

Development of Passive Cooling Mechanisms and Material Selection for Acoustic Well Logging Tool Survival in High-Temperature High-Pressure Geothermal Environments

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ABSTRACT

Geothermal energy is emerging as a promising sustainable energy resource, particularly with increasing interest in exploiting high-temperature, high-pressure (HTHP) reservoirs. The use of downhole acoustic well logging tools is vital for monitoring casing and cement integrity. However, the development of technology for diagnostics in such extreme conditions remains challenging. Conventional acoustic well logging tools fail to obtain reliable measurements for prolonged periods under the combined effects of high pressure and temperature during exposure to highly corrosive fluids present in geothermal wells. Therefore, there is a need to better ruggedize acoustic logging tools for reliable operation and survival in these harsh conditions.

We developed two design approaches to evaluate the passive cooling mechanisms of candidate material composites under HTHP conditions. The first approach focused on thermal energy storage by including layers of Phase Change Materials (PCMs) embedded between silicon aerogel insulation layers. The second method incorporated a vacuum layer enclosed between alternating PCM and silicon aerogel layers. Both designs were evaluated by implementing heat transfer equations in COMSOL Multiphysics under the finite element framework. We employed Fourier's law and the conservation of energy equation to evaluate thermal resistance and heat flow in both configurations under HTHP condition.

Results demonstrated that PCM layers significantly delayed temperature breakthrough by absorbing and storing thermal energy during phase change. Moreover, the hybrid PCM-silicon aerogel configuration significantly outperformed a single aerogel layer supporting enhanced thermal resistance and heat transfer delay at HTHP conditions. The second design with vacuum encapsulated between PCM and aerogel layers displayed the best thermal performance demonstrating the added benefits of controlling latent heat absorption/release. Our designs demonstrate a high potential for passive cooling via thermal energy storage and insulation essential in extended downhole acoustic monitoring of casing and cement integrity.

1. INTRODUCTION

Well logging and monitoring in geothermal environments is particularly challenging due to the high-temperature high-pressure (HTHP) corrosive environment (salts, CO₂, H₂S, and a wide range of pH levels). We anticipate a reasonable maximum bottom-hole pressure less than 15,000 psi and a maximum bottom-hole circulating temperature of 250°C based on recent enhanced geothermal system (EGS) projects. However, deep geothermal systems and plutonic-type geothermal plays, such as the Geysers, can easily reach or exceed static reservoir temperatures of 350°C. Wells reaching these extreme temperatures are a possibility in future geothermal energy sites (Reinsch et al 2017). Acoustic logs are the standard approach for wellbore/cement integrity monitoring; however, high-resolution acoustic logging tools often require downhole electronics packages for signal amplification and data processing. Standard commercial off-the-shelf electronics are typically rated up to 170-180°C (Soares et al. 2016) with some high-temperature options viable up to 225°C for a recommended 5-year period (Soares et al. 2016; Vedum et al. 2017). Thus, well logging tools must be ruggedized to survive harsh pressure and thermal conditions in the presence of corrosion for prolonged periods of time (24-hours). Under these extreme temperature conditions, electronics packages in well logging tools will fail without a thermal cooling mechanism. Passive thermal cooling (i.e. thermal barriers / insulation) is often preferred to active cooling (i.e. downhole fluid injection) as it mitigates damage risk to wellbore casing infrastructure. Additionally, the logging tools outer housing must be designed to survive these high temperatures while remaining structurally sound and mitigating corrosion.

We performed an in-depth study of existing well logging technologies evaluating over 170 commercial well logging products across multiple industries and academia. The tools were categorized based on logging type, maximum temperature, and maximum pressure. The logging tools included: acoustic logs, caliper logs, density logs, electromagnetic logs, flowmeters, fluid sampling logs, gamma ray logs, magnetic resonance logs, neutron logs, optical logs, PVT logs, production logs, spontaneous potential logs, and other logs. Seven products met the 250°C and 15,000 psi requirements, however, we have yet to find a viable option with passive cooling mechanisms that would allow downhole electronics to survive harsh geothermal environments for prolonged periods of time. In an effort to fill this technology gap, we explored various passive cooling designs consisting of aerogels, phase change materials (PCM), and vacuum with various corrosion resistant materials.

1.1 Corrosion resistance materials under high-temperature high-pressure conditions

Corrosion is the degradation of a material caused by a reaction to its environment. Geothermal environments contain several corrosive agents that require consideration when selecting outer housing materials for well logging tools. The most significant chemical species present in geothermal brines are hydrogen ions, chloride, hydrogen sulfide, carbon dioxide, ammonia, sulfate, oxygen, and transition metal ions (Deberry et al. 1978). Some of the common corrosion mechanisms that occur in geothermal environments include uniform corrosion, pitting, crevice corrosion, galvanic corrosion, and CO₂ corrosion (FORCE Technology, 2019). A simplified depiction of these corrosion types is shown in Figure 1.

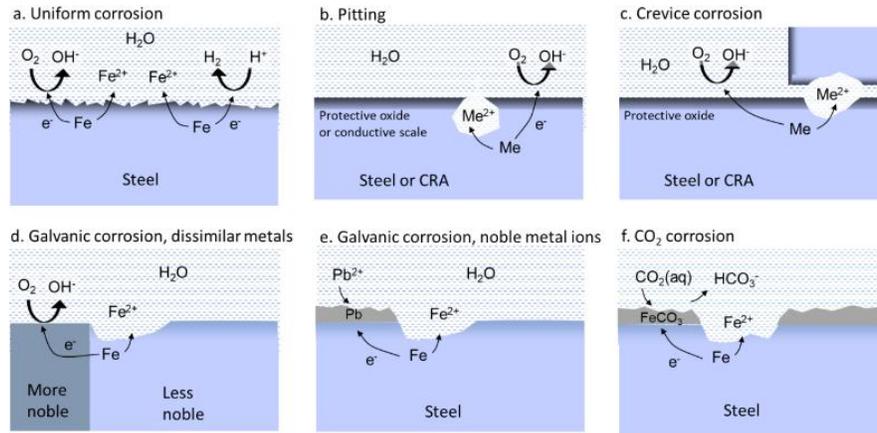


Figure 1 – Simplified depiction of corrosion types that can occur in geothermal brine retrieved from (FORCE Technology, 2019)

Corrosion resistance in metals typically comes in the form of a thermal spray process (providing a protective coating) or a corrosion resistant material that generates its own chemically stable protective oxide layer. Thermal spray coatings are often formed from a composition consisting of nickel (improves strength), chromium (improves ductility and wear resistance), and molybdenum (reduces brittleness). Some considerations for thermal spray use in HTHP environments are the required bond strength to withstand high external pressures and compatibility between the coating and substrate material. Corrosion resistant materials, such as titanium and Inconel, provide similar corrosion resistance to thermal sprays while having the added advantage of a lower thermal conductivity than steel substrates.

1.2 Types of PCM and their corresponding properties

Phase change materials (PCM) are either inorganic, organic, or eutectic. Usually, impure PCMs undergo phase change over a given temperature range; however, pure PCM have more specific phase change temperatures (i.e., the temperature range is small) (Aljabr et al. 2021). Organic phase change materials include paraffin and non-paraffin based materials. Inorganic PCMs include metallics and salt hydrates. Eutectic PCMs include some low melting point metal alloys (Chen et al. 2022) and PCM mixtures (Al-Absi et al. 2020; Tariq et al. 2020; Mahmoud et al. 2021; Barbi et al. 2022). Figure 2 gives an overview of different PCMs, and Appendix A gives the relevant thermophysical properties for the materials considered.

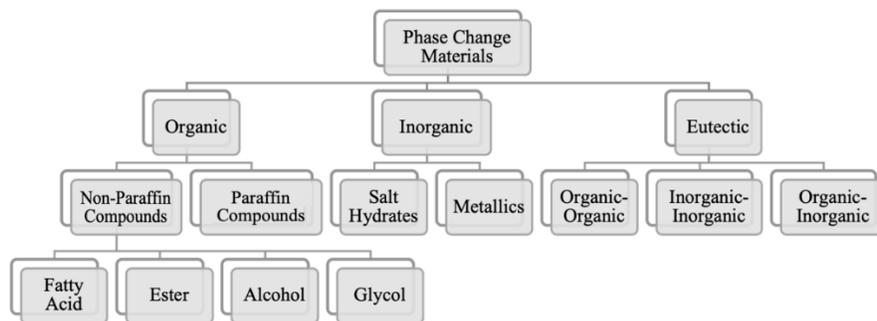


Figure 2 - Classifications of phase change materials retrieved from (Al-Absi et al. 2020; Tariq et al. 2020; Mahmoud et al. 2021; Barbi et al. 2022)

Paraffin wax organic PCM is a mixture of straight chains of n-alkanes containing a melting temperature range between 20°C and 70°C depending on the number of carbon atoms in the chain. Paraffin wax has the same properties as pure alkanes but a melting point which is average of its constituents' melting points (Sharma et al. 2002; Barbi et al. 2022). Non-paraffin compounds are the most common types

of PCMs, their application is limited due to their high flammability. Fatty acid PCM derived from oils and animal fats have melting temperatures between 17°C and 64°C, properties are similar to paraffin waxes however they melt more slowly (Sari 2005). Alcohols have low enthalpy of fusion with a wide range of melting temperatures. Metal inorganic PCMs have not been widely investigated due to their very high density (Sharma et al. 2009). Salt hydrates are the most common inorganic PCM, these have a wider range of melting temperatures which can exceed 250°C (Barbi et al. 2022). In contrast, eutectic PCMs have a sharper melting temperature than their pure constituents. Moreover, they melt and solidify at a temperature lower than at which its pure constituents melt and solidify. Among the eutectics, organic-organic and organic-inorganic PCMs are commonly used, as are metal alloys, such as those used for soldering. Some of the other eutectic PCMs include fatty acids and fatty alcohols binary compounds, poly-fatty acids, and paraffins-fatty acid mixtures (BAYRAKTAR and KÖSE 2022; Sun et al. 2023). Organic PCM is most integrated in the building sector due to suitable melting temperature ranges unlike inorganic PCM (Barbi et al. 2022). The application of PCM has been widely spreading recently due to their several benefits compared to other materials especially their thermal stability and thermal capacity (Mahmoud et al. 2021).

1.3 Advantages and disadvantages of each PCM type

Although PCMs are good candidates for thermal energy storage (TES) applications, every individual PCM type within each PCM category has several drawbacks. Organic PCMs are generally safe to handle, chemically and thermally stable, non-corrosive, and recyclable. Moreover, they are characterized by high heat of fusion, and they undergo negligible volume change, segregation, and supercooling when melting (Minea 2021; Liu et al. 2023). However, organic PCMs are more expensive than inorganic PCMs, such materials can be flammable and possess undesirable properties for TES such as low thermal conductivity and volumetric latent heat storage (Olawoore 2020; Podara et al. 2021; Sharshir et al. 2023). Meanwhile, Inorganics PCMs are non-flammable, have high latent heat capacity, and encounter negligible volume change. However, inorganic PCMs require containers to deal with corroding. Other inorganic PCMs limitations include incongruent melting, performance degradation, toxicity, and incompatibility with construction materials (Podara et al. 2021; Liu et al. 2023). Eutectic PCMs allow designing material with thermal properties exclusive to a certain application whether for building or geothermal energy storage. Although eutectics are uncommon, they have several attractive properties for TES, for instance, no segregation, sharp melting temperature, and congruent melting (Podara et al. 2021; Sharshir et al. 2023). Appendix B addresses potential advantages and disadvantages of each PCM type.

1.4 Silica aerogel

Silica aerogels are ultra-low density, low thermal conductivity materials that contain a large specific surface area (open celled porosity) with varied field applications from thermal insulation to particle capture matrices. There are various types of aerogels; inorganic (i.e. silica and metal oxide), organic and carbon, and polymer-based. Among the various aerogel types, silica aerogel satisfies both thermal conductivity and commercial availability requirements. Silica aerogels have extremely low thermal conductivity, 12–20 mW/(m·K) at room temperature, which is much lower than conventional thermal insulation materials (Fu et al, 2022). They are typically comprised of mesopore (~95 vol%) spanned by a network of linked silica nanoparticles (~5 vol%) in which the network of linked nanoparticles consists of interconnected pores ranging from 20-50 nanometers (Li et al 2020). The large nano-porosity volume, which typically consists of air, traps heat and lowers the material's thermal conductivity. Silica aerogels are manufactured using the sol-gel process. A precursor solution undergoes hydrolysis to create the sol (suspended nano-particles in solution). Condensation then causes sol particle growth. Next, a substance is added to create gelation and aging converts it into a wet-gel. The wet-gel is then dried leaving the aerogel behind.

1.5 Hybrid aerogel PCM designs

Aerogels and phase change materials (PCM) can be combined into a hybrid design through encapsulation or layering. In the encapsulation approach, the PCM material, such as a metal oxide or alloy, is placed into the mesopores of silica aerogels. The aerogel creates a particle trapping matrix that prevents metal leakage during material phase change. Lincu et al (2022) performed experiments on aerogel encapsulated bismuth oxide particles showing the liquid bismuth phase is present and trapped both inside the silica mesopores and in the interparticle space. One drawback of the encapsulation approach is the cost and expertise required for manufacturing these materials. In the layering approach, it is proposed that alternating layers of aerogel and PCM can be used to lower heat transfer by conduction (aerogel layer) and control latent heat absorption/release (PCM layer). Both aerogels and PCM are commercially available and can be layered in a coating process provided the two materials are chemically compatible.

2. METHODS

The following subsections describe the approach used for outer tool housing material selection and analyzing various passive cooling designs.

2.1 Outer housing material selection for acoustic well logging tool

Various outer housing materials were compared based on their elastic properties and corrosion resistance at 250°C, as well as commercial availability and cost. The three best options (Titanium Grade 29, Inconel 718, and MP35N) were selected for further evaluation. We determined the required thickness for each candidate material to handle a 15,000 psi external pressure with an OD of 5 inches by applying the Timoshenko-Gere collapse pressure formula for thin-walled cylinders (Equation 1). The equation was then rearranged to provide an estimate of the required wall thickness (Equation 2).

$$P_{cr} = \frac{2E}{(1-\nu^2)} \times \left(\frac{t}{OD}\right)^3 \quad (1)$$

$$t = OD \times \sqrt[3]{\frac{P_{cr} \times (1-\nu^2)}{2E}} \quad (2)$$

where P_{cr} is the critical buckling pressure, E is the Young's Modulus of the material, ν is the Poisson's ratio, t is the wall thickness, and OD is the outer diameter.

2.2 Heat transfer analytical framework

We evaluated various passive cooling designs by implementing heat transfer equations in COMSOL Multiphysics under the finite element framework. We employed Fourier's law and conservation of energy to evaluate thermal resistance and heat flow in each configuration under HTHP conditions. The following differential equation describes the analytical heat transfer equation based on conservation of energy used, while Figure 3 illustrates the thermal energy storage diagram for PCM.

$$\frac{\partial \rho C_p T}{\partial t} = \nabla \cdot (k \nabla T) - \rho C_p (\mathbf{u} \cdot \nabla T) + S_{gen} + S_{rad} + S_{lat} \quad (3)$$

where $(\partial \rho C_p T) / \partial t$ is the rate of change of sensible internal energy, $\nabla \cdot (k \nabla T)$ is the heat transfer by conduction, $\rho C_p (\mathbf{u} \cdot \nabla T)$ is the heat transfer by convection, S_{gen} is the internal heat generation, S_{rad} is the heat transfer by radiation, and S_{lat} is the latent heat absorption / release.

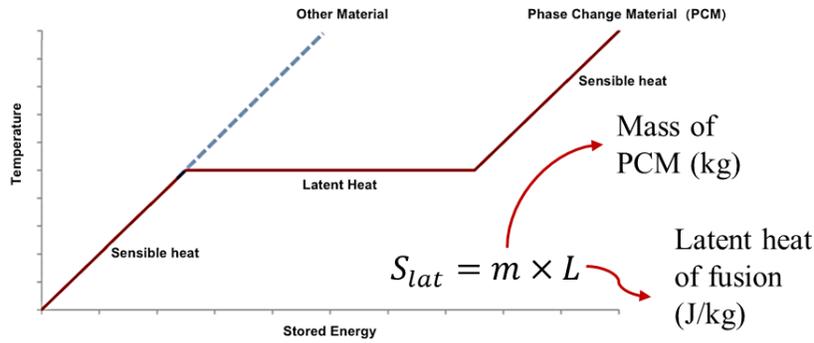


Figure 3: Thermal energy storage diagram for PCM.

The terms on the right-hand side of Equation 3 can be controlled to varying extents to minimize heat transfer. Heat transfer by conduction can be limited by reducing thermal conductivity (k) by means of incorporating thermal insulation layers or implementing a vacuum. Radiative heat transfer, if a dewar is used, can be minimized with low-emissivity coatings or polishing. Heat transfer by convection can be controlled with active cooling mechanisms or by optimizing the velocity of the working fluid (u). In the case of geothermal, this working fluid is often hot steam or brine flowing around the well logging tool. Internal heat generation can be regulated by integrating endothermic chemical reactions into the system. Heat transfer by radiation can be inhibited by lowering surface emissivity with use of a reflective insulation barrier. Latent heat absorption/release can be controlled through the implementation of phase change materials. Our designs focused on reducing sensible internal energy rate of change (left-hand side of Equation 3) by optimizing control over the heat transfer by conduction and latent heat absorption/release using passive cooling mechanism.

2.3 Design and Parametric Study

Our design approach focuses on thermal energy storage by including layers of PCM and silica aerogel insulation layers. This lowers rate of change of sensible internal energy through implementation of phase change materials and lowering thermal conductivity with aerogel insulation layers. The design was customized and modeled based on the maximum expected external temperature (250°C). The melting temperature of the external PCM layer, eutectic $\text{Bi}_{58}\text{Sn}_{42}$, $T_c = 138^\circ\text{C}$, was selected because the melting temperature is rather high, it does not exceed the operating temperature of many electronics, and it does not exceed the expected external temperature. Schematics of a single silicone aerogel layer and PCM alternating silicon aerogel layers are shown in Figure 4. The single silica aerogel layer was modeled as a comparison to the PCM aerogel hybrid approach.

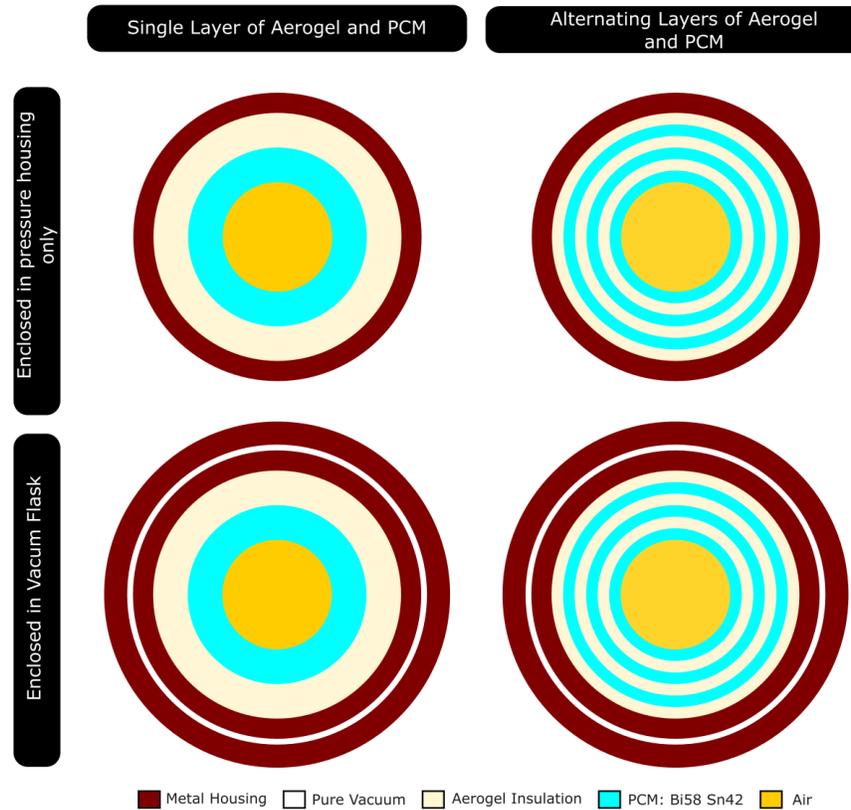


Figure 4: Alternative designs considered for thermally insulating the tool

Several design challenges and limitation were considered with this approach:

- PCM containment and leakage
- Aerogel fragility at high pressure
- Manufacturing complexity and cost
- Limited insulation beyond PCM melting
- PCM melting temperature must match the environment’s temperature range
- Tool design constraints (< 6-inch outer diameter)
- Compatibility between PCM and aerogel layers

We condensed design tradeoffs into 4 different designs that were further parameterized. These included a single layer of PCM underneath a layer of aerogel insulation, an alternating configuration of successive PCM and aerogel insulation layers, and then both of those configurations enclosed in an outer vacuum flask. Each design was parameterized to study the tradeoff between amount of insulation versus PCM used.

3. RESULTS

Results for outer housing material candidates and passive cooling mechanisms designs are described in the following subsections.

3.1 Outer housing material selection for acoustic well logging tool

Our final material choices were narrowed down to titanium grade 29 (Ti29) a 6Al4V0.1Ru titanium alloy, Inconel 718 (In718) a nickel-chromium alloy, and MP35N a nickel-cobalt-chromium-molybdenum alloy. Titanium 475 (Ti-0.4Ni-3.75-Mo-0.75Zr) was also considered as a lower cost alternative to Ti-29. It is a titanium alloy developed for aggressive geothermal fields as a casing material (MacDonald et al 2022). However, due to a lack of commercial availability, Ti-475 was rejected. The remaining three choices were compared and graded based on minimum thickness required (calculated from Equation 2 and Table 1), thermal conductivity at 250°C temperature, corrosion resistance, cost, machinability, and lead time / availability of materials. Results for this comparison are shown in Table 2. All three choices are viable options depending on availability, budget, and space requirements inside the logging tool.

Table 1: Elastic properties of candidate materials at 250°C external temperature.

Item	Ti29	In718	MP35N
Young's Modulus (GPa)	108	190	213
Poisson's Ratio	0.32	0.295	0.3

Table 2: Material candidates grading for outer pressure housing (green = high grade, yellow = moderate grade, red = low grade).

Criteria	Ti29	In718	MP35N
Minimum Required Thickness (in)	0.3773	0.31434	0.30226
Thermal Conductivity at 250 °C (W/m.K)	8.5	12.5	11.3
Corrosion Resistance	Excellent due to formation of TiO ₂ Layer	Good in Oxidizing Environments	Very Good to Excellent
Approximate Cost (\$/lb)	35-50	25-35	60-90
Machinability	Poor to Fair	Poor	Very Poor
Lead Time	Varies depending on specs	Varies depending on specs	Very long

3.2 Results for thermal insulation and PCM study

All the results below were modeled by implementing heat transfer equations in COMSOL Multiphysics under the finite element framework. We employed Fourier's law and the conservation of energy equation to evaluate thermal resistance and heat flow in both configurations under HTHP condition. Each configuration was set at an external temperature of 250°C within a 5.89-in OD outer tool housing for configurations with a vacuum flask and a 5-in OD tool housing for configurations without a vacuum flask. The geometry was parameterized with respect to the thicknesses of aerogel insulation and PCM. We looked at twenty cases of varying aerogel to PCM thickness ratios to find the most suitable configuration for cases containing a vacuum flask, and cases without a vacuum flask. These results are graphically shown in figures 5 and 6. Figure 7 shows various contour maps that summarize the parametric study.

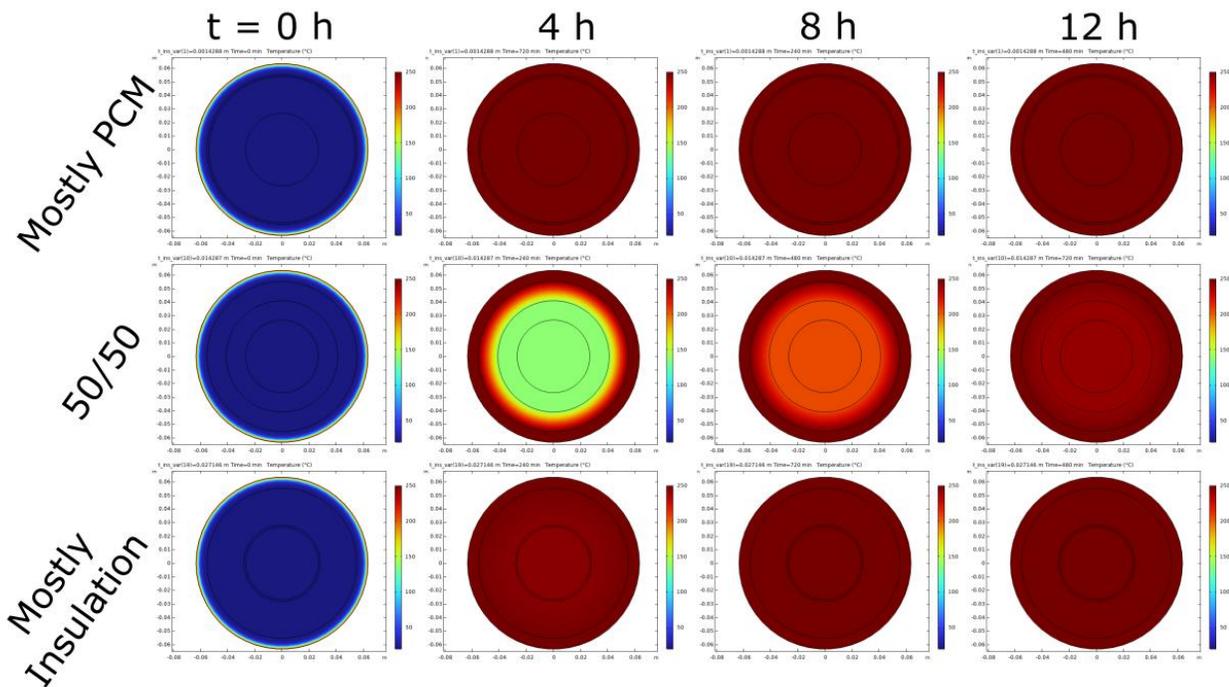


Figure 5: Simulated results comparing different proportional thicknesses of aerogel insulation and PCM within a metal pressure housing with an outer temperature of 250°C. These results show that a combination of insulation and PCM keeps temperatures to a minimum for the longest amount of time.

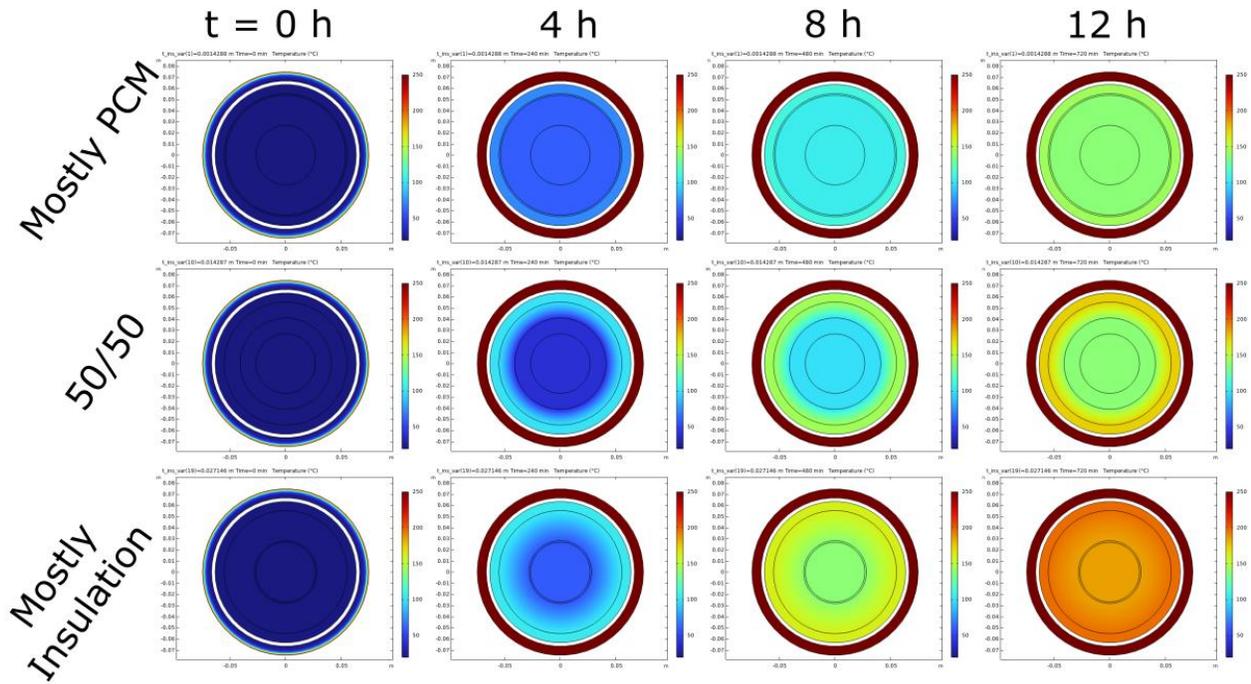


Figure 6: Simulated results comparing different proportional thicknesses of aerogel insulation and PCM. These layers are encased within a vacuum flask which has an outer temperature of 250°C. Emissivity of the radiative surfaces is 0.1. Of these, the case consisting of thin aerogel insulation and a large amount of PCM remains at the lowest temperature after 12 hours

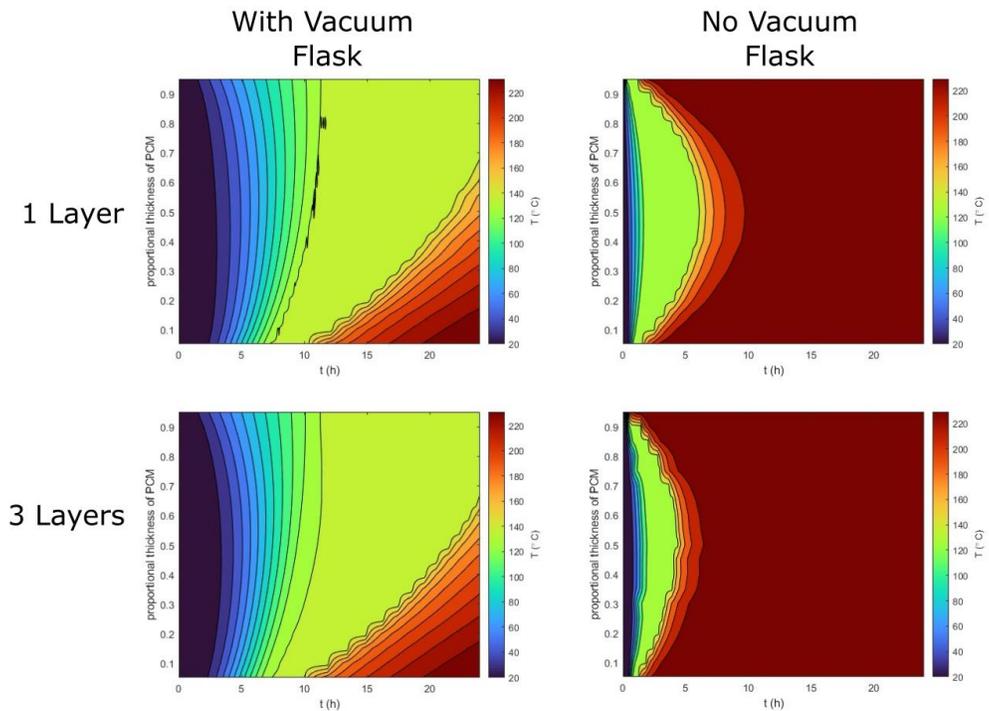


Figure 7: Contour graphs comparing different design configurations and parameters. All graphs indicate proportional thickness of PCM to aerogel on the y-axis, and time in hours on the x-axis. From the top-left going clockwise are results for the single-layer design with a vacuum flask surrounding, the single-layer design without a vacuum flask, the three-layer design without a vacuum flask, and the 3-layer design with a vacuum flask.

Figure 5 demonstrates an equal proportion of PCM and aerogel insulation to be optimal in the absence of an outer vacuum flask. When a vacuum flask is included (as seen in Figure 6), there is substantial performance improvement correlating to maximizing the ratio of PCM to aerogel. The high efficiency of the vacuum layer as an insulator can be improved with a larger thermal mass. Figure 7 illustrates how adding additional layering, without increasing the amount of PCM, had little impact on performance. The optimal design appears to be the use of a vacuum flask in combination with a large heat sink (PCM) with a minimal amount of aerogel for preventing leakage during phase change. Our conclusions seem to agree with previous work on tools for geothermal wells (Vedum et al. 2017), and with literature on sustainable buildings, that suggest energy savings result when designers consider insulation *and* thermal mass with creative solutions like heavy building materials, or even implementing PCMs (Parameshwaran et al. 2012, Hasan et al. 2018).

4. CONCLUSIONS

We present a selection of material choices and passive cooling mechanism designs for ruggedizing an acoustic well logging tool for survival in high-temperature high-pressure (HTHP) corrosive geothermal environments. The minimum requirements included an external temperature of 250°C at an external pressure of 15,000 psi for a 24-hour monitoring period in highly corrosive conditions. Outer tool housing materials are compared for minimum required thickness, thermal conductivity at 250°C, corrosion resistance, cost, machinability, and lead time. The final material selection included titanium grade 29 (Ti29) a 6Al4V0.1Ru titanium alloy, Inconel 718 (In718) a nickel-chromium alloy, and MP35N a nickel-cobalt-chromium-molybdenum alloy.

Additionally, we show a comparison of several design strategies to evaluate the passive cooling mechanisms of PCM plus silica aerogel insulation in HTHP conditions. We've shown that in the absence of an outer vacuum flask, successful implementation of passive cooling is optimized (in terms of layer thickness) through an equal proportion of PCM and aerogel insulation. Cases including the use of a vacuum flask provided substantial improvement in performance, further enhanced by maximizing the volume of PCM over aerogel. The high efficiency of the vacuum layer as an effective insulator indicates design improvements are achievable primarily through a larger thermal mass. Finally, we looked at configurations of alternating layers of PCM and aerogel insulation parameterized in a similar manner as the other studies. Additional layering appears to have little impact on improving thermal transfer results, perhaps slightly diminishing performance. Our recommendation favors using a vacuum flask in combination with a large heat sink (PCM) with a minimal amount of aerogel for preventing leakage during phase change.

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APPENDIX A

Thermophysical Properties for some PCMs

	<i>Material</i>	<i>Latent Heat QL (J/kg)</i>	<i>Transition (°C)</i>	<i>Decomposition / Flash Point (°C)</i>	<i>Density (kg/m³)</i>	<i>K (W/m·K)</i>	<i>Specific Heat (J/kg·K)</i>	<i>Source</i>
<i>Organic PCMs</i>	Paraffin Wax	1.74E+05	44	200	830	0.13	2440	(Hasan et al. 2018)
	Mannitol	3.41E+05	165	280	1489	1	2630.00	(Seppälä et al. 2022, CAMEO Chemical Database, Kaizawa et al. 2018, Shamberg 2016, Solé et al. 2014)
<i>Metals and Metal Alloys</i>	In	2.85E+04	156.61		7310	36.4	230.00	Chen et al. 2022
	Sn	6.05E+04	231.9		5750	15.08	221.00	Chen et al. 2022
	Bi58 Sn42	4.48E+04	138		8720	19	210.00	Chen et al. 2022
	Bi32.5 In51 Sn16.5	2.60E+04	60		8054	21.6	220.00	Chen et al. 2022
	Bi 52 Pb30 Sn18	3.47E+04	96		9600	24	167	Chen et al. 2022

APPENDIX B

Advantages and disadvantages of PCMs

PCM Type		Advantages	Disadvantages	Reference	
Organic	Paraffin Compounds	Paraffin Wax	<ul style="list-style-type: none"> -Safe, reliable, and non-corrosive -Chemically stable -Low toxicity -No phase separation -Low supercooling 	<ul style="list-style-type: none"> -Low thermal conductivity and low density -Moderate flammability -Expensive -Contributes to global warming -Incompatible with plastics -High volume change 	(Sharma et al. 2009; Stamatou et al. 2017; Ghani et al. 2021; BAYRAKTAR and KÖSE 2022; Sharshir et al. 2023; Sun et al. 2023)
	Non-Paraffin Compounds	Fatty Acid	<ul style="list-style-type: none"> -Non-Toxic -Biodegradable -Stable -Congruent Melting -Cost efficiency -Does not require encapsulation -High heat of fusion -No supercooling 	<ul style="list-style-type: none"> -Corrosive -High sublimation rate -Bad odor -Relatively expensive 	(Feldman et al. 1989; Sharma et al. 2009; Ghani et al. 2021; BAYRAKTAR and KÖSE 2022)
		Ester	<ul style="list-style-type: none"> -No supercooling -Negligible volume change due to melting -Chemical stability -High latent heat of fusion 	<ul style="list-style-type: none"> -Toxic and unsustainable -Flammable -Low thermal conductivity -Undergo thermal degradation at high temperatures -Low availability 	(Stamatou et al. 2017; Ravotti et al. 2020)
		Alcohol	<ul style="list-style-type: none"> -Negligible volume change -Undergoes no segregation -Long lifespan -High latent heat -Good stability -Non-toxic -Non-corrosive 	<ul style="list-style-type: none"> -Low enthalpy of fusion -Undergo supercooling -Low thermal conductivity 	(del Barrio et al. 2017; Liu et al. 2023)
		Glycol	<ul style="list-style-type: none"> -Congruent phase change -Good nucleation rate -Relatively cheap -Chemically stable -Recyclable and biodegradable -High enthalpy -No supercooling -Commercially available -Cheap 	<ul style="list-style-type: none"> -Low thermal conductivity -Easy leakage which reduces the rate of heat exchange 	(Wang et al. 2019; Minea 2021)
Inorganic	Salt Hydrates	<ul style="list-style-type: none"> -Abundant and cost effective -Non-flammable -High latent heat of fusion per unit volume -Negligible volume change on melting -High density -Sharp phase change temperature 	<ul style="list-style-type: none"> -Low thermal conductivity but higher compared to organic PCMs -Poor stability and dehydration -Phase separation and incongruent melting -Supercooling and encounters segregation -Toxic -High volume change on melting 	(Sharma et al. 2009; Stamatou et al. 2017; BAYRAKTAR and KÖSE 2022; Sulaiman and Mohamad Amini 2022; Sharshir et al. 2023)	
	Metallics	<ul style="list-style-type: none"> -Non-flammable -High heat of fusion per unit volume -High thermal conductivity -Low specific heat and vapor pressure 	<ul style="list-style-type: none"> -Poor stability -Phase separation -Supercooling -Low melting enthalpy per unit weight 	(Sharma et al. 2009; Noro et al. 2014; BAYRAKTAR and KÖSE 2022; Sulaiman and Mohamad Amini 2022; Sharshir et al. 2023; Sun et al. 2023)	
Eutectic	Organic-Organic	<ul style="list-style-type: none"> -Congruent melting -No phase separation -High volumetric heat storage density -Long term stability -High chemical compatibility and surface tension -Higher density than pure organic PCM -Can be customized to achieve desired properties 	<ul style="list-style-type: none"> -Low thermal conductivity -High cost 	(Sharma et al. 2009; Podara et al. 2021; Singh et al. 2021; BAYRAKTAR and KÖSE 2022)	
	Inorganic-Inorganic	<ul style="list-style-type: none"> -No phase separation -Congruent melting -High volumetric heat storage density -Low thermal expansion -No supercooling 	<ul style="list-style-type: none"> -Relatively expensive -Some are corrosive and toxic 	(Sharma et al. 2009; Chadha et al. 2022; Sulaiman and Mohamad Amini 2022)	
	Organic-Inorganic	-	<ul style="list-style-type: none"> -Scarce data on thermophysical properties of many combinations. -Phase separation and supercooling 	(Khaled Mahmoud et al. 2018; Sulaiman and Mohamad Amini 2022)	

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