

THERMAL ANALYSIS OF SPENT NUCLEAR FUEL TRANSPORTATION CASK SHIELDED WITH PHASE CHANGE MATERIAL

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Abstract - The "Closed Fuel Cycle" model, in which spent nuclear fuel is viewed as a resource, has found support in India. The methods used in India to handle nuclear waste are equivalent to those used elsewhere and adhere to International Atomic Energy Agency (IAEA) regulations. In accordance with the waste management procedures, Cat-III and Cat-IV high beta-gamma (alpha and non-alpha) waste canisters must be temporarily stored inside designed storage vaults. Depending on the radioactivity of the canisters, they are eventually disposed of in safe concrete tunnels or deep geological repositories. However, since this nuclear waste is radioactive in nature, transporting it from the facility to the dump yards or vicinity has proven to be a major obstacle for many studies. Contact with this waste can cause serious bodily harm as well as cell damage to any nearby living things. In this research, we look at how to make a nuclear waste storage container that can endure extreme heat, pressure, and shock. Researchers examined the thermal conductivity, compressive strength, and latent heat of different PCM materials to discover which is most efficient for carrying nuclear waste barrels.

Keywords: Closed Cycle Fuel, International Atomic Energy Agency, Peak Cladding Temperature, Phase Changing Material, Radioactivity, Storage Cask.

1. Introduction

Parts of uranium-containing fuel that have been utilised in commercial nuclear reactors but no longer have enough energy to support a nuclear reaction are referred to as spent nuclear fuels. As the old fuel is removed from the reactor, the fission process stops, but the spent fuel assemblies continue to produce a lot of heat and radiation. Transporting spent fuel in containers or barrels that block radiation and distribute heat is necessary due to the ongoing risk [1-2].

Numerous commercially generated spent nuclear fuel shipments have been transported throughout the nation over the past 30 years without endangering the environment or the general public's health. The majority of these exports are moved among reactors managed by the same utility in order to divide spent fuel storage space, or they might be delivered to a research centre for spent fuel testing [3-4]. As a potential high-level waste landfill is developed, it is anticipated that the volume of these shipments by road and rail will increase in the near future. [5].

With a 220 MW average unit size and a 5.2 GW total installed capacity, India has 20 nuclear power reactors. Just 3.5 percent of India's electricity was

generated by nuclear power in 2013, a record-low compared to the previous high of 3.7 percent set in 2001/2002, when only around 17 TWh of nuclear energy was produced [6]. The updated rules have classed one reactor, Rajasthan-1, as LTO because it hasn't produced any power since 2004. The 1998 nuclear weapons tests stunned the international community and heralded a new era of instability in the region, which included a second set of nuclear tests by Pakistan. The two countries were hit with a number of international sanctions [7]. This situation began to alter with the announcement of the US-India accord by the Bush administration in 2005. After continuous US pressure, the IAEA ratified a "safeguards agreement" with India in August 2008 which was supported by France and Russia. On September 6, 2008, the Nuclear Suppliers Group (NSG), a 45-nation organisation that controls international trade to stop the proliferation of nuclear weapons, granted an exception to its own rules [8]. India is therefore permitted to receive nuclear assistance and conduct nuclear trade with other nations while being a non-signatory to the NPT, having established and maintained a nuclear weapons programme, and rejecting full-scope safeguards. This departure from the previous non-proliferation consensus appears to be driven by

geopolitical and commercial factors. IAEA safeguards are now in place for 14 civilian reactors thanks to India's adoption of an Additional Protocol to its Safeguards Agreement in June 2014. [9]. The Fukushima disaster sparked much more criticism. Before September 11th, "when the fast formation of a large local opposition movement had essentially brought commissioning to a halt," two Russian-made reactors were built in Kudankulam. The commissioning of the reactors, which had been legally contested by citizens' organisations, was made possible by the Indian Supreme Court in May 2013 after finding that the facility is "in the largest interest of the nation, particularly the State of Tamil Nadu." [10]. Another proposal for up to six Russian reactors at the Haripur coastline area has since been rejected by the state of West Bengal. The current five-year plan is for constructing an additional 19 units as well as doubling the installed capacity at this time. M.V. Ramana of Princeton University finishes a landmark historical review of the Indian programme with a question and answer: Is India's rapid and extensive nuclear power expansion, as envisioned by the Department of Atomic Energy (DAE), feasible? Our exploration of the country's nuclear project's history has led us to the conclusion that it is incredibly unlikely, if not impossible, for it to happen. The technological implausibility of the DAE's objectives, its institutional inability to learn from past failures, and local opposition are only a few of the numerous reasons for this judgment [11-12]. The business journal Nuclear Intelligence Weekly put it succinctly this way: "Of course, there's no reason to expect that the government can meet this schedule." Indian nuclear policy has, in fact, always been too optimistic, if not outright absurd. Indian entrepreneurs, on the other hand, have shown effectiveness at swiftly scaling competitive, modular, short-lead-time, renewable technology, mostly in thriving private sector businesses rather than huge state-owned businesses. In terms of cumulative installed wind, concentrated solar (CSP), and solar water heating capacity, as well as overall renewable power capacity (excluding hydro), India ranked sixth in the world in 2013 [13]. Figure 1 depicts the process used to create a fuel assembly.

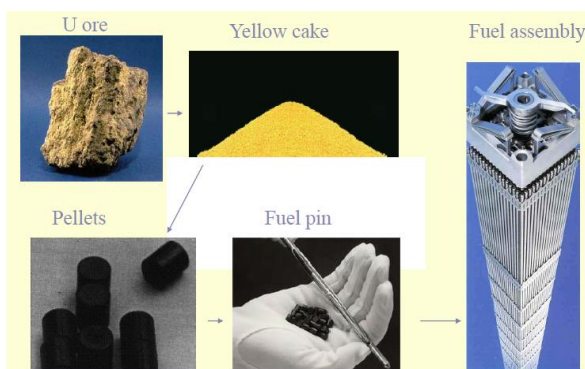


Figure 1: Fuel Assembly setup

1.1 Problems in Nuclear Transportation Cask

Transporting radioactive waste is frequently done using shielded shipping containers. Such a barrel must demonstrate conformity with a temperature test, among other tests, in order for the regulatory authority to approve its design. For the protection of heat energy transmission, thermal shielding is typically offered. Accidental fires that start during barrel transportation could result in melting of the material intended to shelter the casks. The molten substance may spill out in case of mechanical seal failure resulting in thermal shielding loss. Hence, cask has to keep its structural integrity under normal and accidental (fire) conditions, and needs to be qualified with the required code guidelines by the regulatory authorities. However, while having low heat conductivity, organic phase change materials (PCMs) are unable to withstand high pressure due to their significant volumetric change and ease of leaking, which necessitates the use of "leak-proof" packing materials. Thus, there is a need to create a novel thermal shielding for transportation cask by considering crucial conditions of shipping and study the performance under various thermal condition.

2. Literature Survey

2.1. Nuclear Waste Classification

The IAEA has established a commonly accepted categorization system for nuclear waste that considers various waste kinds and disposal choices and provides a helpful starting look at disposal possibilities, despite the fact that it does not specifically mention them, the disposal options for the various waste types are always determined by specific safety evaluations for each discarding facility used. [14]. the sole criterion the IAEA uses to classify nuclear waste is the last or conclusion sites of disposal. Based on the half-lives of degradation, the IAEA first divides radionuclides into two groups: (a) short-lived and (b) long-lived. The half-life of short-lived radionuclides is less than 31 years. The IAEA categorization method divides radioactive waste into five categories: very short-lived waste (VSLW), very low-level waste (VLLW), low-level waste (LLW), intermediate-level waste (ILW), and high-level waste (HLW) [15-16]:

- The radioactive waste known as VSLW can be held for a restricted amount of time to decay with eventual regulatory approval. It typically contains radioactive waste created when nuclear energy is used for research and treatment.
- VLLW can be disposed of in locations with minimal regulatory oversight because it doesn't require a high level of isolation or confinement. A typical VLLW is made up of soil and debris with a

low activity concentration that typically doesn't go beyond 100 times the radioactive clearance criteria. VLLW can also be disposed of with LLW, however in other countries it is disposed of in facilities designed for the purpose, including clay pits with constructed coverings.

- Since LLW contains only a small amount of long-lived radionuclides, it needs to be carefully monitored and kept apart for several hundred years. In the sites for proposed near-surface disposal, LLW is appropriate for disposal (NSDF). Long-lived radionuclides are only found in LLW at extremely small concentrations, which encompass a very wide spectrum of waste. The vast majority of nuclear power plants, research reactors, and medical reactors all create LLW. Although there are less complex solutions for LLW disposal, such as built ditches or concrete vaults where waste containers are placed, NSDFs often utilise this type of disposal. The trash bins are then covered with an engineered or earthen lid to reduce water intrusion. The NSDFs are under observation until the risk from the radioactive waste has decreased to levels that are acceptable (such as clearance). Some nations prefer to dispose of LLW in facilities under the surface or to combine LLW with ILW or spent nuclear fuel (SNF) at deeper facilities.

- While ILW does not require any provision for radiogenic heat dissipation, it does require more isolation and confinement than NSDFs. The ILW necessitates disposal between tens and hundreds of metres under the surface. The idea that ILW should be dealt of at depths more than a few tens of metres is also often held. Co-disposal of ILW with SNF and HLW is a workable substitute in many nations. Although there is no clear distinction between LLW and ILW, many nations have set a limit content for individual packages of long-lived alpha releasing radionuclides at 400 Bq/g on median & up to 4000 Bq/g in compliance with IAEA recommendations. The real boundary-limiting values are determined by the performance and safety study reports in each unique scenario and cannot be generalised to all facilities. Although they are usually site- and disposal facility-specific, allowable average activity concentrations can be significantly greater (tens of kBq/g) for long-lived beta- and/or gamma releasing radionuclides including ^{14}C , ^{36}Cl , ^{63}Ni , ^{93}Zr , ^{94}Nb , ^{99}Tc , and ^{129}I .

- High-level radioactive waste (HLW) is a kind of radioactive waste that results from the radionuclide decay of nuclear waste and generates a substantial amount of radiogenic heat. HLW heat generation levels are often over a few W/m³ for average quantities of roughly one cubic metre, depending on waste volume. It's crucial to consider the likelihood of HLW—nuclear excess with a huge concentration of long-lived radionuclides—when building disposal facilities. The widely accepted option for HLW disposal is deep geological disposal facilities (GDF),

which are buried several hundred metres or more under the surface in stable geological strata. Deep geological disposal facilities (GDF), which are primarily situated several hundred metres or more below the surface in stable geological strata, are the most frequently recognised alternative for the discarding of HLW. The schematic of IAEA radioactive waste classification scheme shown in Fig.2.

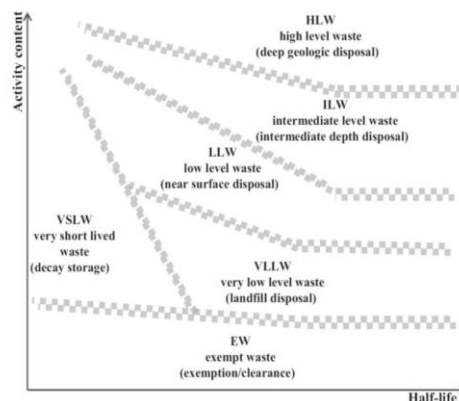


Figure 2: Schematics of IAEA radioactive waste classification [16]

2.2. Phase Changing Material (PCM)

PCMs are fascinating applicants for storing thermal energy because they have the ability to reversibly store & emit a significant amount of temperature during the phase transitional stage. Organic PCMs are perfect for thermal protection application since they have high latent head and poor thermal conductivity [17]. However, the application effect of organic PCM leakage through the solid-liquid phase transition procedure is quite important. To address this issue, form stabilised composite PCMs may be made by integrating PCMs into different porous supporting resources [18]. These porous carbon-based substrates with high heat conductivity, such as expanded graphite, carbon nanotube sponge, and graphene aerogels, are ineffective for enhancing thermal insulation. Examples of porous mineral materials that can be used to load PCMs to create composite PCMs with low heat conductivity include expanded vermiculite, diatomite, and perlite [19]. The PCM leakage caused by macropore exudation after prolonged heat cycling, however, affects porous mineral materials with high PCM loading.

The majority of porous-based composite PCMs reported thus far are powdery, have a low compressive strength, and are typically created through physical combination techniques like solution impregnation or melt infiltration. As a result, for practical use, high compressive strength monolithic form-stable composite PCMs must be directly created in a single process. Monolithic

porous resources with free-standing 3D structures have recently been investigated as supports for the fabrication of monolithic composite PCMs [20]. In order to create monolithic composite PCMs, silica aerogel is the best material due to its low density, great porosity, with physical & chemical properties. The Schematics of PCM has been shown in Fig.3.

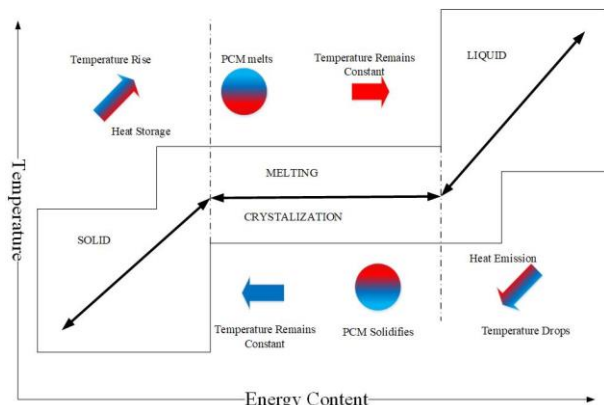


Figure 3: PCM Reaction flow chart

2.3. Transportation Casks

At nuclear power facilities, medium-level waste is cast into concrete or steel barrels after being protected. Depending on the kind of waste, it is then carried in transport barrels with thick (7–20 cm) steel walls. Low-level trash can be carried in common sheet metal containers without the requirement for radioactive protection. Radiation from spent nuclear fuel is quite strong. As a result, it has to be protected when being handled, transported, or stored. The fuel is transferred into a transport cask with a steel wall that is roughly 30 centimetres thick before being transported. This simultaneously defends against radiation and safeguards the fuel element. Copper cooling flanges are installed on the casks' outside surfaces to transmit heat away from the gasoline.

The barrels are built to endure significantly worse handling than is often anticipated during transit. They must meet international criteria, which include being able to endure pressure equivalent to immersion at a depth of 200 metres under water without leaking, a drop of nine metres onto a completely unyielding surface, and more than 30 minutes in a fire at more than 800°C. With huge margins, the barrels meet these standards. For instance, they are capable of withstanding the pressure of immersion to a depth of more than 4,000 metres.

Yumei Xu et al [21] in this work, a finite element model for the NAC-STC cask is created utilising the proper configuration and heat transfer process simplifications. The equivalency approach is offered to define the material properties of the complicated components and gaps. Then boundary conditions are defined by the addition of an analogous convection

coefficient. The temperature field is then collected and analysed using ANSYS software in both normal and accident transit scenarios. The accuracy of the computation is demonstrated by comparing the outcomes of numerical and theoretical calculations. Obtaining the integral distribution laws of temperature as well as the highest temperature readings of all significant components will allow you to evaluate and certify the security of the cask.

Othman et al [22] As an illustration of the suggested design, this work employs the dry storage container (DSC), which is often used in Canadian nuclear reactors. Under various loading conditions, the new UHP-FRC alternative has been designed to have structural stiffness that is comparable to that of the current steel-concrete-steel container. The size optimization approach is utilised to meet the design stresses and construction requirements while also optimising stiffness and decreasing cost. The integrity of the revised design has then been assessed based on actual drop scenarios against accidental drop-impact occurrences. The optimization findings show that the rigidity of the UHP-FRC container (300 mm wall thickness) is 1.35 to 1.75 times more than that of the present DSC (550 mm wall thick). The weight of the container is reduced by more than 60% as a result of using UHP-FRC. The UHP-FRC container performed significantly better in the tested accidental drop impact scenarios compared to the present DSC design.

Schwartz [23] High-level nuclear waste is normally buried in carbon steel containers coated with a 5 cm layer of corrosion-resistant native copper (Cu⁰) and a 35 cm thick bentonite buffer. The copper shield's rate of corrosion is significantly influenced by the auxiliary minerals in the buffer. According to reactive-transport modelling, dependent on the groundwater chemistry, the Cu⁰ corrosion depth is three to eight times superior in a buffer comprising calcium sulphates (gypsum or anhydrite) than in a buffer without calcium sulphates. Iron oxides (hematite, goethite, or lepidocrocite) are not significantly affected by their presence or absence, according to reactive-transport modelling. On the other hand, iron oxides significantly reduce corrosion depth when they are present, according to mineral equilibrium thermodynamics. This theory is maintained by the development of naturally occurring native copper deposits, in which hydrothermal fluids reacted with iron oxide to generate native copper.

Dong-Won Lim et al [24] this study's unique design optimization approach for cask shielding will be used to carry the first time the spent fuel assembly in a prototype SFR. Shielding & barrel weight trade-offs have been created using the PSO approach. In order to prevent an inert sodium area from entering the air-cooling space, the barrel is built as a double-cylinder. Taking into account both the weight and the shielding thickness, the PSO

method produced a shielding thickness of 26 cm. Calculating the radiation dosage of spent fuel extracted during and after a year of cooling allowed us to verify the shielding performance. In order to take a functional issue in a cask drive system into consideration, two distinct fuel locations discovered during transportation were also examined. This investigation comes to the conclusion that the existing cask design, when used normally, complies with regulatory requirements.

Alsmadi et al [25] the shielding characteristics of the greatest popular structurally amorphous metals (SAMs) have remained computationally examined for potential usage on spent fuel dry cask canister applications as coating barriers for corrosion and radiation shielding. The outcomes showed that SAM1651 had the uppermost attenuation coefficients and the lowest exposure rates at low photon energies due to its great elemental content in molybdenum (Mo) and yttrium (Y). As a consequence of its high density (7.6 g/cm³) and elemental manganese (M) content, SAM2X5 exhibited the lowest exposure rates and the maximum attenuation coefficients at high photon energies (Si). The highest iron concentration (52.3%) was found in the third SAM substance, SAM 40, however because to its higher density and other associated components, the results were similar to those of SAM2X5. All three of the studied SAM materials had a fairly comparable Mean- Free Path (MFP) and Half- Value Layer (HVL).

Yi-Sin Chou et al [26] in this study, a high-temperature treatment technique and a K₂CO₃ flux are used to assess the volume loss of perlite. The glass transition temperature (T_g) & weight loss are determined by differential thermal analysis/thermo gravimetric analysis after the perlite has been processed with 0–30 wt% K₂CO₃. With the addition of 10 wt% K₂CO₃, the T_g ranged between 772.2 and 837.10C, with minima at 643.50C. When K₂CO₃ is added, it is shown that the volume reduction ratio (VRR) rises in comparison to pure perlite. In contrast to the VRR of 5.56 without K₂CO₃ at 7000C, the VRR of 11.20 is recorded with 5 wt% K₂CO₃ at that temperature. X-ray photoelectron spectroscopy and scanning electron microscopy are utilized to characterise perlite examples after being heated at 7000C with or without 5 wt% K₂CO₃. Additionally, the suggested heat-treatment method appears to be able to totally preserve the radionuclides found in the perlite RTIW, according to the results of atomic absorption spectroscopy.

3. Comparative Analysis

3.1. Phase Changing Material (PCM)

Phase change materials (PCMs) are substances that, as they melt and solidify, absorb and release thermal energy. A PCM absorbs a lot of heat (energy)

from the surroundings as it melts. On the other hand, once a PCM solidifies, Latent heat, a major source of energy release, is produced. PCMs run through this process continually, which makes them perfect for a range of commonplace applications that need temperature control. Long-term temperature stability and reduced temperature fluctuations are two benefits of PCMs. PCMs are used in a number of industries, including thermal energy storage, HVAC, textiles, electronics, building & construction, and refrigeration. Because they are energy-efficient and environmentally beneficial, PCMs are employed in various applications. Applications for PCM include:

- High-performance fabrics and foams that protect against cold and heat.
- Energy-efficient freezers and refrigerators.
- Long-lasting shipping containers that keep cargo at the proper temperature.
- Construction material that lowers heating and cooling expenses while maintaining comfort in living areas.

There are various PCM products available that are made to withstand a variety of temperatures. Temperatures can range from -50 to +150 degrees Celsius. PCM materials may hold up to 15 times more heat per volume than water and rocks. The best PCMs typically turn on at about 28 degrees Celsius to provide the most comfortable atmosphere for human contact. Latent and sensible heat are the two types of heat energy that drive a PCM. The quantity of energy required to transform matter from one condition to another is known as latent heat. For instance, from a liquid to a solid. An ice cube is the most typical illustration of this kind of heat energy. The heat energy from the beverage will be absorbed by an ice cube using its latent heat capacity. The ice cube melted because it expended all of the latent energy it had stored. The amount of energy needed to change a substance's temperature without changing its phase is known as sensible heat, in contrast. A water heater is one illustration of this. The precise temperature that is required can be sustained for a long time when latent and sensible heat combine. Finally, PCM goods usually last for the whole useful life of the product they are applied to or utilised in. The latent heat energy and transition temperature have to be constant throughout the melting and solidifying cycles.

To discover the best material with low thermal conductivity, high heat resistance, and stress analysis, we will analyse several phase-changing materials and compare the results with one another.

3.1.1. Graphene Based Phase Changing Material

In the research of Si Wu et al [27] in a unique method, the functional matrix of PCMs is constructed from dual polymer and graphite Nano platelet networks to produce exceptionally flexible, leakage-proof, and thermally conductive PCCs. The high heat

conductivity of PCCs is made possible by expanded graphite (EG) with a long-chain structure, it establishes a graphite Nano platelet percolation net that is both ordered and connected. The macromolecular olefin block copolymer (OBC), which also provides the composite film its flexibility, creates a cross-linked polymer network that surrounds the liquid PCM. At EG loadings of 5–40 wt%, the radial thermal conductivities can approach values of 4.2–32.8 W m⁻¹ K⁻¹. Due to the good thermal management properties of the flexible composite sheet, the operating temperature of a commercial lithium-ion battery is reduced by more than 12°C at high discharge rates. This technology enables a wide range of heat-related applications, including thermal renewable energy harvesting, building energy management, and thermal control of electronics. The high-performance PCCs may be constructed quickly and affordably thanks to our research.

3.1.2. Research Outcome for Graphene Based PCM

As EG loading is increased, the gap between them widens because radial heat conductivity is significantly higher than axial heat conductivity. Additionally, the radial thermal conductivity rises almost linearly when EG loading is increased. The maximum axial and radial thermal conductivities are 5.5 and 17.2 W m⁻¹ K⁻¹, respectively, when the EG loading is 20 wt%. Here, we establish an improvement factor (η) to assess the improvement in thermal conductivity:

$$\eta = \lambda_{com} / (100 \cdot \lambda_{PCM} \cdot \phi_{additive})$$

This shows the thermal conductivity enhancement factor for composites per 1 weight percent injection of additives.

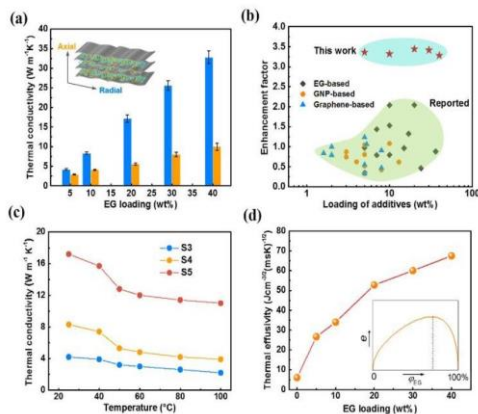


Figure 4: The thermal conductivity and thermal diffusivity of PCCs [29]

A significant amount of loosely packed composite particles was mechanically compressed into a hand-made mould at a temperature slightly below the

melting point of PW and to create the PW-OBC/EG composite film or block, a maximum compression of 20 MPa is required. The overall result has been mentioned in Table.1.

Table 1: Result of Graphene PCM

GRAPHENE BASED PCM	
Thermal Conductivity (W.m ⁻¹ .k ⁻¹)	5.5
Latent Heat (J/g)	113.7
Compression Strength (Mpa)	20

The material parameters of grapheme-based PCM are represented in the aforementioned table.1; the results show that the compression strength is 20 Mpa and the thermal conductivity is 5.5 Wm-1K-1. Since this material have low thermal conductivity, this material can be used in heat shield or heat protection layer

3.1.3. Magnetically Tightened Form Based Phase Changing Material

A smart phase change material may be effectively used for low-grade waste heat utilisation and electronic thermal management, according to the study of Yongyu Lu et al. [28]. Due to their potential applications in a number of industries, including chip cooling and solar energy, phase transition materials have attracted a lot of attention. But they have a low heat conductivity and leak during the phase shift process. By introducing hard magnetic particles, we in this case produce a specific class of magnetically bound form stable phase transition materials. They have exceptionally high electrical (>104 S/m) and thermal conductivities (increasing between 1400 and 1600%), to achieve multifunction including leakage-proof, dynamic assembly, and morphological reconfiguration, in addition to well defined compressive strength. High-performance thermal & electrical conversion methods as well as free-standing temperature control are also made with these materials.

3.1.4. Research Outcome for MTPCM

The MTPCM's linked 3D structure provides effective internal thermal conduction pathways. Modified NdFeB@Ag particles, which make up the basic unit of this network, have a high thermal conductivity resembling silver. The two factors indicated above work together to significantly increase the thermal conductivity of MTPCMs compared to organic paraffin (0.21Wm⁻¹ K⁻¹), reaching 2.97, 3.11, and 3.41Wm-1 K-1 for three dissimilar volume ratio samples. The MTPCMs'

anisotropic character was clear, as was already mentioned. In light of the heat transmission mechanism in MTPCMs, we looked at the thermal conductivity of MTPCMs in the parallel and perpendicular directions to the magnetic field. It was evident that MTPCMs had greater thermal conductivity in the direction of the magnetic field, and when sample volume rose (0.61 Wm⁻¹ K⁻¹ for 15.84%, 0.7 Wm⁻¹ K⁻¹ for 19.12%, and 0.76 Wm⁻¹ K⁻¹ for 23.31% sample), the gap between the thermal conductivity in these two directions somewhat extended. The anisotropy in the structure is the primary contributor to the anisotropic thermal performance in MTPCMs, and the influence is amplified by the rise in volume ratio. When a magnetic field is applied, both soft & hard magnetic particles spin and align, eventually creating chains and magnetic flux profiles. The primary contrast is that soft magnetic particles collapse back into a mass of powders whereas hard magnetic particles may keep their structure for a considerable amount of time after the magnetic field has disappeared. Our investigation into whether NdFeB@Ag particle alignment inside the MTPCM can sustain the composite and improve its mechanical effectiveness is prompted by this representation. Fig.5 shows the output result of the MTPCMs.

temperatures over the paraffin melting point. The head-to-tail alignment of the magnetic particles, which results in an anisotropic structure, also contributes to a small anisotropy in the thermal and mechanical performance of MTPCMs. The overall result has been shown in table 2.

Table 2: Result of MTPCM

MTPCM	
Thermal Conductivity (W.m ⁻¹ .k ⁻¹)	0.21
Latent Heat (J/g)	141.63
Compression Strength (Mpa)	2.1

Table 2 above shows the material characteristics of MTPCM; the findings indicate that the thermal conductivity is 0.21 Wm⁻¹K⁻¹ and the compression strength is 2.1 Mpa. These materials can be utilized in heat shields or heat protection layers since they have a low thermal conductivity. The compression strength, however, is comparatively extremely weak.

3.2 Composite-Based Aerogel Phase Changing Material

Panpan Liu et al. [29] used a unique in situ one-step approach to create monolithic silica aerogel-based composite PCMs. Because PCMs like polyethylene glycol (PEG) and octadecanol have poor heat conductivity, silica aerogels are utilised to surround them to make composite PCMs. In contrast to PEG2000@silica aerogel, the resultant monolithic octadecanol@silica aerogel has improved thermal cycle stability, a substantial compressive strength of 11 MPa, strong hydrophobicity (contact angle of 124°), with great latent heat (127.73 J/g). This monolithic silica aerogel-based composite PCM's synergistic mixture of great latent heat with poor thermal conductivity may be able to prolong the time that heat is maintained. This material may be used directly in appliances that offer thermal insulation and thermal protection.

3.2.1. Research Outcome for Silica Aerogel PCM

It is essential for the usage of composite PCMs to have excellent thermal reversibility. The composite PCMs were already reused 50 times to show the specimens' dependability & durability. The samples' outstanding thermal endurance and stability are evidenced by the fact that after 50 thermal cycles, their latent heat and phase transition temperatures do not alter noticeably. Eventually, the phase transition process converts the ordered PCM crystal into a disordered amorphous substance. Additionally, in practical applications, composite PCMs will always be impacted by mechanical force.

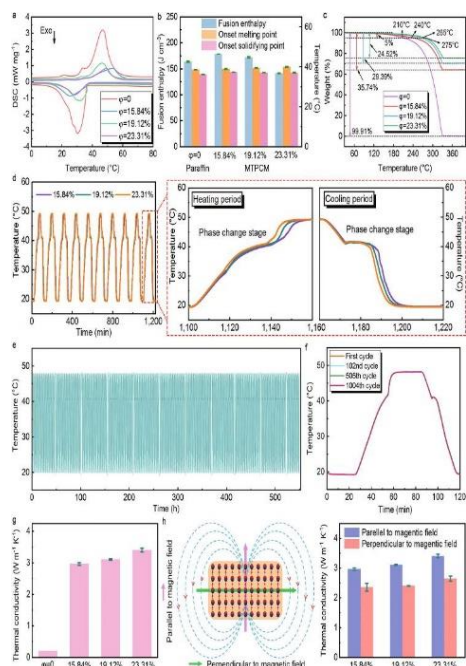


Figure 5: Thermal performance of magnetically tightened form-stable phase change materials (MTPCMs).

As regards mechanical performance, unlike ordinary PCMs, MTPCMs' compressive strength is reinforced by the supporting framework. At room temperature, MTPCMs have a compressive yield strength of 5.19 MPa, which is 2.5 times greater than paraffin's 2.1 MPa value. MTPCMs can work as leakage-proof components when squeezed, even at

The composite PCMs must be mechanically robust enough for direct application. The findings show that no matter the temperature, octadecanol@silica aerogel composite PCMs have strong compressive strength (11 MPa). Figure 6 shows the graph for heat flow rate and thermal conductivity.

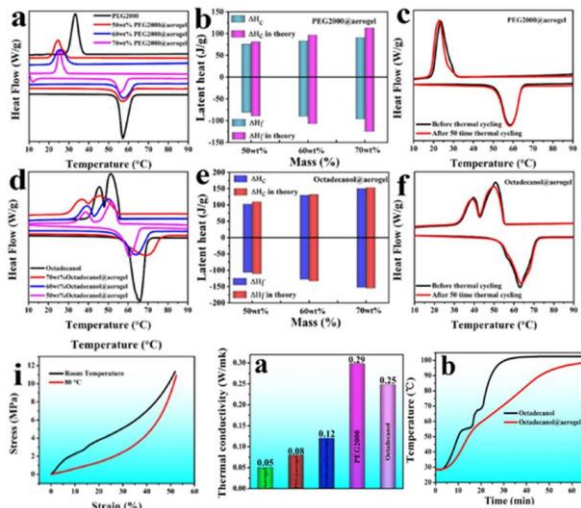


Figure 6: Stress and latent heat graph for Aerogel PCM

PEG2000@silica aerogel, octadecanol@silica aerogel, and pure silica aerogel have respective thermal conductivities of 0.05, 0.08, and 0.12 W m⁻¹k⁻¹.

Silica aerogel, which has a poor thermal conductivity, allows composite PCMs to successfully resist some heat, giving them excellent thermal insulation capability. More specifically, because PCMs have a high latent heat and silica aerogel has a poor thermal conductivity, the composite PCMs material may effectively absorb heat first with PCMs and then insulate it with silica aerogel. Because silica-based composite PCMs are less thermally conductive than pure PCMs, silica aerogel has the potential to slow down rapid heating by significantly lowering the thermal conductivity of composite PCMs. Octadecanol@silica aerogel composite PCMs' thermal insulation performance was compared to that of many conventional materials, including glass and polytetrafluoroethylene, in order to assess the real application impact (PTFE). An infrared thermal camera takes thermal images of the samples when they are put on a heated plate heated to 650°C. Composite PCMs have good thermal insulation properties and can sustain a temperature of roughly 500C for up to 16 minutes, according to thermal imaging data. Additionally, octadecanol@silica aerogel composite PCMs have a significant hydrophobicity of 124°C, which may prevent moisture absorption and improve the usefulness even more. After 50 heat cycles, the composite PCMs' FTIR and XRD were examined to help further assess their stability. The exceptional thermal cycling steadiness of silica aerogel-based composite PCMs is demonstrated by the fact that the peaks' locations

hardly ever shift after the heat cycles. The overall result has been shown in table 3.

Table 3: Result of Aerogel PCM

AEROGEL PCM	
Thermal Conductivity (W.m ⁻¹ .k ⁻¹)	0.12
Latent Heat (J/g)	127.73
Compression Strength (Mpa)	11

The material properties of Aerogel PCM are shown in Table 3 above; the results reveal that the compression strength is 11 Mpa and the thermal conductivity is 0.12 Wm⁻¹K⁻¹. Due to their poor thermal conductivity, these materials can be used as heat shields or heat protection layers.

4. Summary

In this study, we analysed several PCM materials and took into account which one had the lowest thermal conductivity, highest latent heat, and highest compressive strength. This research has carried out a thorough investigation via literature review. From the previous study we have extracted the below results and concluded our study. For almost 50 years, clean, inexpensive electricity has been produced by nuclear power in various regions of the world. It now meets 16% of the world's energy demands with more than 400 reactors dispersed over 31 countries, and it is projected that it will continue to contribute significantly to meeting the growing need for affordable and sustainable electricity throughout the globe. Materials for the nuclear fuel cycle must be transported both domestically and internationally in order to sustain this activity. Transporting fuel cycle materials securely and effectively is necessary to maintain the nuclear power industry. International nuclear fuel cycle transport operations are important due to the nature of the industry, as the majority of countries with sizable nuclear power businesses are unable to provide all the required fuel cycle services.

The table. 4 below displays the overall analysis for the chosen PCM materials.

Table 4: Over all comparison of PCM materials

PARAMETERS	GRAPHENE	MTPCM	SILICA AEROGEL
Thermal Conductivity (W.m ⁻¹ .k ⁻¹)	5.5	0.21	0.12
Latent Heat (J/g)	113.7	141.63	127.73
Compression Strength (Mpa)	20	2.1	11

The research indicates that silica aerogel is a suitable PCM material for the construction of transportation casks in the future because of its extremely low thermal conductivity and high compressive strength. We will eventually contribute our research to the silica aerogel PCM for the nuclear waste transportation cask.

5. Conclusions

In the contemporary world, electricity is a necessity, yet producing it is difficult. The production of clean energy is the next difficult task, and nations like India, Japan, and the United States heavily rely on nuclear power. Uranium is used as the fuel for nuclear reactors because it is highly radioactive. We can generate more electricity with this nuclear reactor than we can with any other. However, radioactive nuclear waste is also created during the process of producing power in nuclear reactors; this highly radioactive waste needs to be contained in barrels and kept underground or beneath a deep ocean bed. Therefore, it is necessary to get this nuclear waste from the nuclear reactor to the storage facility or dump site. The used fuel transportation cask is required for this to be done. There are several nuclear shipping casks, but these casks are not the best for storing this fuel because the material would shatter from the extra heat. Therefore, in order to create a barrel that is both more effective and safer, we should locate an appropriate material to add within these casks. We have thoroughly compared and contrasted a number of Phase Changing Materials (PCM) in this research and discovered that silica aerogel PCM has very low thermal conductivity, high compression strength, and latent heat. Therefore, to produce the nuclear transportation barrel for our future investigation, we will be using PCM, which is based on silica aerogel.

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