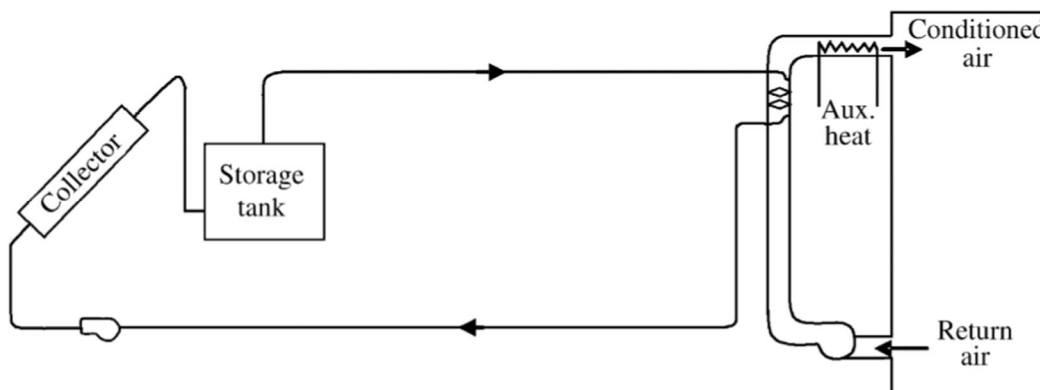


Fig. 17. A schematic diagram of the basic solar energy system [42].

Nallusamy N et al. [40] studied a combined sensible and latent heat unit with spherically encapsulated PCM inside a water tank for DHW application using Paraffin with melting temperature of 60°C as shown in fig 16. It was concluded that combined system with both sensible and latent heat storage gives better performance than SHS system additionally it was also found that batchwise recovery of hot water or discharging of TES give better performance than continuous process to recover stored heat. A similar setup with multiple PCM in form of cascade system can be designed to improve the dynamic performance of TES system

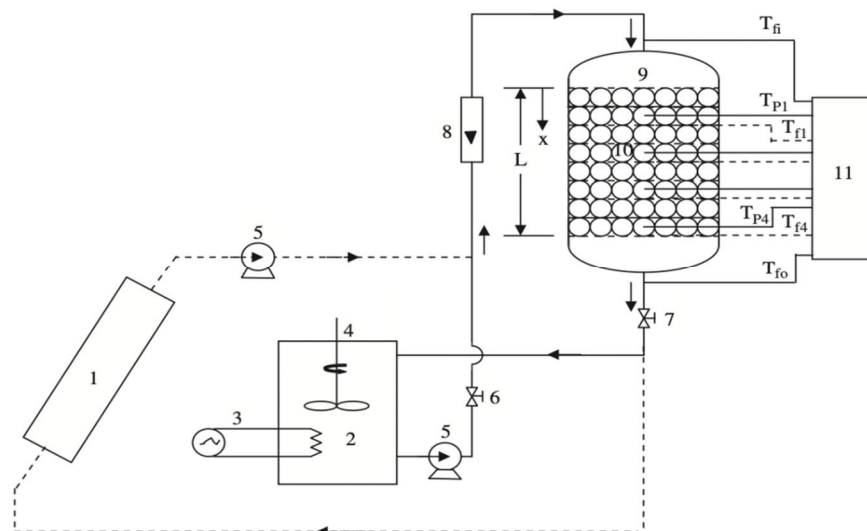


Fig. 16. Schematic of experimental setup: (1) solar flat plate collector (varying heat source); (2) constant temperature bath; (3) electric heater; (4) stirrer; (5) pump; (6 and 7) flow control valves; 8. flow meter; (9) TES tank; (10) PCM capsules; (11) temperature indicator; T_p and T_f —temperature sensors (RTDs) [40].

Solar air heaters integrated with PCM TES system as shown in Fig 17 has certain inherent advantages like, no requirement of water pump, does not freeze at very low temperatures and no heat loss in plumbing. The method of charging and discharging of PCM TES remains same, but due to above advantages air has been widely investigated as HTF in PCM TES systems integrated with HVAC system or integrated with solar air heaters directly. Strithet et al. [41] investigated a PCM TES system placed inside duct with solar air collector and a fan as shown in Fig 17 using numerical model using TRNSYS and validated with experimental data. It was seen that an annual cost saving of 91% and 93% respectively was achieved with and without PCM TES integrated with a solar air heater system.

All the above heating application using PCM TES overcomes the intermittency of solar energy and helps in making it a workable solution for providing thermal comfort in light weight pre fab shelters as well as provision of hot water in areas having temperatures below freezing point. PCM can also be incorporated in HVAC systems to improve its efficiency but it has a limited applicability considering the remoteness and off-grid locations where military operates.

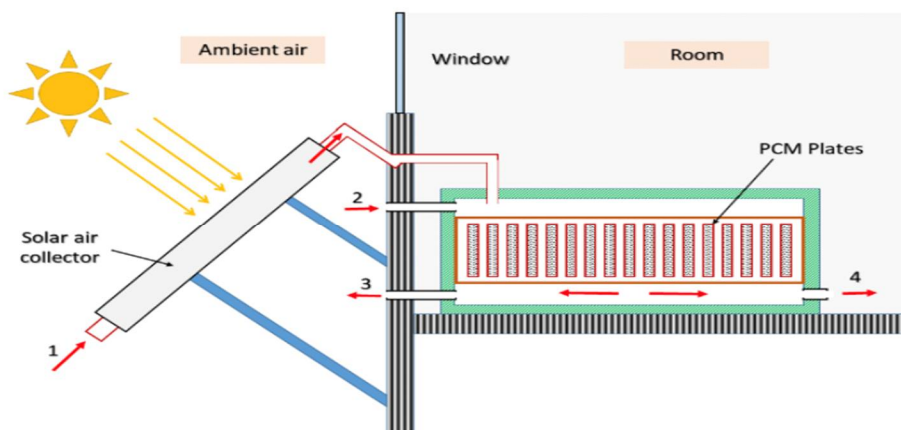


Fig 17. Schematic of Solar Air Heater system [41].

IV CONCLUSION

This study has focused on the potential of PCM materials in providing solutions to various thermal management problems faced by Security forces guarding the vast frontiers of country having harsh terrain and extreme weather conditions. Mostly these places remain disconnected from main grid, hence the aim of this study was to look for sustainable solutions for the challenges faced by Security forces due to extreme hot and cold temperatures. The challenges related to the malfunctioning of sophisticated electronic equipment as well as the starting and overheating troubles related to vehicles and plants were discussed. Thermal comfort of security personnel in such extreme weather conditions was also discussed both in terms of individual thermal comfort using wearable PCM jackets and helmet as well as exploring the possibility of making solar a viable option for heating of light weight pre-fabricated shelters.

Application of PCM TES system can help in overcoming the intermittency of solar which is available in abundance across the country and thus it can help in providing a sustainable solution to heating requirements of security personnel located at off-grid and remote locations in high altitude areas having extreme cold conditions. There is a possibility to develop such modular PCM TES tanks which are portable and can be connected in series to increase its capacity, providing hot water and space heating solution at locations having sub-zero temperatures. PCM is a promising and evolving technology for future having limitless potential in providing solution to challenges encountered under extreme climatic condition by Indian armed forces.

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