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EXPERIMENTAL ANALYSIS OF NATURAL CONVECTION HEAT TRANSFER USING AL_2O_3 NANOFLUIDS FOR HIGHER THERMAL EFFICIENCY

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Abstract. *The increasing demand for more compact and efficient electronic devices has brought significant challenges in heat dissipation, particularly in natural convection processes. In this context, nanofluids (NFs), composed of base liquids with added nanoparticles, emerge as a promising alternative for improving heat transfer. This work aims to develop an experimental setup to evaluate the thermal performance of distilled water-based nanofluids with alumina nanoparticles (Al_2O_3) at different concentrations (0.01%, 0.03%, 0.10%, and 0.20% by volume). The experimental setup was designed using additive manufacturing and components such as an electrical resistor, a quartz channel, and temperature sensors coupled to an Arduino-based data acquisition system. The nanofluid was prepared using the two-step method, involving nanoparticle synthesis, drying, and ultrasonic dispersion. Results indicated that the 0.03% concentration exhibited the best thermal performance, with an average increase of 35.55% in the heat transfer coefficient (h) compared to distilled water. Concentrations of 0.01% and 0.10% also showed relevant gains. However, at 0.20%, performance degradation was observed due to nanoparticle sedimentation, which compromised colloidal stability and, consequently, thermal efficiency. The study concludes that there is an optimal nanoparticle concentration range to maximize heat transfer, balancing thermal conductivity and nanofluid stability. Higher concentrations, though potentially more conductive, increase viscosity and promote precipitation, limiting thermal gains. For future work, the use of stabilizing agents and detailed rheological analysis is recommended to mitigate sedimentation effects and expand the applicability of nanofluids in natural convection systems.*

Keywords: *Alumina, Experimental Analysis, Heat Transfer, Nanofluids, Natural Convection.*

1. INTRODUCTION

Electronic devices present significant challenges related to heat dissipation. Furthermore, energy efficiency is directly linked to effective heat transfer. According to Goodarzi *et al.* (2020), modern device technologies are characterized by high efficiency and compact designs, requiring effective removal of substantial thermal loads. In such cases, natural convection is the primary heat transfer mode. Moreover, the absence of an efficient heat removal system can lead to elevated device temperatures, resulting in unsafe and unreliable operation (Liang and Mudawar, 2019; Marseglia *et al.,* 2024).

Traditionally, fluids such as oil, water, ethylene glycol, and acetone have been used to enhance heat transfer. However, with scientific advancements and increasing demands for thermal performance improvements, nanofluids (NFs) have emerged as a promising alternative. Uddin and Rasel (2019) highlight that NFs exhibit significant potential for improving heat conduction, as they consist of a base liquid combined with nanoscale particles.

Studies like Babar *et al.* (2022) demonstrate that adding metallic or non-metallic nanoparticles to the base fluid leads to substantial enhancements in thermal properties. Sanches *et al.* (2021) emphasize that alumina-based nanofluids exhibit high chemical stability. This is because the thermal properties of nanofluids are influenced by the physical characteristics of nanoparticles, such as size, shape, and concentration. Thus, the thermal conductivity of NFs varies according to these parameters (Rafiq *et al.,* 2021).

Therefore, this study aims to develop an experimental setup to characterize distilled water-based nanofluids containing alumina nanoparticles (Al_2O_3). Based on natural convection principles, we seek to evaluate the behavior of NFs at different Al_2O_3 concentrations and under varying heat flux gradients.

2. METHODOLOGY

This study was developed in three main stages: (1) construction of the experimental setup, (2) preparation of nanofluids, and (3) data collection.

2.1 EXPERIMENTAL SETUP

Initially, a system was designed for the study of natural convection with nanofluid, using additive manufacturing to build the experimental setup presented in Fig. 1, employing PLA polymer to form the enclosure and the heating support. The cavity on the right side of the system functions as a reservoir for ice and water, acting as the cold source. On the left side is the heating wall, also made of PLA, with 20% honeycomb-type infill and coated with fiberglass mat for thermal insulation.

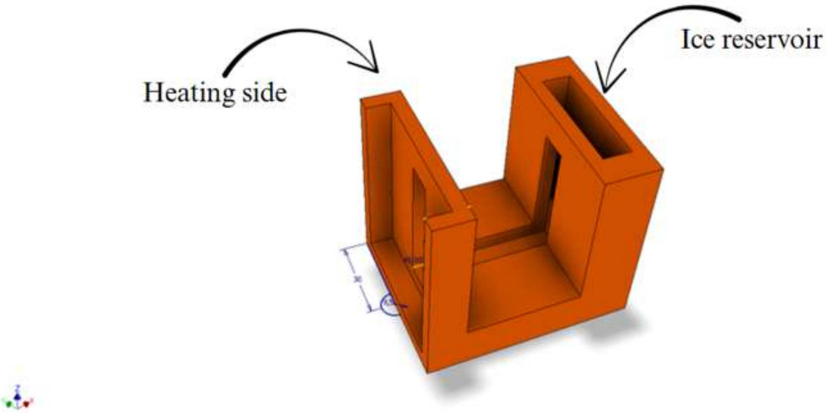

Figure 1. 3D design of the experimental system structure for the sides with heat source and cold source, from authors (2025)

As the heat source, a 40 W adhesive flexible electric heater was used, attached to a carbon steel plate measuring 50 × 60 mm (Fig. 2).

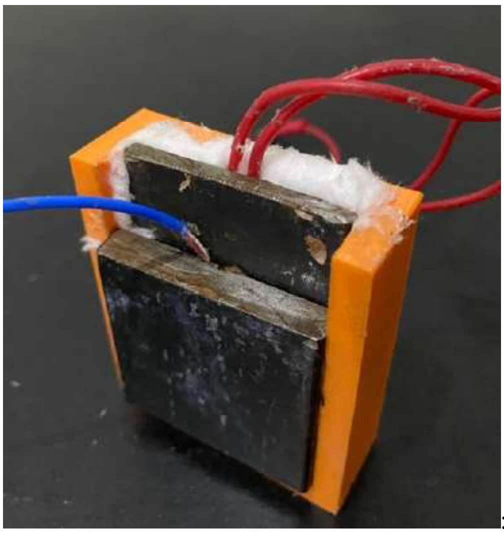
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Figure 2. Heating support with carbon plates along with the flexible heater, from authors (2025)

To contain the fluid, a quartz channel was used, selected for its high thermal resistance (withstanding up to approximately 900 °C under continuous operation). This channel was positioned so that one end was in contact with the cold source and the other with the hot source (Fig. 3).

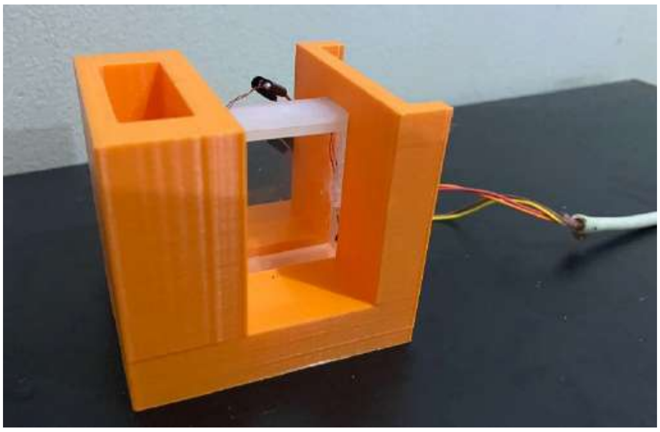


Figure 3. Quartz channel positioned on the system support with lateral thermistors, from authors (2025)

The thermal characterization of the nanofluid was based on the natural convection Eq. (1), which requires the area of the heated surface and the temperature difference between the ends of the channel:

$$Q = hA(T_{heated} - T_{fluid}), \quad (1)$$

To obtain these measurements, two thermistors were positioned at each end of the quartz channel, connected to the data acquisition system via an Arduino board. The sensors were secured using silicone adhesive (Fig. 4). The heat source temperature was monitored with a pre-calibrated K-type thermocouple (0°C to 70°C range). The entire system was thermally insulated with fiberglass matting and Silver Tape adhesive to minimize heat exchange with the environment.

2.2 PREPARATION OF AL_2O_3 NANOFLUIDS

Following experimental setup construction, the nanofluids were prepared using the two-step method as proposed by Mukherjee et al. (2020). First, functionalized alumina nanoparticles (Al_2O_3) were synthesized. For this process, 2.00097 g of aluminum hydroxide ($Al(OH)_3$), 40 mL of nitric acid (HNO_3) and 150 mL of distilled water, were used as reagents, homogenized in a beaker with magnetic stirring (Fig. 4).

Figure 4. Nitric acid, aluminum hydroxide, and water being homogenized by magnetic stirring, from authors (2025)

While the mixture was still in the acidic medium, neutralization was performed by gradually adding 50 mL of ammonium hydroxide (NH_4OH) using a burette. Following neutralization, the suspension was filtered under vacuum for approximately 20 minutes using a vacuum pump, with the crucible washed with 300 mL of distilled water. This process yielded neutralized alumina in solid form (Fig. 5).

Figure 5. Nanoparticles after filtration using a vacuum pump, from authors (2025)

The solid material was then subjected to oven drying. The calcination process lasted 4.5 hours, with controlled temperature variations between 35°C and 895°C. After calcination, the sample was cooled inside the switched-off furnace, remaining in a controlled environment for an additional 12 hours. Following drying, the alumina nanoparticles exhibited a final mass of 1.97 g, with an approximate loss of 0.03 g. Finally, the particles were ground, completing the preparation process (Fig. 6).

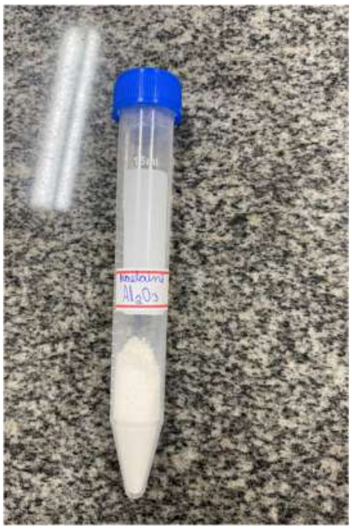


Figure 6. Alumina nanoparticle production completed, from authors (2025)

Furthermore, distilled water was used as the base fluid for nanofluid preparation. Following the nanoparticle volume fractions (0.01% to 1.00%) investigated by Sadegh Moghanlou *et al.* (2020), four samples were prepared with volume fractions of 0.01%, 0.03%, 0.1%, and 0.2% in 17 mL of base fluid. Table 1 shows the corresponding mass ratios for these fractions.

Table 1. Masses of Al_2O_3 and water relative to the final solution volume for different Concentrations.

Volume percentage of nanofluids	0,01% vol	0,03% vol	0,1% vol	0,2% vol
Al2O3 (g)	0,007	0,020	0,068	0,135
H2O (g)	16,998	16,995	16,983	16,966

After weighing the corresponding nanoparticle quantities, each solution underwent ultrasonic agitation for 15 minutes (Fig. 7) to ensure suspension homogeneity, as performed by Mukherjee et al. (2020). This process yielded stable aqueous-based nanofluids containing alumina nanoparticles.

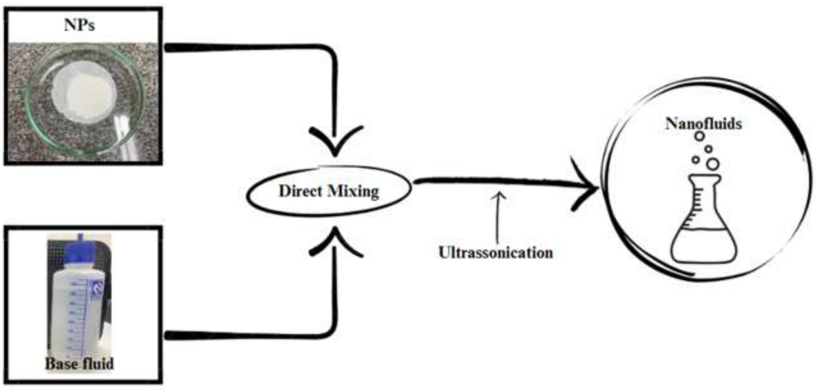


Figure 7. Flowchart of the nanofluid preparation process, from authors (2025)

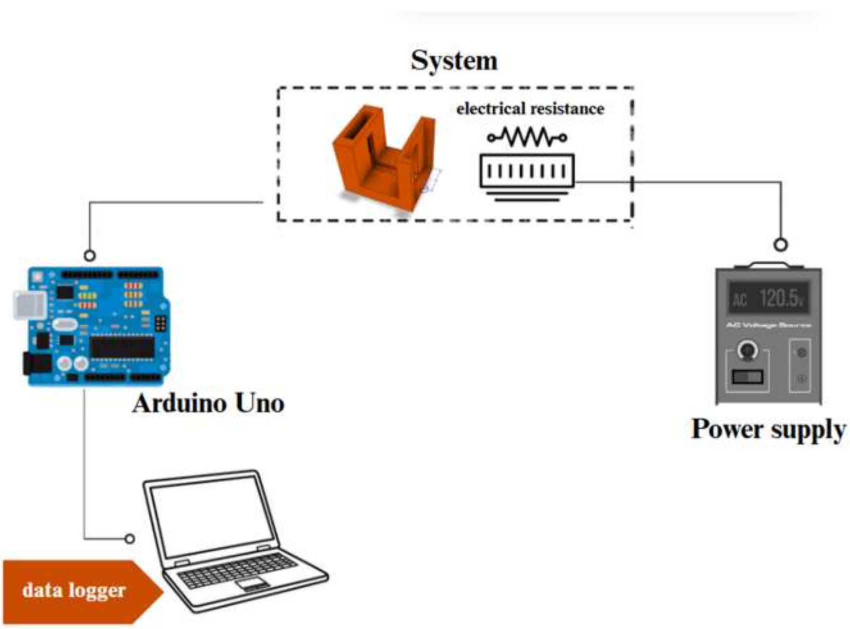
2.3 DATA COLLECTION

For the acquisition of experimental data, a measurement system was developed based on temperature sensors and an Arduino board. The system employed two NTC (Negative Temperature Coefficient) thermistors and a type K thermocouple, allowing precise monitoring of the temperatures at the ends of the flow channel. Thermistor readings were based on the voltage variation generated in conjunction with 10 kΩ resistors, while the thermocouple measurements used the MAX6675 module, with an accuracy of 2.00%, calibrated according to the sensor's characteristic curve.

The embedded algorithm, developed in C++, was programmed to perform 20 readings every 1000 milliseconds (1 second) and compute the average of these readings every 30000 milliseconds (5 minutes), ensuring noise reduction and greater data stability. The sensors were connected to analog pins A0 and A1 (thermistors) and to the digital pins dedicated to the SPI interface of the MAX6675 module (type K thermocouple). The main constants used in the code included: nominal thermistor resistance (10 kΩ) with 1.00% tolerance, Beta coefficient (3950), and supply voltage (5 V), which are essential parameters for calculating temperature using the Steinhart–Hart equation.

During the experiment, data collection was conducted in 5-minute cycles over a total of 30 minutes for each analyzed condition. The voltage applied to the heating resistor ranged from 2.6 V to 7.6 V, with average increments of 2 V. The electric current varied between 0.19 A and 0.57 A, controlled by a programmable power supply. The thermal power supplied to the hot source was then calculated as the product of voltage and current, and used as a key parameter for analyzing the thermal performance of the fluids.

Additionally, communication between the Arduino and Excel was established via a serial communication protocol, with data transmitted in text (CSV) format using embedded C/C++ commands. Microsoft Excel's Data Streamer add-in was used to capture the data directly from the serial port and organize it in real time (Fig. 8).



a)

b)

Figure 8. Experimental setup: a) Schematic diagram of the experimental setup; b) Photograph of the experimental setup, from authors (2025)

Under controlled conditions, a cold source was maintained using a mixture of ice cubes and distilled water in the thermal cavity opposite the heat source (Fig. 9). This configuration was chosen to maximize the thermal contact area and ensure a stable temperature throughout the experiment, optimizing heat transfer by natural convection. Furthermore, the temperatures at the cold source ranged from 8.77 °C to 39.14 °C, while the heat source ranged from 11.78 °C to 60.94 °C.

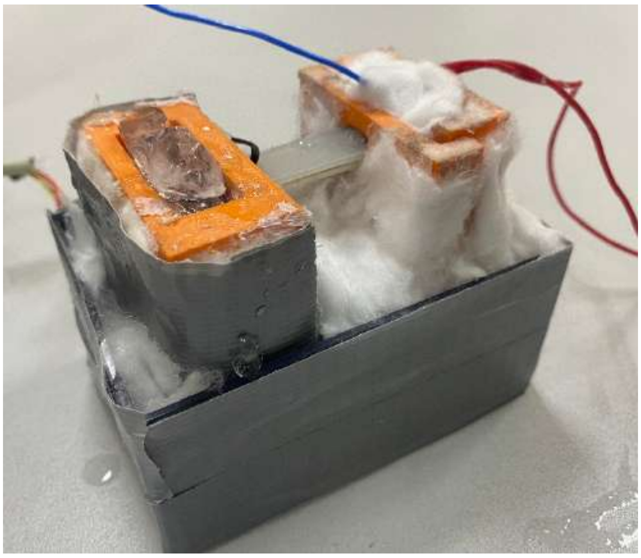


Figure 9. Assembled system with ice in the left cavity and heat source on the right, insulated with fiberglass 1blanket, from authors (2025)

The same experimental protocol, including time intervals, voltage and current ranges, and data collection methodology, was replicated for all nanofluid samples with different concentrations of alumina nanoparticles. Additionally, the heating source in all samples started at an initial temperature of approximately 20 °C. This standardization ensured the reproducibility and reliability of the results, enabling consistent comparisons among the different fluids analyzed.

3. RESULTS

The use of 0.03% nanoparticles by volume resulted in an average percentage increase of approximately 35.55% compared to distilled water, Fig.10. Additionally, concentrations of 0.01% and 0.10% also showed improvements in the convective heat transfer coefficient, “h”, of the fluid. However, the initial increase in “h” followed the increase in nanoparticle concentration, with the exception of 0.10% and 0.20%, which is attributed to the precipitation of nanoparticles during the experimental process (Fig. 11).

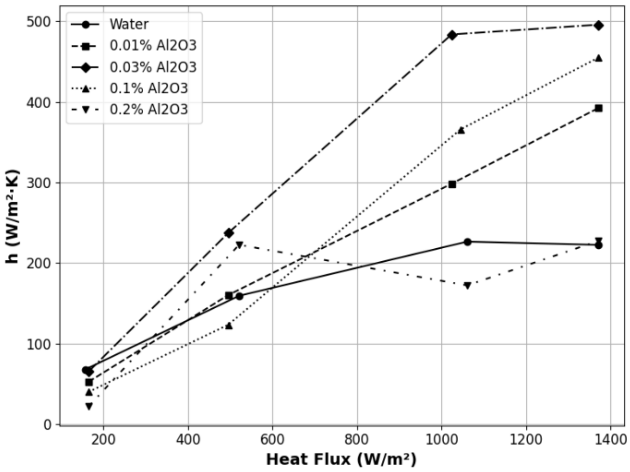
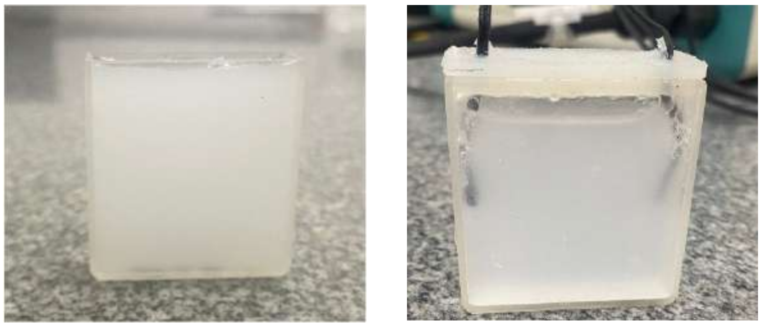


Figure 10. Graph showing the relationship between heat flux and convection coefficient for different nanoparticle concentrations, from authors (2025)



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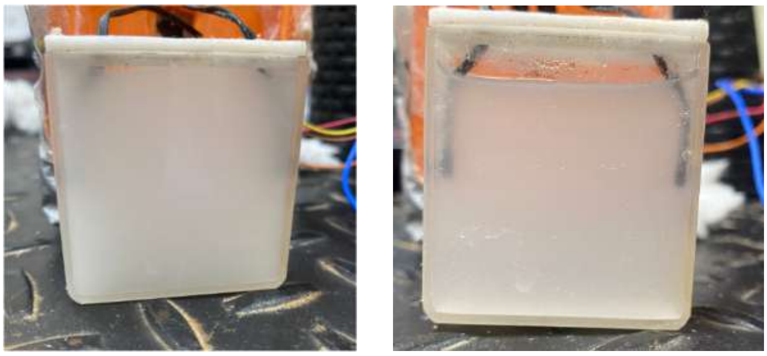

c) d)

Figure 11. Nanofluids before and after the experiment: a) 0.10% Al_2O_3 concentration before the experiment; b) 0.10% Al_2O_3 concentration after the experiment; c) 0.20% Al_2O_3 concentration before the experiment; d) 0.20% Al_2O_3 concentration after the experiment, from authors (2025)

Thus, it was observed that even with precipitation, the 0.10% concentration still yielded better results than water, while at 0.20% the values were close to those of water. The higher the amount of nanoparticles present in the nanofluid, the more likely and faster their precipitation occurs, influencing the results (especially at higher rates).

Furthermore, regarding thermal resistance with increasing heat flux (Fig. 2), a reduction was observed in all cases, all approaching near zero. However, starting from 500 W/m², nanofluids with concentrations between 0.01% and 0.10% exhibited lower thermal resistance than water, and this behavior persisted until the end of the experiment. Additionally, the 0.20% concentration showed higher values due to the larger number of agglomerates, which had already undergone significant sedimentation within the first 30 minutes. Nevertheless, increasing the power helps molecular movement, reducing the presence of agglomerates affecting natural convection.

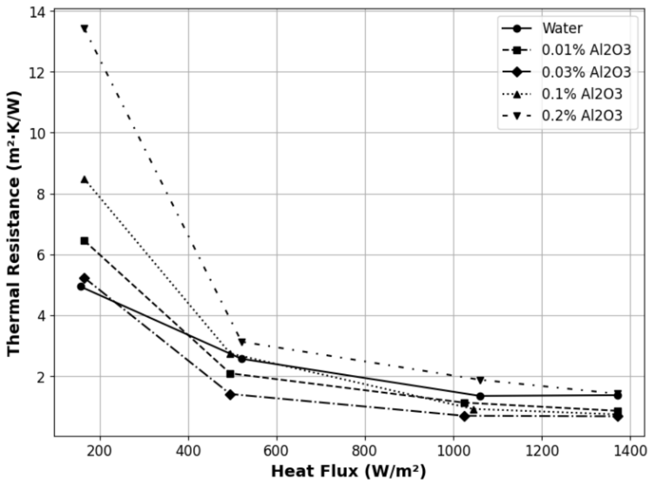

Figure 12. Graph showing the relationship between heat flux and thermal resistance for different nanoparticle concentrations, from authors (2025)

The temperature differential error observed when applying the same heat flux remained below 2.00%, confirming that the system operated under steady-state convection conditions.

4. CONCLUSION

Experimental tests enabled the characterization of the thermal behavior of Al_2O_3 nanofluids under natural convection conditions, using a test bench specifically developed for this purpose. The results showed that the addition of nanoparticles significantly enhances the heat transfer coefficient, with a notable improvement observed at a volumetric concentration of 0.03%, which yielded an average increase of 35.55% compared to distilled water.

Lower (0.01%) and slightly higher (0.10%) concentrations also demonstrated performance gains, although less pronounced. However, higher concentrations (0.10% and 0.20%) suffered from colloidal instability and sedimentation, reducing thermal efficiency, particularly under higher thermal gradients.

The operating regime near steady state, with deviations below 2%, validated the reliability of the data. It is concluded that there is an optimal range of nanoparticle concentration, constrained by factors such as colloidal stability and viscosity.

For applications involving natural convection, nanofluid stability is essential to maintain strong thermal performance. Future studies should focus on improving stability through the use of dispersing agents or functionalization techniques, aiming to expand the operational range while maintaining consistent thermal efficiency.

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7. RESPONSIBILITY NOTICE

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