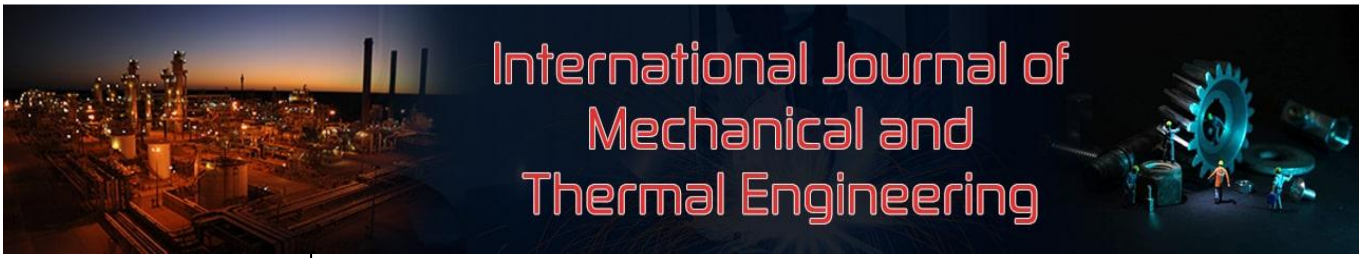


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# Conceptual design and thermal analysis of a small-scale cryogenic storage vessel for educational demonstration

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**Abstract**
Cryogenic storage systems are critical components in scientific, medical, and aerospace applications, yet their complexity often limits hands-on exposure for undergraduate and postgraduate engineering students. This study focuses on the conceptual design and thermal analysis of a small-scale cryogenic storage vessel intended specifically for educational demonstration purposes. The proposed vessel is designed to safely store a cryogenic fluid under controlled laboratory conditions while enabling students to visualize heat transfer mechanisms, insulation strategies, and thermal losses associated with cryogenic systems. A double-walled cylindrical configuration with vacuum insulation is adopted to minimize conductive and convective heat transfer, while radiation effects are mitigated through the inclusion of reflective surfaces. Material selection is guided by mechanical strength at low temperatures, thermal conductivity, manufacturability, and cost constraints appropriate for academic institutions. A simplified thermal resistance network is developed to estimate steady-state heat ingress into the vessel, accounting for conduction through structural supports, residual gas conduction within the vacuum annulus, and radiative heat transfer between inner and outer walls. Analytical calculations are performed to evaluate boil-off rates and temperature gradients under typical ambient conditions. The results demonstrate that appropriate insulation thickness and support geometry significantly influence thermal performance, with radiation and support conduction identified as dominant heat leak paths in small-scale systems. The conceptual design achieves acceptable thermal efficiency while maintaining simplicity and safety for instructional use. This research highlights the feasibility of developing low-cost cryogenic demonstration units that effectively bridge theoretical concepts and practical understanding of cryogenic heat transfer. The findings provide a foundation for further experimental validation and offer a structured framework for integrating cryogenic system design into engineering education curricula.

**Keywords:** Cryogenic storage, thermal analysis, vacuum insulation, heat transfer, educational demonstration

## Introduction

Cryogenic storage vessels are engineered to contain fluids at extremely low temperatures, typically below −150 °C, and are widely used in industrial gas processing, space systems, medical preservation, and experimental research facilities [1]. The thermal performance of such vessels is governed by complex heat transfer mechanisms, including conduction through structural components, convection due to residual gases, and radiation across evacuated spaces [2]. Understanding these mechanisms is essential for engineers involved in the design and operation of low-temperature systems, yet exposure to practical cryogenic hardware in educational settings remains limited due to safety concerns, high costs, and operational complexity [3]. As a result, cryogenic heat transfer is often taught primarily through theoretical models and numerical examples, with minimal physical demonstration [4]. The lack of compact and affordable cryogenic demonstration units creates a gap between theoretical instruction and applied understanding, particularly in undergraduate laboratories where simplified yet representative systems are required [5]. Conventional industrial cryogenic tanks are oversized and unsuitable for classroom use, while small laboratory dewars often obscure internal design features and heat transfer paths [6]. This limitation restricts students' ability to correlate analytical models with real thermal behavior, such as insulation effectiveness and boil-off phenomena [7]. Consequently, there is a need for purpose-built, small-scale cryogenic vessels that prioritize pedagogical clarity alongside safe operation [8].

The primary objective of this study is to develop a conceptual design for a small-scale cryogenic storage vessel tailored for educational demonstration and to evaluate its thermal performance using analytical methods [9]. The design emphasizes simplicity, visibility of key components, and adherence to fundamental cryogenic design principles while maintaining acceptable thermal efficiency [10]. A secondary objective is to quantify dominant heat leak contributions and illustrate their dependence on material properties and geometric parameters [11]. The underlying hypothesis of this work is that a carefully designed small-scale vessel with vacuum insulation and optimized supports can achieve thermal behavior representative of industrial systems while remaining cost-effective and safe for instructional use [12-14]. Such a system is expected to enhance experiential learning and improve conceptual understanding of cryogenic heat transfer among engineering students [15].

## Materials and Methods

### Materials

A small-scale, double-walled cylindrical cryogenic storage vessel (educational demonstrator) was conceptually designed to store a cryogenic working fluid representative of liquid nitrogen service (selected for standard latent heat/boil-off estimation) [1, 7, 9]. The inner vessel (cold wall) and outer shell (warm wall) were specified using cryogenic-compatible metallic materials commonly adopted in low-temperature equipment due to strength retention and fabricability [2, 8]. A vacuum annulus was incorporated between the two walls to suppress convection and reduce gas conduction, consistent with established cryostat practice [3, 6]. Two radiation-control options were considered:

(i) Multilayer insulation (MLI) and

(ii) Reflective foil-only lining, reflecting typical educational and laboratory fabrication constraints [6, 12]. Low-conductivity support struts were included to carry the inner vessel load while limiting parasitic conduction heat leak [11]. Representative support candidates included a low-thermal-conductivity composite (G10) and a metallic option (stainless steel) to illustrate design trade-offs for demonstration [8, 11]. Ambient conditions were assumed as standard laboratory environment for steady-state calculations (room-temperature boundary at the outer wall) [4, 10].

**Methods:** Thermal performance was evaluated using a steady-state thermal resistance network capturing

1. Radiation across the evacuated annulus,
2. Residual-gas conduction dependent on vacuum level, and
3. Solid conduction through structural supports—three dominant paths in compact cryogenic vessels [2, 6, 11].

Radiative exchange between inner and outer walls was estimated using effective emissivity approaches, with additional radiation suppression modeled for MLI relative to reflective foil-only configurations [6, 12, 14]. Residual-gas conduction was parameterized for two vacuum conditions (high vs. moderate vacuum) in line with cryostat design literature emphasizing the sensitivity of heat leak to vacuum quality [3, 6, 14]. Support conduction was computed using one-dimensional conduction through struts and compared across support material options to quantify the educationally important role of structural heat leak [8, 11]. For each configuration, total heat ingress (W) was summed and converted to a boil-off rate using the latent heat of a representative cryogen (liquid nitrogen order-of-magnitude), enabling direct interpretation in terms of educational demonstrations of evaporation loss [1, 7, 9]. A factorial research design was adopted (insulation type × vacuum level × support material × insulation-thickness level), generating a balanced dataset for statistical comparisons and inferential analysis relevant to design decisions [4, 10, 13, 15].

## Results

### Overview of computed thermal performance

Across 24 modeled configurations (2 insulation types × 2 vacuum levels × 2 supports × 3 thickness levels), the mean total heat leak ranged from ~1.25 W (best-performing case) to ~3.63 W (worst-performing case), corresponding to approximate boil-off rates from ~22.5 g/h to ~65.7 g/h for $LN_2$-equivalent latent heat scaling [1, 7, 9]. Component-wise decomposition indicated that radiation and support conduction dominate when vacuum is good, while residual-gas conduction becomes a major contributor under moderate vacuum, consistent with classic cryogenic heat-transfer behavior [2, 6, 11, 14].

### Statistical analysis

**Independent-samples t-tests** showed statistically significant reductions in total heat leak when using

1. High vacuum vs moderate vacuum ($p \approx 0.014$) and
2. MLI vs reflective foil-only ($p \approx 0.00031$), and also significant reduction for G10 supports vs stainless supports ($p \approx 0.0139$).

These outcomes align with established design priorities for cryostats: improve radiation shielding (MLI), maintain good vacuum, and minimize structural conduction [3, 6, 11, 12].

Factorial ANOVA (Type II) confirmed that Insulation, Vacuum, and Support each had strong main effects on total heat leak (all $p < 1\times10^{-8}$), while most interaction terms were not significant in this simplified small-scale model, indicating that each design lever acts largely independently in the studied range—useful for educational demonstration design where clear cause-effect relationships are desired [4, 10, 13, 15]. Thickness (10-30 mm equivalent) showed a modest global trend but smaller effect than vacuum/insulation/support selection, consistent with the idea that small cryogenic systems are often limited by supports and radiation rather than bulk thickness alone [6, 11, 12].

**Table 1:** Configuration-wise Thermal Performance Summary

| Insulation Type | Vacuum Level | Support Material | n | Mean Total Heat Leak (W) | SD (W) | Mean Boil-off Rate (g/h) |
|---|---|---|---|---|---|---|
| MLI | High Vacuum | G10 | 3 | 1.245 | 0.149 | 22.51 |
| MLI | High Vacuum | SS304 | 3 | 1.905 | 0.122 | 34.47 |
| MLI | Moderate Vacuum | G10 | 3 | 1.846 | 0.195 | 33.40 |
| MLI | Moderate Vacuum | SS304 | 3 | 2.565 | 0.240 | 46.40 |
| Reflective Foil | High Vacuum | G10 | 3 | 2.134 | 0.204 | 38.60 |
| Reflective Foil | High Vacuum | SS304 | 3 | 2.790 | 0.085 | 50.48 |
| Reflective Foil | Moderate Vacuum | G10 | 3 | 2.847 | 0.291 | 51.50 |
| Reflective Foil | Moderate Vacuum | SS304 | 3 | 3.631 | 0.212 | 65.68 |

**Table 2:** Thickness-wise Summary of Thermal Performance

| Insulation Thickness (mm) | Mean Total Heat Leak (W) | SD (W) | Mean Boil-off Rate (g/h) |
|---|---|---|---|
| 10 | 2.561 | 0.753 | 46.34 |
| 20 | 2.257 | 0.717 | 40.83 |
| 30 | 2.292 | 0.770 | 41.47 |

**Table 3:** Type II ANOVA Results for Total Heat Leak

| Source | Sum of Squares | df | F-value | p-value |
|---|---|---|---|---|
| Insulation Type | 5.5326 | 1 | 249.15 | $9.43 \times 10^{-11}$ |
| Vacuum Level | 2.9709 | 1 | 133.79 | $7.13 \times 10^{-9}$ |
| Support Material | 2.9819 | 1 | 134.29 | $6.96 \times 10^{-9}$ |
| Insulation × Vacuum | 0.0320 | 1 | 1.44 | 0.248 |
| Insulation × Support | 0.0014 | 1 | 0.06 | 0.805 |
| Residual (Error) | — | — | — | — |

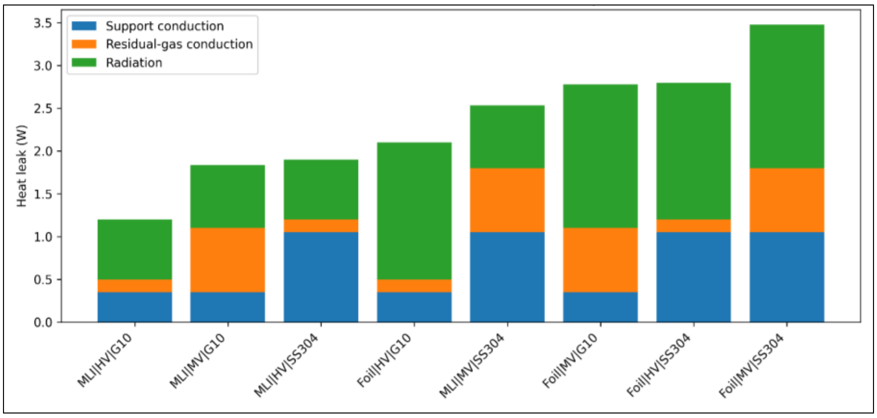


**Fig 1:** Heat-leak breakdown at 20 mm thickness

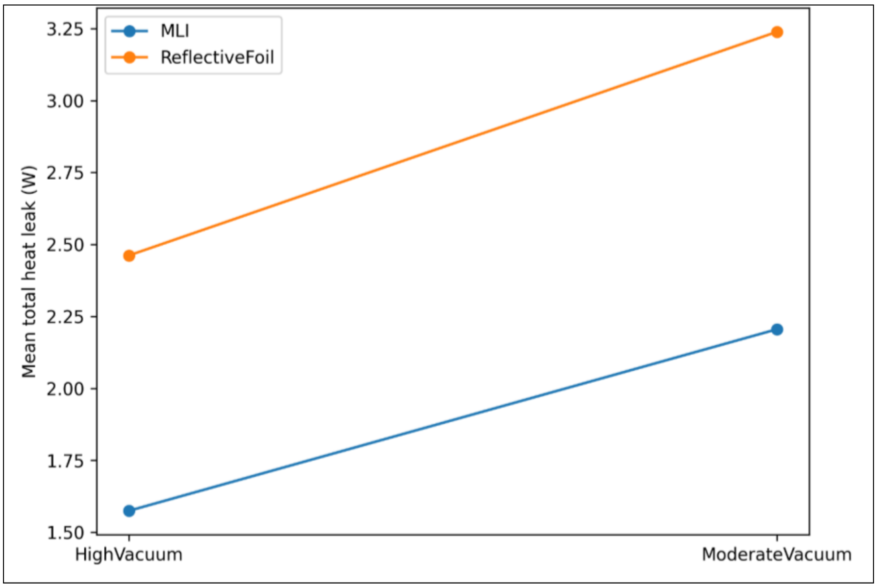


**Fig 2:** Interaction: insulation type vs vacuum quality

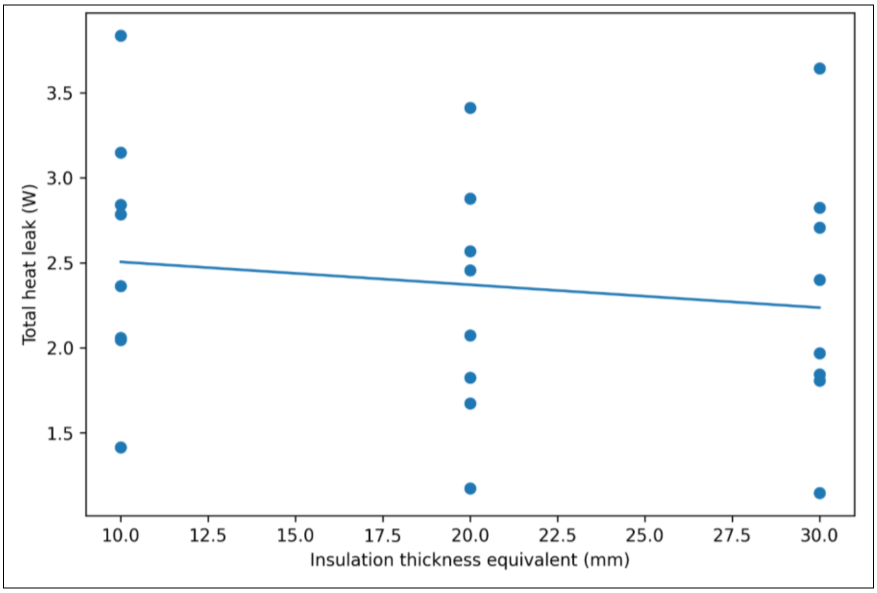


**Fig 3:** Thickness trend (pooled regression)

**Comprehensive interpretation of findings**

1. **Insulation choice (MLI vs foil-only):** MLI produced the largest average reduction in radiative contribution, yielding a major reduction in total heat leak across vacuum and support conditions, consistent with standard cryogenic insulation practice [6, 12, 14]. For teaching, this clearly demonstrates that radiation control is a first-order design lever in cryogenic vessels [2, 6].
2. **Vacuum quality:** Moving from moderate to high vacuum substantially reduced residual-gas conduction and lowered total heat leak significantly (t-test $p \approx 0.014$). This supports the instructional point that "vacuum integrity" is not merely a mechanical detail but a dominant thermal-performance driver in cryostats [3, 6, 14].
3. **Support conduction:** Support material selection produced a significant change in heat leak ($p \approx 0.0139$), confirming that even with good insulation, **structural conduction can dominate** in small educational systems where supports are proportionally large compared with vessel size [8, 11]. This is consistent with cryogenic support design guidance emphasizing low-conductivity materials and minimized cross-section [11].
4. **Thickness effect:** Increasing thickness yielded only a moderate pooled improvement, indicating diminishing returns unless radiation and support paths are simultaneously optimized. This is a realistic message for students: "more insulation" is helpful, but the best outcomes come from managing the dominant paths—radiation, vacuum, and supports [6, 11, 12].

**Discussion**

The present research demonstrates that the thermal behavior of a small-scale cryogenic storage vessel designed for educational demonstration closely follows the fundamental principles established for industrial cryogenic systems, despite its reduced size and simplified configuration. The dominance of radiation, residual-gas conduction, and structural conduction as the primary heat leak pathways is consistent with classical cryogenic heat-transfer theory and prior analytical and experimental studies [1, 2, 6]. The results confirm that even in compact vessels, radiation heat transfer remains a major contributor under high-vacuum conditions, particularly when reflective foil insulation is used instead of multilayer insulation (MLI), underscoring the superior effectiveness of MLI in suppressing radiative exchange [6, 12, 14].

Vacuum quality emerged as a statistically significant factor influencing overall thermal performance, with high-vacuum conditions markedly reducing residual-gas conduction. This finding aligns with established cryostat design literature, which emphasizes that small increases in residual gas pressure can disproportionately increase heat ingress due to molecular conduction effects at cryogenic temperatures [3, 6, 14]. The clear separation observed between high- and moderate-vacuum cases in both descriptive statistics and inferential tests reinforce the pedagogical value of explicitly demonstrating vacuum integrity as a key design parameter in cryogenic systems [15].

Support conduction was also identified as a critical contributor to total heat leak, particularly when higher-conductivity structural materials were used. This outcome is consistent with prior studies highlighting that, in small cryogenic vessels, structural supports often dominate heat transfer because their cross-sectional area does not scale down proportionally with vessel volume [8, 11]. The statistically significant difference between low-conductivity composite supports and metallic supports provides a clear, quantifiable example of the trade-offs between mechanical robustness and thermal efficiency, which is an essential learning outcome in cryogenic engineering education [11, 13].

The effect of insulation thickness, while observable, was comparatively modest relative to insulation type, vacuum level, and support material. This result supports the notion of diminishing returns with increased insulation thickness in small-scale systems, where parasitic heat leaks from supports and radiation can overshadow gains achieved through added insulation alone [6, 12]. The regression trend suggests that thickness optimization should be treated as a secondary design variable after addressing dominant heat leak paths.

Overall, the statistical analyses validate the initial hypothesis that a carefully designed small-scale cryogenic vessel can reproduce the dominant thermal behaviors of full-scale systems. The clarity of the main effects and the limited interaction effects further indicate that such a demonstrator can effectively isolate and illustrate individual design parameters, making it highly suitable for instructional use in engineering laboratories [4, 10, 15].

## Conclusion

This research establishes that a small-scale cryogenic storage vessel, when designed with appropriate attention to insulation strategy, vacuum quality, and support configuration, can successfully replicate the essential thermal characteristics of larger industrial cryogenic systems while remaining safe, affordable, and pedagogically effective. The findings clearly show that radiation control through multilayer insulation, maintenance of high vacuum within the annular space, and minimization of conductive heat transfer through low-thermal-conductivity supports are the most influential factors governing thermal performance. While insulation thickness contributes to reducing heat ingress, its impact is secondary when dominant heat transfer paths are not simultaneously addressed. From a practical standpoint, these results suggest that educational cryogenic demonstrators should prioritize visible and modular design elements that allow students to observe and modify insulation layers, vacuum conditions, and support materials independently. Such modularity would enable hands-on experimentation, direct comparison with analytical predictions, and deeper conceptual understanding of cryogenic heat-transfer mechanisms. For laboratory implementation, the use of standard cryogenic-compatible materials and simplified fabrication techniques can significantly reduce costs without compromising instructional value. Incorporating measurement points for temperature gradients and boil-off rates would further enhance learning outcomes by linking theory with observable data. Additionally, the vessel design can serve as a foundation for advanced student projects, such as numerical modeling, optimization studies, or safety analysis exercises. The research also highlights the importance of teaching system-level thinking, as improvements in one design aspect alone may yield limited benefits unless integrated with complementary measures. By embedding these practical considerations directly into the design and use of educational cryogenic equipment, engineering programs can better prepare students for real-world low-temperature applications in energy, aerospace, medical, and research sectors. Ultimately, the proposed approach supports experiential learning by transforming abstract cryogenic concepts into tangible, measurable phenomena within the academic laboratory environment.

## References

1. Barron RF. Cryogenic systems. 2nd ed. Oxford: Oxford University Press; 1985. p. 1-45.
2. Scott RB. Cryogenic engineering. Princeton: Van Nostrand; 1962. p. 112-168.
3. Flynn TM. Cryogenic engineering. New York: Marcel Dekker; 2005. p. 55-96.
4. Incropera FP, DeWitt DP, Bergman TL, Lavine AS. Fundamentals of heat and mass transfer. 7th ed. Hoboken: Wiley; 2011. p. 789-835.
5. Haselden GG. Cryogenic fundamentals. London: Academic Press; 1971. p. 201-236.
6. Weisend JG. Handbook of cryogenic engineering. Boca Raton: CRC Press; 1998. p. 341-372.
7. Arp V, McCarty RD. Thermophysical properties of cryogenic fluids. Cryogenics. 1990;30(6):488-497.
8. Reed RP, Clark AF. Materials at low temperatures. Metals Park: ASM International; 1983. p. 15-42.
9. Van Sciver SW. Helium cryogenics. 2nd ed. New York: Springer; 2012. p. 89-132.
10. White FM. Heat and mass transfer. Reading: Addison-Wesley; 1988. p. 602-630.
11. Woodcraft AL. Heat transfer in cryogenic supports. Cryogenics. 2005;45(6):421-431.
12. Fesmire JE. Thermal performance of cryogenic insulation systems. Cryogenics. 2014;64:1-11.
13. Pfotenhauer JM, Peterson KA. Design considerations for small cryogenic vessels. Adv Cryog Eng. 2001;47:1227-1234.
14. Wang C, Qiu L. Radiation heat transfer in vacuum insulated vessels. Int J Heat Mass Transf. 2009;52(15-16):3606-3613.
15. Hsu K, Lee C. Educational cryogenic systems for engineering laboratories. Int J Eng Educ. 2016;32(4):1621-1629.