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Development of a High-Performance Computing Liquid Cooling System

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Abstract

As High-Performance Computing (HPC) has grown, traditional air-cooling methods have become ineffective at handling heat fluxes over 500 W/cm², which has caused performance throttling and reliability problems. This study focuses on the development and computational evaluation of a liquid cooling system model specifically designed for high-performance computing (HPC) environments. A weighted selection matrix showed that single-phase immersion cooling was the best method; it worked better thermally, it could be used on a larger scale, and it used less energy. In Autodesk Inventor, a simplified geometric model of a CPU, GPU, and PCB submerged in a dielectric fluid tank was created. In ANSYS Fluent, the model was then simulated. The thermal performance of four dielectric fluids, 3M Novec 7000, Fluorinert FC-72, Mineral Oil, and Silicone Oil, was evaluated under a constant heat flux of 400,000 W/m³. The results show that 3M Novec 7000 and Fluorinert FC-72 had the lowest component temperatures, which shows that they are very stable at transferring heat. However, Mineral Oil had the best heat absorption capacity (22.52 kJ/kg) and was the cheapest option (ZAR 123.50/L), making it perfect for large-scale HPC deployments. The study confirms the hypothesis that simulated liquid cooling can provide efficient, cost-effective thermal management, with implications for South Africa's HPC sector and global sustainability.

Keywords

High-Performance Computing (HPC), Liquid Cooling, Single-Phase Immersion Cooling, Dielectric Fluids, Thermal Management, ANSYS Fluent, Energy Efficiency

1. Introduction

A major thermal management issue has emerged due to High-Performance Computing's (HPC) relentless pursuit of processing power. With power densities often surpassing the cooling capabilities of traditional air-cooling systems, modern multi-core processors and GPUs generate significant amounts of heat (Azarifar et al. 2024) (Meijer,2010). This thermal inefficiency leads to performance degradation, hardware failures, and high energy consumption; cooling alone can account for nearly 40% of a data centre's energy use (Nadjahi., Louahlia., and Lemasson 2018).

Liquid cooling has become a better option because it uses the high thermal conductivity of fluids to move significantly higher heat transfer performance depending on conditions (Uti,2023). Immersion cooling, which submerges hardware directly in a dielectric coolant, is one of the best liquid cooling technologies because it keeps temperatures even and allows for high-density server rack setups (Pambudi, et. al., 2022).

This research enhances the thermal management of HPC systems, energy efficiency, and system reliability and durability. It demonstrates how to optimise liquid cooling technology, significantly reducing energy consumption and operational costs in data centres. Addressing the critical challenge of heat dissipation, this work explores innovative solutions for better management of heat dissipation in HPC systems, which is vital for system stability and extending the lifespan of computing equipment. The study's findings will contribute to the field of thermal management and cooling technologies, potentially fostering further advancements and new applications across various engineering and scientific domains.

The novelty of this research lies in the development of a high-performance liquid cooling system for HPC, introducing a parallel flow design that improves thermal efficiency and reduces energy consumption, thereby providing a practical and innovative solution beyond existing conventional cooling systems.

The motivation for developing the liquid cooling system stems from the expanding HPC sector in South Africa, which hosts half of the continent's data centres. The Lengau supercomputer highlights the importance of designing advanced, cost-effective cooling solutions locally (CSIR n.d). This research focuses on creating and simulating a single-phase immersion cooling system to meet this demand. The main goal is to model the system computationally and assess different dielectric fluids to find a solution that offers both high thermal efficiency and economic practicality.

2. Methodology

The present study adopted a descriptive, simulation-based methodology to design, select, and evaluate a liquid cooling system for high-performance computing (HPC) applications.

2.1 Concept Selection

Three cooling concepts DTC, Single-Phase Immersion, and Two-Phase Immersion were modelled in Autodesk Inventor. A weighted selection matrix evaluated them against criteria including Thermal Performance (30%), Energy Efficiency (20%), Scalability (15%), System Complexity (15%), and Cost (10%). Single-phase immersion cooling achieved the highest weighted score of 8.85, establishing it as the most suitable concept for this study due to its excellent balance of performance, scalability, and operational simplicity**.** Figure 1 illustrates the selected schematic concept, while Figure 2 presents the 3D model of the single immersion system.

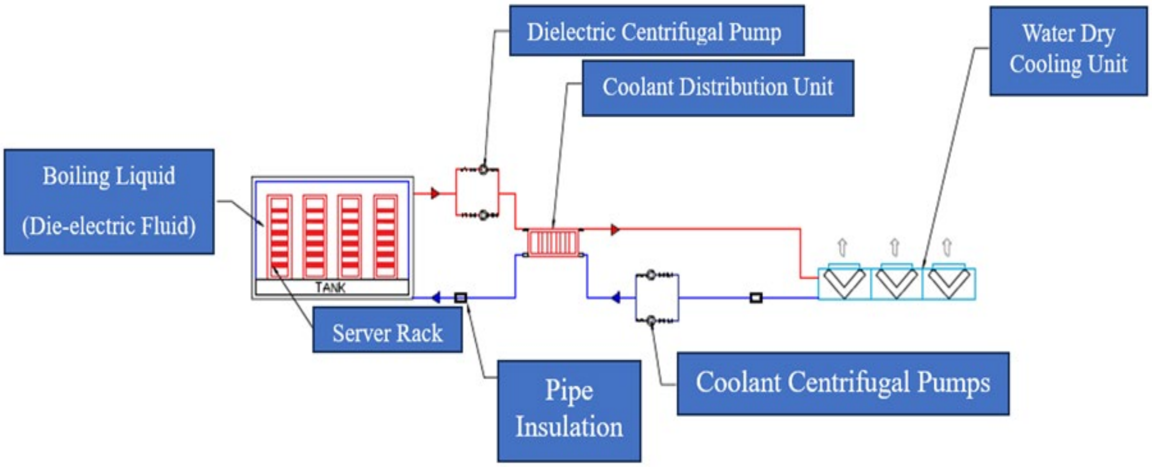
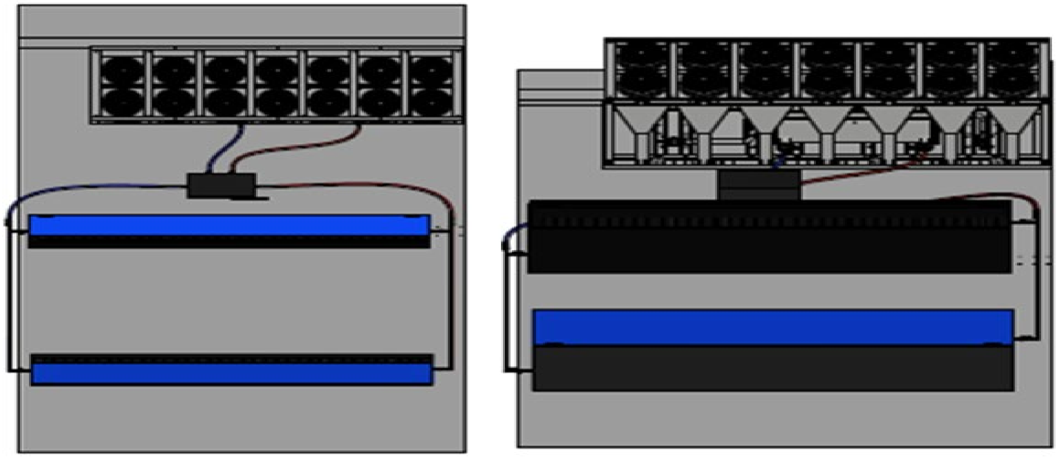


Figure 1. Single Immersion Schematic

2.2 Model Development and Simulation

A simplified 3D model of an HPC module was created for simulation in ANSYS Fluent. The model consisted of a CPU and GPU (modelled as aluminium heat sources with a volumetric generation of 400,000 W/m³), a PCB, and an enclosure tank, as shown in Figure 2 and Figure 3.



a) Top View b) Front View

Figure 2. Single Immersion Model a) Top View and b) Front View.

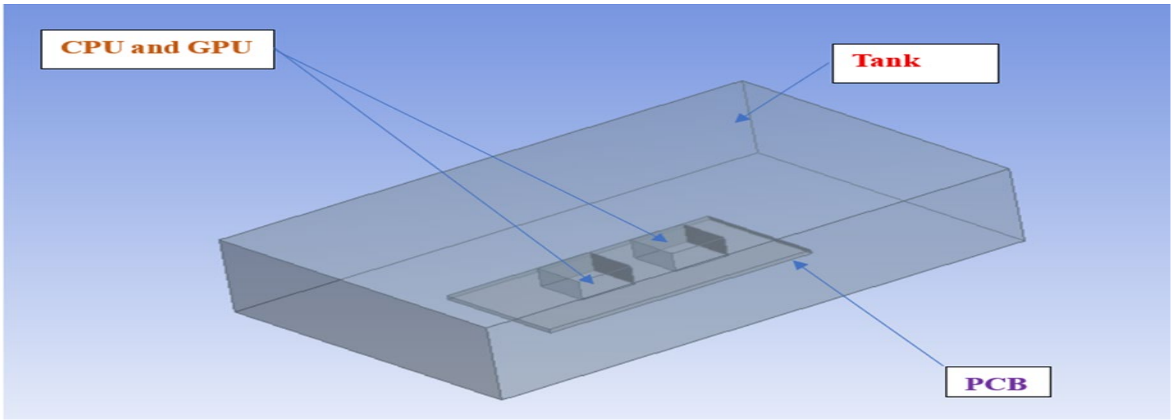


Figure 3. Simplified geometric model of the HPC immersion cooling module.

The computational domain was discretised into a mesh of 315,047 elements and 57,748 nodes, with skewness maintained within acceptable limits to ensure solution accuracy. A pressure-based, steady-state solver was employed with the SIMPLEC algorithm for pressure-velocity.

2.3 Boundary Conditions and Materials

The inlet boundary was set as a velocity inlet at 0.1 m/s and 293 K (20°C). The outlet was defined as a pressure outlet. The walls of the tank and components were set as coupled for conjugate heat transfer. The thermal performance of four dielectric fluids was evaluated, with their properties listed in Table 1.

Table 1. Material Properties of Dielectric Fluids

Property	**3M Novec 7000**	**Fluorinert FC-72**	**Mineral Oil**	**Silicone Oil**	**Units**
Density (ρ)	1400	1740	860	965	kg/m³
Specific Heat (Cp)	1200	1100	1800	1630	J/kg·K
Thermal Conductivity (k)	0.07	0.057	0.13	0.14	W/m·K
Dynamic Viscosity (μ)	0.00061	0.00064	0.02	0.048	Pa·s

3. Results and Discussion

3.1Thermal Performance of Dielectric Fluids

The simulations converged successfully, with residuals falling below 10^{-3}. The outlet temperature and maximum heat source temperature were the key metrics for comparison. Figures 4 (a - d), illustrate the simulated dielectric fluid, while Table 2 presents the summary of the thermal performance results.

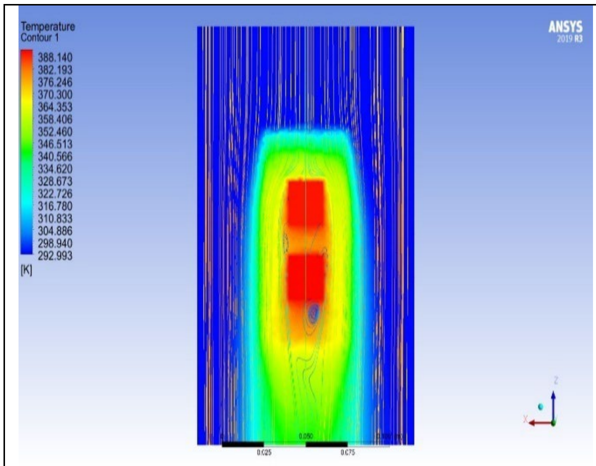


Figure 4a): 3M NOVEC 7000

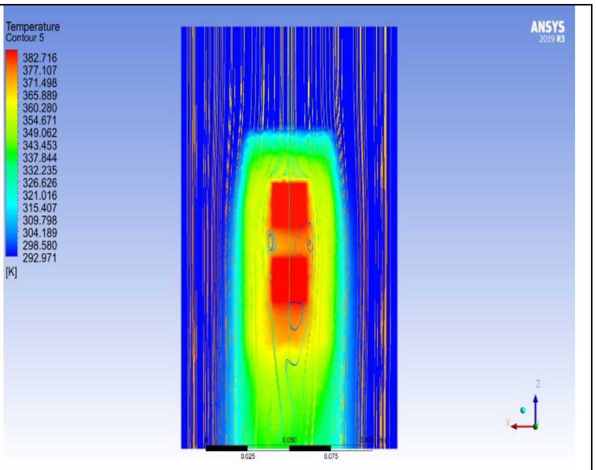


Figure (b): FC 72

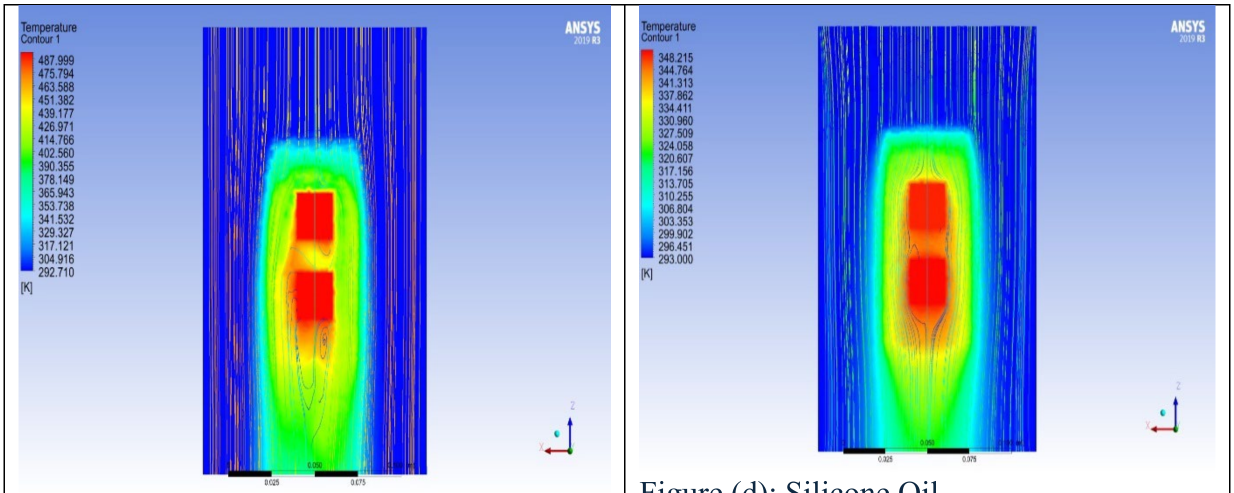


Figure (c): Mineral Oil

Figure (d): Silicone Oil

Figure 4. System simulation outputs

Table 2. Thermal Performance Summary

Dielectric Fluid	Outlet Temp. (K)	Heat Source Temp. (K)	Heat Absorbed (kJ/kg)
3M Novec 7000	302.61	389.88	12.34
Fluorinert FC-72	301.52	384.29	9.37
Mineral Oil	305.11	317.6	22.52
Silicone Oil	298.00	348.81	7.55

3.1.1 3M Novec 7000 and Fluorinert FC-72

The two fluorinated fluids achieved the lowest maximum heat source temperatures (384.29 K for FC-72 and 389.88 K for Novec 7000). This indicates superior convective heat transfer from the component surfaces to the bulk fluid. Their low viscosity (typically ~0.4 cSt) and favorable thermal properties enable thinner boundary layers and higher heat transfer coefficients, making them highly effective at removing heat directly from hot surfaces (Figure 5).

Although their heat absorption per unit mass is moderate, these fluids excel in applications where maintaining low junction temperatures is critical, such as high-power CPUs, GPUs, or power electronics.

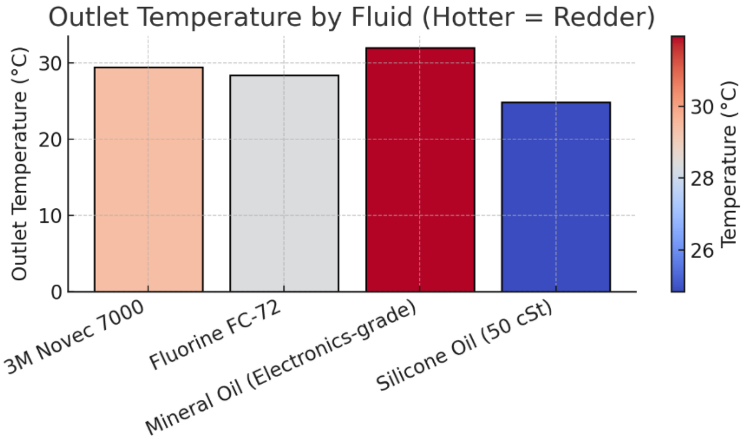


Figure 5. Comparative outlet temperatures for the four dielectric fluids.

3.1.2 Mineral Oil (Electronic Grade)

Mineral Oil recorded the highest heat source temperature control in this study (~317.6 K / 44.5°C) alongside the highest specific heat absorption (22.52 kJ/kg). This performance stems primarily from its significantly higher specific heat capacity compared to fluorinated fluids, allowing it to store more thermal energy per unit mass with a moderate temperature rise.

While the outlet temperature was the highest among the tested fluids (305.11 K), the strong thermal mass helps buffer against rapid temperature spikes under transient or high-load conditions. Electronic-grade mineral oil is widely recognized for its low cost and good dielectric properties, making it attractive for large-scale or cost-sensitive immersion cooling deployments, despite higher viscosity that may increase pumping power requirements.

3.1.3 Silicone Oil (50 cSt)

Silicone Oil produced the lowest outlet temperature (298 K) but only moderate heat source cooling (348.81 K). Its heat absorption capacity was the lowest (7.55 kJ/kg). The relatively high viscosity (50 cSt) likely results in thicker boundary layers and reduced convective efficiency under the simulated flow conditions. Silicone oils offer excellent thermal and chemical stability over a wide temperature range and are commonly used in transformer applications but may require higher flow rates or optimized channel designs to compete with lower-viscosity alternatives in electronics cooling.

3.2 Effect of Inlet Velocity

The inlet velocity was varied from 0.1 m/s to 1.0 m/s. As shown in Figure 6, increasing the velocity reduced the outlet temperature for all fluids due to enhanced convective heat transfer. This performance gain must be balanced against the increased pumping power required at higher flow rates.

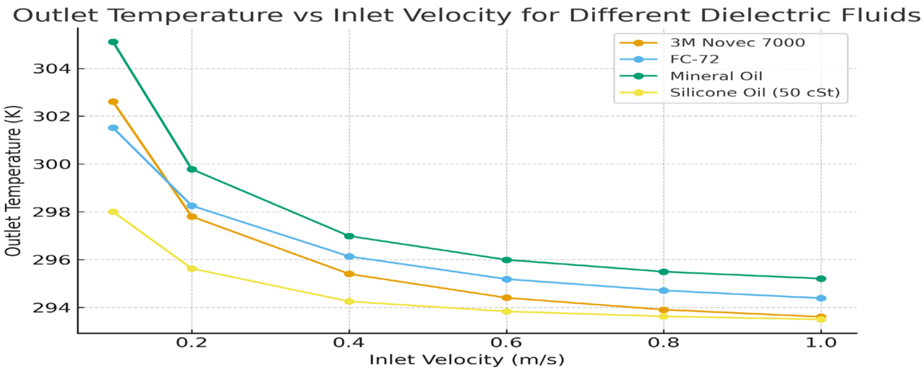


Figure 6. Variation of outlet temperature with inlet velocity.

3.3 Cost Analysis

A critical finding was the significant cost disparity between the fluids. As shown in Table 3, Mineral Oil is the most economical option by a substantial margin.

Table 3. Comparative Cost of Dielectric Fluids

Dielectric Fluid	**Cost (ZAR/L)**
Mineral Oil	123.50
Silicone Oil	617.50
Fluorinert FC-72	2,470.00
3M Novec 7000	2,964.00

4. Discussion

The simulation results showed significant differences in the thermal performance of the four dielectric fluids when subjected to the same flow and heat load conditions. The main metrics of outlet temperature, maximum heat source temperature and specific heat absorption (kJ/kg) elucidated distinct trade-offs between the performance of the fluids. The lowest maximum heat source temperature was achieved with Fluorinert FC-72 (384.29 K), then with 3M Novec 7000 (389.88 K). These two fluorinated fluids showed the best heat transfer from the electronic components to the coolant. They are especially attractive for high-reliability electronics where tight thermal margins are crucial, as their superior performance in keeping lower component temperatures is important. However, the heat absorption capacities of both fluids were relatively moderate at 9.37 kJ/kg and 12.34 kJ/kg, respectively.

Mineral Oil showed a different performance profile. It had the highest outlet temperature, 305.11 K, and the lowest heat source temperature, 317.60 K, of all fluids tested. Additionally, Mineral Oil absorbed the maximum thermal energy per unit mass at 22.52 kJ/kg. This result indicates a high heat storage capacity, implying that the fluid can efficiently buffer thermal loads and avoid fast temperature spikes in the components, despite its higher bulk temperature rise. The lowest outlet temperature of 298.00 K was obtained with Silicone Oil (50 cSt) which means the least temperature rise of the fluid itself while flowing through the system. However, it was only capable of a moderate cooling of the heat source with a maximum temperature of 348.81 K and the lowest heat absorption.
The results illustrate important trade-offs between thermal performance and cost. Although Fluorinert FC-72 and 3M Novec 7000 delivered the best component temperature control, their high costs may limit their adoption in large-scale or budget-sensitive applications. Conversely, Mineral Oil offered excellent overall thermal performance, particularly in heat absorption and component temperature management, at a fraction of the cost, positioning it as a highly competitive option. Silicone Oil, despite its moderate thermal results and higher cost relative to Mineral Oil, may still be considered where long-term fluid stability is prioritised.

In summary, the simulation outcomes and cost analysis indicate that fluid selection must be driven by the specific requirements of the cooling system. For applications demanding the lowest possible heat source temperatures and where budget permits, fluorinated fluids remain strong candidates. For cost-effective solutions with robust heat absorption capacity, Mineral Oil emerges as a compelling choice.

The single-phase immersion model proved effective in maintaining component temperatures within safe operating limits. The positive correlation between inlet velocity and cooling efficiency provides a lever for performance tuning, though system designers must consider the associated energy penalty for pumping. It has been observed that an increase in inlet velocity leads to a corresponding decrease in outlet temperature, as shown in Figure 6. Based on the cost analysis of the four dielectric fluids, mineral oil was identified as the most economical option, whereas 3M Novec 7000 exhibited the highest cost, as presented in Figure 7.

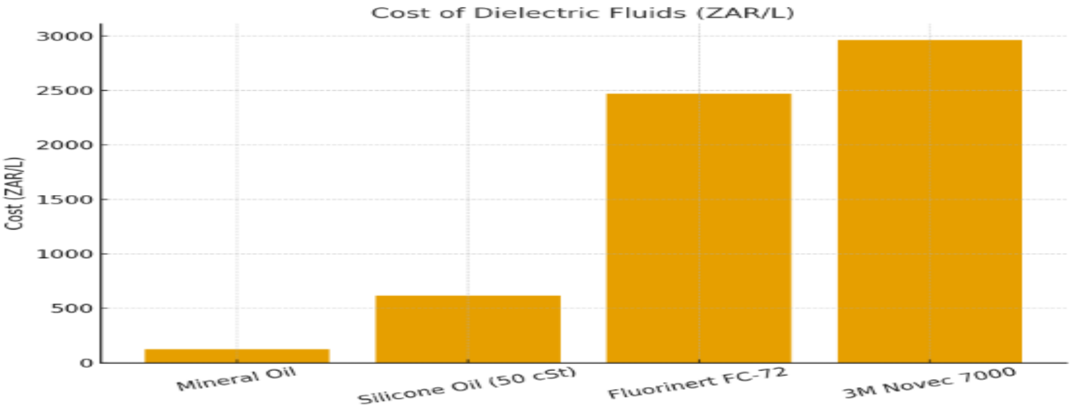


Figure 7. Comparative Cost per Litre of Dielectric Fluids (ZAR).

The study acknowledges its limitations, such as the absence of a physical prototype for validation. Future research should examine Mineral Oil's, Novec 7000 , FC 72 and Silicone long-term stability and material compatibility in immersion settings, as well as provide experimental validation.

5. Conclusion and Recommendations

This study developed and simulated an HPC liquid cooling system, selecting single-phase immersion as optimal. Mineral Oil offers cost-effective heat management, with fluorocarbons providing superior thermal stability. Findings advance HPC cooling, particularly for South Africa (Nicis n.d). Future research will focus on building a physical prototype for experimental validation and exploring hybrid cooling systems that integrate the cost-benefits of Mineral Oil with targeted high-performance cooling for the most critical components.

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