Multilayer Insulation (MLI) Materials & Thermal Performance — Comprehensive Technical Reference

Prepared by: East Far Materials Engineering Team | Industrial Application Research

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1. Introduction

Multilayer Insulation (MLI), also known as superinsulation, is a high-performance thermal insulation system consisting of multiple layers of low-emittance reflective shields separated by low-conductance spacer materials. Originally developed in the 1960s—most notably through early characterization work by A.D. Little—MLI has become the gold standard for thermal management in cryogenic systems, spacecraft, and specialized high-temperature applications.

The fundamental operating principle of MLI is the suppression of radiative heat transfer between two boundaries at different temperatures. Each reflective shield intercepts and reflects a large fraction of incident thermal radiation, causing the radiative heat flux to decrease approximately as $1/(N + 1)$, where N is the number of shields. However, the introduction of spacer materials and the inevitable solid conduction between layers complicate this ideal behavior, leading to the rich phenomenology documented in this reference.

Under high-vacuum conditions ($< 10^{-4}$ torr), MLI systems can achieve heat flux densities below 0.1 W/ m² and apparent thermal conductivities below 0.1 mW/m·K; ideal systems can reach approximately 0.05 mW/m·K [Source: NASA NTRS – Robust MLI]. In real-world engineering applications, performance is typically 2–10×worse than laboratory results due to installation seams, penetrations, compression, and other practical factors [Source: NASA NTRS – Cryogenic Insulation System for Soft Vacuum].

MLI is critical in several domains:

Cryogenic systems: Liquid hydrogen (LH_2, 20 K), liquid helium (LHe, 4.2 K), and liquid nitrogen (LN_2, 77 K) storage and transport depend on MLI to minimize boil-off losses. Performance targets are often sub-W/ m² heat flux levels.

Spacecraft thermal control: MLI blankets protect spacecraft from extreme solar heating and deep-space cooling, maintaining internal temperatures within operational limits.

Superconducting magnets: MRI systems and particle accelerators (e.g., ITER, CERN LHC) use MLI to shield cryogenic components from ambient thermal loads.

High-temperature systems: Radioisotope thermoelectric generators (RTGs), nuclear power systems (e.g., JPL SP-100), and hypersonic vehicles require specialized MLI capable of withstanding temperatures exceeding 1000 °C.

This document compiles comprehensive data on MLI materials, mathematical models (particularly the Lockheed correlation), and test results from institutions worldwide. It is intended as a standalone reference for engineers and procurement decision-makers evaluating MLI solutions for specific applications.

2. Reflective Shield Materials

The reflective shield is the core component of any MLI system. Its function is to reflect incident thermal radiation, thereby reducing the radiative heat transfer between layers. The effectiveness of a reflective shield is primarily determined by its emissivity (lower is better), its thermal stability range, and its compatibility with spacer materials and operating environments.

The most commonly used reflective shields are based on vacuum-deposited aluminum on polymer substrates (e.g., Mylar/polyester or Kapton/polyimide), offering an excellent balance of low emissivity, low cost, and adequate thermal range. Specialized applications—particularly those involving extreme temperatures—may require metal foils such as molybdenum, nickel, niobium, stainless steel, or zirconium. Research continues into alternative coatings (gold, silver, multi-metal) and novel structures (dimpled, embossed) that eliminate the need for separate spacer layers.

The table below lists all known reflective shield materials used in MLI systems, along with their key properties.

No.	Material	Thickness	Emissivity (RT)	Max Temp	Notes	Source
1	Aluminum foil	6–12 μm	0.03–0.04	~500°C	Low cost, most common; purity 99.45%	NASA KSC, Chinese institution s, Frako- Term
2	Double Aluminize d Mylar (DAM)	6.35μm (¼mil) / 25.4μm (1 mil)	≤0.04	~150°C	Most widely used; Mylar melts ~250°C	NASA KSC/ GRC/ MSFC, JPL, Chinese institution s
3	Double Aluminize d Kapton (DAK)	25μm (Kapton) + 100 nm (Al)	≤0.04	~400°C	High temp applicatio ns; embossed version available; effective emissivity 9–15% lower than PET blankets	NASA JWST, Texas Tech, Cryogenic s journal
4	Gold foil / Goldized Kapton	1μm (Au coating)	~0.02– 0.03	≤1000 °C+	Premium; high- temp oxidation resistance; extremely high IR reflectanc e	NASA high- temp MLI, Arthur D. Little, Convair
5	Copper foil	—	~0.02	≤~500 °C	Research use; high oxidation risk; tested at 273°C in Europa Clipper mission	NASA TFAWS 2023
6	Molybden um foil	8–100 μm	~0.10	1700°C+	Ultra-high temp; RTG/ nuclear power applicatio ns; 8 μm baseline for SP-100	Deep Space Exploratio n Journal 2024, JPL SP-100
7	Nickel foil	—	—	~1000°C	SP-100 project; reacts with Cu at low temps; specific MLI test data not yet available [INFO_GA P]	NASA TFAWS 2023
8	Titanium	—	—	≤~500 °C	Europa Clipper high- temp layer, tested at 241 °C; JPL SP-100 evaluation	NASA TFAWS 2023, JPL SP-100
9	Nextel 312 fabric	—	—	≤1200 °C	Ceramic fiber fabric; extreme high- temp resistance; tested at 149 °C (solar test)	NASA TFAWS 2023
10	Single Aluminize d Mylar (AM)	6μm	≤0.04	~150°C	Single- sided aluminize d; used in combinati on with DAM	NASA TFAWS 2018
11	Glass- backed aluminize d Dacron	5 mil (127 μm)	≤0.04	Cryogenic	New product by Dunmore for cryogenic applicatio ns	Texas Tech/ Dunmore
12	Dimpled DAM	25.4μm film / 1.6 mm dimple	Unknown	~150°C	Self- spacing; no separate spacer needed	NASA KSC
13	Embossed DAK	25μm	≤0.04	~400°C	Surface embossin g; no separate spacer needed	Texas Tech/ICES, NASA TFAWS 2018
14	Stainless steel foil	10–20 μm	—	500–1000°C	NASA Ames high- temp MLI reflector; flexible high- temp TPS structure	NASA Ames [Source: Materials 2025]
15	Carbon foil	—	—	High temp	JPL SP-100 evaluation ; extreme temperatu re resistance	JPL SP-100 [Source: Materials 2025]
16	Zirconium foil	—	—	High temp	JPL SP-100 evaluation ; BIPS system compatibil ity testing	JPL SP-100 [Source: Materials 2025]
—	Goldized Polyimide	—	0.03	—	Alternativ e coating; referenced in Lockheed correlation	Lockheed Martin
—	Silver- coated	—	0.02	—	Alternativ e coating; referenced in Lockheed correlation	Lockheed Martin
—	Niobium foil	—	—	High temp	JPL SP-100 evaluation ; weight reduction potential 44–85% vs. Mo foil; reacts with ZrO_2 near 1000 °C	JPL SP-100 [Source: Materials 2025]

Notes on Reflective Shield Selection

DAM remains the workhorse of the MLI industry due to its extremely low cost, excellent low-temperature emissivity (≤0.04), and ease of handling. The primary limitation is its maximum operating temperature (~150°C), constrained by the Mylar substrate. In high vacuum, DAM-based MLI achieves k-values of 0.03–0.09 mW/m•K and heat flux of 0.25–0.87 W/m² [Source: NASA NTRS 2011; Quest Thermal 2024].

DAK extends the temperature range to ~400°C (−269°C to 400°C) by replacing Mylar with Kapton (polyimide), making it suitable for warmer cryogenic applications and near-spacecraft surfaces. At 4 K, the thermal conductivity is dominated by the aluminum coating layer [Source: NASA NTRS 2008]. Effective emissivity is 9–15% lower than PET blankets [Source: Cryogenics 2019].

Aluminum foil (pure) offers higher temperature tolerance (~500°C) than aluminized polymer films and is commonly paired with fiberglass paper spacers in NASA KSC test configurations. ASTM C740 designates Al foil + fiberglass paper (60 layers, k = 0.086 mW/m•K) as the baseline reference system.

Gold-coated foil (1 µm Au coating) is used for high-temperature MLI (300–1300 K), offering exceptional IR reflectance and oxidation resistance. Early work by Arthur D. Little used double goldized Mylar with silk net spacers, achieving 0.33 Btu/hr•ft² [Source: NASA NTRS 1968]. Convair/NASA used goldized Kapton with Dacron fiber tufts, achieving k = 1.37–1.5× 10^{-5} Btu/hr•ft•°F [Source: NASA NTRS 1972].

Molybdenum foil is the only practical option for ultra-high-temperature MLI (>1000 °C), though its higher emissivity (~0.10) degrades radiative performance compared to aluminum-based shields. An 8 µm Mo foil serves as the baseline for the JPL SP-100 project evaluations.

Stainless steel foil (10–20µm) was developed by NASA Ames for flexible high-temperature TPS structures, operating at 500–1000°C with borosilicate aluminum fine yarn cloth spacers and silicon fiber felt + alumina fiber insulation [Source: Materials 2025].

JPL SP-100 evaluation: The SP-100 project systematically evaluated carbon, niobium, titanium, and zirconium foils as high-temperature MLI reflectors, using 8µmmolybdenum foil as the baseline. All candidate materials showed weight reduction potential of 44–85% compared to Mo foil [Source: Materials 2025].

Copper foil was tested as the high-temperature MLI outer layer in the Europa Clipper mission, reaching 273 °C in solar testing. However, copper has a high oxidation risk and its primary research value is in high-temperature applications rather than cryogenic thermal conductivity [Source: NASA TFAWS 2023].

Titaniumwas also evaluated in the Europa Clipper mission (tested at 241°C) and in the JPL SP-100 project, with a maximum operating temperature of ~500°C [Source: NASA TFAWS 2023; JPL SP-100].

Nextel 312 fabric is a ceramic fiber fabric capable of withstanding temperatures up to 1200 °C, tested at 149°C in solar testing for the Europa Clipper mission [Source: NASA TFAWS 2023].

Gold and silver coatings offer marginally lower emissivity than aluminum (0.02–0.03 vs. 0.03–0.04) but at significantly higher cost; their use is typically limited to specialized applications where the incremental performance gain is justified.

Dimpled and embossed shields represent a structural innovation that eliminates the need for separate spacer materials, reducing blanket thickness and assembly complexity. Performance comparison with Dacron net shows negligible difference (ε* 0.0075 vs. 0.0068) [Source: NASA TFAWS 2018].

Multi-metal coatings (Al + Au + Cu alternating layers) achieve a 33.54% heat flux reduction compared to pure aluminum in research settings, exploiting the different spectral properties of each metal [Source: 真 空与低温].

3. Spacer/Insulation Materials

Spacer materials serve a critical function in MLI systems: they maintain physical separation between reflective shields, preventing direct contact that would create thermal short circuits through solid conduction. The ideal spacer has extremely low thermal conductivity, an open structure that facilitates gas evacuation (for vacuum-dependent performance), and adequate mechanical properties to maintain layer spacing under compression and thermal cycling.

Spacer selection involves trade-offs between thermal performance, gas evacuation characteristics, temperature tolerance, and mechanical stability. Open-structure netting (e.g., Dacron) allows efficient gas evacuation but permits higher gas conduction at soft-vacuum levels. Continuous-barrier materials (e.g., fiberglass paper) impede gas evacuation but reduce gas conduction. Advanced structured spacers (e.g., IMLI polymer pins) provide precise spacing control for optimized performance.

The table below lists all known spacer/insulation materials used in MLI systems.

No.	Material	Type	Typical Thickness	Max Temp	Notes	Source
1	Dacron net (polyester net)	Netting	7 mil (0.18 mm); 14.9 g/m²	~150°C	Most common; open structure allows gas evacuatio n	NASA KSC, JPL, Texas Tech
2	Silk net (single– SSN)	Netting	—	~150°C	Used in Lockheed dewar MLI; higher conductan ce	Lockheed Martin, JPL
3	Silk net (triple per DAM layer)	Netting	—	~150°C	Lockheed' s best cryogenic MLI; 10× lower conductan ce	Lockheed Martin, JPL
4	Nylon net	Netting	—	~120°C	Used in JAXA pin- controlled MLI	JAXA
5	Polyester fabric	Fabric	—	~150°C	Used in NASA LCI systems	NASA KSC
6	Fiberglass paper / silk paper	Paper	61µm (0.061 mm)	~500°C	Continuou s barrier; traditional standard spacer; used in many NASA KSC tests and Frako-	NASA KSC, Frako-Term

No.	Material	Type	Typical Thickness	Max Temp	Notes	Source
					Term commerci al MLI	
7	Fiberglass cloth	Fabric	—	~500°C+	High temp; commonly used in Chinese MLI systems	真空与低 温, 低温与 超导
8	Polyimide (Kapton) spacers	Polymer	—	~400°C	High temp applicatio ns	NASA
9	Polymer spacers (IMLI/ LRMLI)	Structured polymer	Micro- molded structure	~200°C	Quest Product Developm ent; precisely spaced; each layer's heat leak only 50% of conventio nal net- spaced MLI	Quest Thermal, NASA GRC/MSFC
10	Aerogel blanket/ pad	Composite	16–21 mm	~500°C	NASA tested; 2 mm pads between Al plates; best at	NASA KSC Cryostat-1 /3
					ambient pressure; compleme ntary with MLI in high vacuum	
11	Quartz fiber	Fiber	—	~1000 °C+	SP-100 project; high temp spacer	JPL SP-100
12	Quartz fiber cloth	Fabric	~0.3 mm/ layer	~1050°C	High- temp MLI spacer; Mo foil + quartz fiber cloth (60 layers, ~18 mm) achieves $k = 10^{-2}$– 10^{-3}W/(m•K) at 1000 °C in high vacuum; long-term temp resistance ~1050 °C	[Source: Materials 2025]
13	Zirconia (ZrO_2) fiber /	Fiber / Particulate	0.1 mm (lattice height)	~2000 °C+	Ultra-high temp; replaces quartz	Deep Space Exploratio
	ceramic lattice				fiber; sprayed on Mo foil as 0.075– 0.1 mm height, Φ0.5–2 mm particles, 15 mm spacing	n Journal 2024
14	Zirconia ceramic particles	Particulate coating	~10μm thick	~2000 °C+	Sprayed on Mo foil; SP-100 legacy	JPL SP-100
15	Alumina fibrous insulation (Saffil)	Fiber	Variable	~1200°C	High- temp MLI spacer; used with gold- coated reflective foils	NASA NTRS 2006
16	Fumed silica	Powder composite	—	~1000°C	Used in NASA LCI (Layered Composite Insulation)	NASA KSC
17	PEEK tags	Pin structure	—	~250°C	JAXA; replaces sewing for layer spacing control	JAXA
18	Embossed polymer	Textured film	—	~150°C	Self- spacing DAM/DAK; no separate spacer	NASA TFAWS 2018
19	Hollow Glass Microsphe res (HGMs)	Particulate	—	—	Novel spacer; lightweigh t; 14.1% lower insulation than Dacron net at LH_2 temps but structurall y lighter	Shanghai Jiao Tong University 2026
20	Dry paper	Paper	—	—	Chinese simulation study; variable- density optimizati on	真空与低 温 2024
21	Polyester film	Film	—	~150°C	Chinese simulation study; variable- density optimizati on	真空与低 温 2024
22	Borosilicat e	Fabric	—		NASA Ames	NASA Ames
	aluminum fine yarn cloth			500–1000°C	high- temp MLI spacer; paired with stainless steel foil	[Source: Materials 2025]
23	Pyrogel aerogel blanket	Composite	—	—	ESA- supported R&D; replaces fiber spacers to enhance insulation	ESA [Source: Materials 2025]
24	Dacron fiber tufts	Fiber tufts	—	~150°C	Superfloc design; attached to reflective shields	Convair/ NASA 1972
25	Chemical fiber	Fiber	60–70 μm	—	Commerci al MLI product	Frako- Term

Notes on Spacer Selection

Dacron net is the industry standard for cryogenic MLI due to its open mesh structure, which facilitates gas evacuation in high-vacuum environments. Its temperature limit (~150°C) aligns well with DAM reflector constraints. Comparison with embossed design shows negligible performance difference (ε* 0.0075 vs. 0.0068) [Source: NASA TFAWS 2018].

Silk net was extensively studied by Lockheed and demonstrates a remarkable 10× improvement in conductance when triple-layered per DAM sheet (k_0 = 1.5 vs. 25 mW/m^2•K), achieving the best known cryogenic MLI performance [Source: JPL CEC2015].

Fiberglass paper extends temperature capability to ~500°C and acts as a continuous barrier that suppresses gas conduction—particularly beneficial at soft-vacuum levels. It is the traditional standard spacer referenced in ASTM C740.

Polymer spacers (IMLI) represent a paradigm shift from blanket-style MLI to precision-engineered insulation with controlled layer spacing. Each layer's heat leak is only 50% of conventional net-spaced MLI. A 20-layer IMLI at 77 K–295 K achieves heat flux of only 0.45 W/m², more than 37% better than conventional MLI [Source: Quest Thermal 2024; AIP Conf. Proc. 1218, 2010].

Quartz fiber cloth has demonstrated excellent performance in high-temperature MLI: paired with Mo foil (60 layers, ~18 mm thick), it achieves $k = 10^{-2}$–10^{-3}W/(m•K) at 1000°C in high vacuum, with longterm temperature resistance of ~1050°C [Source: Materials 2025].

Hollow Glass Microspheres (HGMs) are a novel lightweight spacer material. At liquid hydrogen temperatures, HGM-based MLI shows 14.1% lower insulation performance than Dacron net MLI, but offers significant structural weight advantages. A 36-layer HGM configuration improves performance by 21.8% over 12-layer HGM [Source: 低温工程2026].

Aerogel composite blankets are the best insulation material at ambient pressure. In high vacuum, aerogel + MLI combinations cover the full vacuum range. An aerogel + 15-layer MLI combination achieves k = 0.15 mW/m•K (HV) [Source: NASA NTRS 1999]. ESA-supported R&D further uses Aspen Pyrogel aerogel to replace fiber spacers, significantly enhancing insulation [Source: Materials 2025].

Zirconia-based spacers (fiber, ceramic particles) are essential for ultra-high-temperature MLI systems using molybdenum foil reflectors, with temperature capabilities exceeding 2000 °C. Three application methods were evaluated: PVD (poor high-temp adhesion), sintering (weak adhesion, easy detachment), and plasma spray with Ni alloy bond coat (best method; good adhesion + thermal match) [Source: Deep Space Exploration Journal 2024].

Dry paper and polyester filmwere studied in Chinese simulation research for variable-density optimization. The optimal variable-density configuration (sparse-to-dense from cold to hot side) achieved 0.3213 W/m² vs. 0.3596 W/m² for uniform polyester film—a 10.7% improvement [Source: 真空 与低温2024].

Borosilicate aluminum fine yarn cloth is paired with stainless steel foil in NASA Ames' flexible hightemperature TPS structure, operating at 500–1000°C [Source: Materials 2025].

Embossed/dimpled self-spacing films eliminate the spacer entirely, reducing assembly complexity but offering only moderate thermal performance.

4. Lockheed Equation (Core Mathematical Model)

The Lockheed equation is the most widely used semi-empirical correlation for predicting MLI thermal performance. Developed at Lockheed (now Lockheed Martin) based on extensive cryogenic dewar

testing, it separates the total heat flux into solid conduction and radiation components. The equation has been extended to include gas conduction for non-ideal vacuum conditions.

This model is essential for MLI system design, performance prediction, and comparison of different configurations. It is incorporated into industry standards including ASTM C740.

4.1 Standard Lockheed Equation

The standard Lockheed equation predicts total heat flux through an MLI blanket under high-vacuum conditions:

$$q = (C_s \times \bar{N}^{2.56} \times T_m \times (T_h - T_c)) / N_s + (C_r \times \varepsilon \times (T_h^{4.67} - T_c^{4.67})) / N_s$$

Where:

Parameter	Description	Value / Formula
q	Total heat flux (mW/m²)	— (output)
Cs	Conduction constant	8.95×10^{-8} (unperforated) or 7.30×10^{-8} (perforated)
Cr	Radiation constant	5.39×10^{-10} (unperforated) or 7.07×10^{-10} (perforated)
N̄	Layer density (layers/cm)	Input parameter
Ns	Number of reflective shields	Input parameter
Th	Hot boundary temperature (K)	Input parameter
Tc	Cold boundary temperature (K)	Input parameter
Tm	Mean temperature = (Th + Tc) / 2	Derived
ε	Room temperature emissivity	0.031 (unperforated DAM) or 0.043 (perforated DAM)

Notes on the standard equation:

The first term represents solid conduction through spacer materials. The exponent 2.56 on layer density N̄ captures the nonlinear increase in conduction with compression (higher layer density = more contact points).

The second term represents radiation between layers. The exponent 4.67 (rather than the theoretical 4.0 for blackbody radiation) accounts for the temperature dependence of emissivity.

Perforation of reflective shields reduces solid conduction (lower Cs) but increases radiation (higher Cr) and emissivity, because perforations create additional radiative pathways.

4.2 Extended Lockheed Equation (with Gas Conduction)

For non-ideal vacuum conditions where interstitial gas pressure is significant, the extended Lockheed equation includes a gas conduction term:

$$
\begin{aligned}
q = {} & C_s \times [0.017 + 7\times10^{-6}(800 - T_{avg}) + 0.0228 \times \ln(T_{avg})] \times \bar{N}^{2.63} \times (T_h - T_c) / N_s \\
& + C_r \times \varepsilon \times (T_h^{4.67} - T_c^{4.67}) / N_s \\
& + C_g \times P \times (T_h^{\alpha} - T_c^{\alpha}) / N_s
\end{aligned}
$$

其中 $\alpha = 0.52$ (氮气 N_2) 或 $\alpha = 0.26$ (氦气 He)

Where the additional parameters are:

Parameter	Description	Value
Cs	Conduction constant (extended)	2.4×10^{-4}
Cr	Radiation constant (extended)	4.944×10^{-10}
Cg	Gas conduction constant	14,600 (nitrogen) or 48,900 (helium)
P	Interstitial gas pressure (torr)	Input parameter
Tavg	Average of hot and cold boundary temperatures (K)	(Th + Tc) / 2

Notes on the extended equation:

The conduction term includes a temperature-dependent correction factor: $0.017 + 7\times10^{-6}(800 - Tavg) + 0.0228 \times \ln(Tavg)$, which accounts for the temperature dependence of spacer thermal conductivity.

The layer density exponent changes from 2.56 to 2.63 in the extended model, reflecting refined fitting to broader data sets.

The gas conduction term scales linearly with pressure P and uses a fractional power of temperature (0.52 for nitrogen, 0.26 for helium), reflecting free-molecular heat transfer physics.

The helium gas conduction constant (48,900) is approximately 3.3× higher than nitrogen (14,600), consistent with helium's higher thermal conductivity and molecular velocity.

4.3 Emissivity Temperature Dependence

The emissivity of reflective shields is not constant but varies with temperature according to:

$\varepsilon = 6.8 \times 10^{-4} \times T^{0.67}$

This relationship is critical for cryogenic applications, where temperatures may span several hundred Kelvin. At room temperature (300 K), this yields $\varepsilon \approx 0.031$, consistent with measured values for unperforated DAM. At cryogenic temperatures (e.g., 77 K), the predicted emissivity drops to approximately 0.0107, though actual values may differ due to surface condition and measurement methodology.

The √T (more precisely, $T^{0.67}$) dependence has a profound effect on MLI performance at very low temperatures: as the cold-side temperature decreases, the emissivity of all shields decreases, suppressing radiation but also altering the conduction-to-radiation balance.

4.4 Lockheed Correlation Parameters Table

The following table provides the complete set of correlation parameters for all combinations of perforation state and interstitial gas atmosphere:

Perforati on	Atmosp here	Exps (Ñ exponen t)	Expg (T exponen t)	Cs	Cr	Cg	εTR
	Nitrogen	2.63	0.52				0.043
Perforat ed				7.30×10^{-8}	7.07×10^{-10}	1.46×10^{4}	
Perforat ed	Helium	2.63	0.26	7.30×10^{-8}	7.07×10^{-10}	4.89×10^{4}	0.043
Unperfo rated	Nitrogen	2.56	0.52	8.95×10^{-8}	5.39×10^{-10}	1.46×10^{4}	0.031
Unperfo rated	Helium	2.56	0.26	8.95×10^{-8}	5.39×10^{-10}	4.89×10^{4}	0.031

(Source: NASA KSC, AIP Conference Proceedings; ASTM C740)

4.5 Practical Application Notes

The Lockheed equation is valid for high-vacuum conditions (typically < 10^{-3} Pa or < 10^{-5} torr). At softvacuum levels, the gas conduction term becomes dominant and performance degrades dramatically.

The equation assumes one-dimensional heat flow through a flat or large-radius-curved MLI blanket. Corrections are needed for complex geometries, seams, and penetrations.

The model does not account for edge effects, stitching, or penetrations, which can significantly increase actual heat flux in real installations. Engineering safety factors of 2–5× are common.

The emissivity valueε_{TR} used in the radiation term is a room-temperature value; the temperature dependence (Section 4.3) is implicitly captured in the $T^{4.67}$ exponent rather than being applied separately.

The optimal layer density determined from NASA Cryostat-100 testing is in the range of 1.5–2.6 layers/ mm, with the practical optimum approximately 2× the theoretical prediction [Source: NASA NTRS 2011].

5. Comprehensive Test Data Compilation

This section presents the most comprehensive available compilation of MLI thermal performance test data from institutions worldwide. The data spans cryogenic to ultra-high-temperature regimes (4.2 K to 1300 K), multiple material combinations, and various test methodologies. All data is presented with source citations for traceability.

5.1 NASA Kennedy Space Center – Cryostat-100 Tests

(Sources: NASA NTRS [1], AIP Conference Proceedings [3], NASA KSC [4][5], ASTM C740 [11])

NASA Kennedy Space Center's Cryostat-100 calorimeter is one of the most extensively used MLI test facilities, providing high-precision heat flux measurements for a wide range of material combinations and configurations. The Cryostat-100 apparatus (1 m long × 168 mm diameter) enables testing under controlled vacuum conditions (760–10^{-4} torr) with accurate boundary temperature control (77–353 K). Tests follow ASTM C740 methodology where applicable.

The following table compiles test results from multiple NASA KSC test campaigns, including conventional MLI, layered composite insulation (LCI), and proprietary configurations.

Test ID	Refl ecto r	Spa cer	Lay ers	Lay er Den sity	Thic kne ss (m m)	TH (K)	TC (K)	Vac uu m	Hea t Flux (W/ m²)	k- valu e (m W/ m· K)	Ref ere nce
N01	Al foil	Fibe rgla ss pap er	60	1.5/ mm	—	293	78	HV	0.73 4	0.08 6	AST M C74 0
N04	DA M	Pap er	30	—	—	293	78	HV	0.37 3	0.03 3	AST M C74 0
P10	Al foil	Fibe rgla ss pap er	29	—	—	293	78	HV	0.76 0	0.03 8	AST M C74 0
C10 8	Al foil + pap er	Pap er	40	1.8/ mm	22.3	293	78	HV	—	0.08 6	NAS A KSC
C11 6	Al foil	Poly este r fabr ic	15	—	18.7	293	78	HV	—	—	NAS A KSC
C12 3	Al foil + pap er	Pap er	60	—	24.5	293	78	HV	—	0.09 1	NAS A KSC (be nch mar k)
C13 0	Myl ar + pap er + fum ed silic a	Co mp osit e	30	—	22.3	293	78	HV	—	0.09 1	NAS A KSC (LCI)
C13 0	LCI	—	30	—	22.3	293	78	SV (1 torr)	—	1.6	NAS A KSC
C12 3	MLI	—	60	—	24.5	293	78	SV (1 torr)	—	10.0	NAS A KSC

Test ID	Refl ecto r	Spa cer	Lay ers	Lay er Den sity	Thic kne ss (m m)	TH (K)	TC (K)	Vac uu m	Hea t Flux (W/ m^2)	k- valu e (m W/ m· K)	Ref ere nce
A12 5	DA M	Dac ron net	40	2.58 / mm	—	294	78	HV	0.42 7	—	NAS A KSC
A12 6	DA M	Pap er	40	3.60 / mm	—	294	78	HV	0.66 2	—	NAS A KSC
A12 8	DA M	Pap er	80	3.80 / mm	—	294	78	HV	0.44 5	—	NAS A KSC
A14 2	Pro prie tary	Plas tic stan d- offs	20	0.52 / mm	—	294	78	HV	1.01 1	—	NAS A KSC
A13 8	DA M (Ball Aer o)	Dac ron net	60	0.95 /cm	63.3	305	78	HV	~0.2 6	0.07 – 0.09	NAS A KSC
A13 9	DA M (Ball Aer o)	Dac ron net	40	0.95 /cm	42.7	305	78	HV	~0.3 8	0.07 – 0.09	NAS A KSC
A14 0	DA M (Ball Aer o)	Dac ron net	60	0.94 /cm	63.6	305	78	HV	~0.3 8	—	NAS A KSC
A14 1	DA M (Ball Aer o)	Dac ron net	60	1.45 /cm	41.4	305	78	HV	~0.4 7	—	NAS A KSC
A14 4	DA M (Ball Aer o)	Dac ron net	60	2.6/ cm	23.0	305	78	HV	—	—	NAS A KSC
A11 2	Aer ogel laye red	Aer ogel blan ket	—	—	—	~29 3	~80	HV	—	0.15	NAS A KSC (Cry osta t-1)
A11 3	Al foil + MLI	Aer ogel blan ket + SI	15 SI + aero gel	—	—	~29 3	~80	HV	—	0.15	NAS A KSC (Cry osta t-1)
AST M ref	Al foil + fibe rgla ss pap er + Dac ron	Fibe rgla ss pap er + Dac ron	40 (tot al)	—	—	293	77	HV (10^{-3} torr)	0.58 6	—	AST M C74 0

(Sources: NASA NTRS 2011; NASA NTRS 2013; NASA NTRS 1999; ASTM C740-2025)

Notes:

HV = High Vacuum (< 10^{-3} Pa); SV = Soft Vacuum (~1 torr)

Tests N01–N04 and P10 follow ASTM C740 methodology; tests C-series and A-series are NASA KSC internal test campaigns.

The LCI (Layered Composite Insulation) configuration (C130) incorporates fumed silica into the spacer system for improved soft-vacuum performance, demonstrating k = 1.6 mW/m•K at 1 torr versus 10.0 mW/m•K for conventional MLI at the same pressure—a 6.25× improvement.

Ball Aerospace configurations (A138–A144) demonstrate the effect of layer density on performance: at 60 layers, increasing density from 0.95/cm to 2.6/cm increases heat flux from ~0.26 to ~0.47 W/m^2, a 1.8× degradation.

Test A142 (proprietary plastic stand-offs, 20 layers, 0.52/mm density) shows the highest heat flux (1.011 W/m^2), highlighting the penalty of low layer count and high-conductivity spacers.

The aerogel + MLI combination (A112, A113) achieves k = 0.15 mW/m•K in high vacuum, demonstrating the complementary benefits of aerogel (ambient pressure) and MLI (high vacuum) [Source: NASA NTRS 1999].

5.2 Lockheed/JPL Cryogenic Dewar Tests

(Sources: JPL CEC2015 [2]; NASA Lewis [10])

Lockheed's cryogenic dewar testing program produced the foundational data for the Lockheed equation and established benchmark performance levels for cryogenic MLI. The tests were conducted at the Jet Propulsion Laboratory (JPL) and focused on liquid helium temperature (4.2 K) applications, where the conduction-radiation balance is qualitatively different from higher-temperature regimes.

A key finding from this body of work is that MLI conductance varies by a factor of approximately 600 between standard spacecraft MLI and Lockheed's best cryogenic MLI configuration (triple silk net). This enormous range underscores the importance of configuration optimization for specific temperature regimes.

Config uration	Reflect or	Spacer	Layers	TH (K)	TC (K)	Heat Flux	Condu ctance k_0	Notes
37- layer broadr ange	DAM	Single silk net (SSN)	37	278	4.2	~275 mW/ m^2	25 mW/ m²•K	Direct contact both walls
37- layer	DAM	SSN	37	40	4.2	—	25 mW/ m²•K	Condu cts 10× more than radiati on at low T
9-layer special	DAM	Triple silk net (3 per DAM)	9	40	4.2	~1.2 mW/ m^2	1.5 mW/ m²•K	Best cryoge nic perfor mance
9-layer	DAM	Triple silk net	9	27–75	4.2	0.5– 50 mW/ m^2	1.5 mW/ m²•K	Separa ted from hot wall
	DAM	—	21	328	87	—	—	
21- layer Cassini								Spacec raft applica tion
34- layer LH_2 tank	DAM	Double silk net	34	350/27 8/152	20	164/96 /16 BTU/hr	—	NASA Lewis, 1991; 45 layers/ in; 87.6 in dia. LH_2 tank; include s penetr ations

(Sources: JPL CEC2015; NASA NTRS 1991)

Key Findings:

At the 4.2 K cold boundary with a 40 K hot boundary, solid conduction dominates over radiation by a factor of 10× for single silk net (SSN) spacers. This is because radiative heat transfer scales as T^4 and becomes negligible at cryogenic temperatures.

The triple silk net configuration (three silk net layers per DAM reflector) achieves 10× lower conductance (1.5 vs. 25 mW/m²•K) compared to single silk net, despite using fewer total layers (9 vs. 37). This demonstrates that spacer optimization is more impactful than layer count at cryogenic temperatures.

The 9-layer triple-silk-net configuration with hot-side separation achieves heat flux as low as 0.5 mW/m² at 27 K hot boundary—the lowest reported MLI heat flux in the literature.

The Cassini spacecraft configuration (21 layers, 328 K / 87 K) represents a typical spacecraft MLI application where radiation dominates.

The 34-layer LH_2 tank test (NASA Lewis, 1991) demonstrates real-world performance with multiple thermal zones on an 87.6-inch diameter LH_2 storage tank (45 layers/inch density, including penetrations):

at TH = 350 K (630 R), the heat load is 164.4 BTU/hr; at TH = 278 K (530 R), it drops to 95.8 BTU/hr; at TH = 152 K (152 R), it further decreases to 15.9 BTU/hr.

5.3 IMLI/LRMLI Tests (Quest Product Development + Ball Aerospace)

(Sources: SciSpace [6]; Quest Thermal Group IMLI Product Sheet v3, 2024)

Integrated Multilayer Insulation (IMLI) and Load-Responsive Multilayer Insulation (LRMLI) represent a new generation of MLI technology developed by Quest Product Development in collaboration with Ball Aerospace. Unlike traditional blanket-style MLI, IMLI uses precisely positioned polymer spacers to maintain controlled layer spacing, enabling predictable thermal performance and load-bearing capability.

The IMLI concept addresses a key limitation of conventional MLI: the variability of layer density due to compression, handling, and installation. By structurally controlling spacer position, IMLI achieves consistent thermal performance that can be reliably predicted by models.

5.3.1 IMLI Comparative Tests

Type	Layers	TH (K)	TC (K)	Heat Flux (W/m²)	Conducta nce (W/ m²)	Notes
IMLI	10	295	77	1.22	—	Rectangul ar calorimete r
Conv MLI	10	295	77	1.45	—	Same fixture for compariso n
IMLI	10	295	77	1.06	—	Cylindrical calorimete r; 37% less than conv
IMLI (modeled)	40	293	77	—	0.16	60% of conventio nal MLI
						conductan ce
IMLI	20	295	77	0.45	0.061	ε* = 0.00095; tested at NASA KSC
IMLI	10	295	77	0.95	—	ε* not reported
IMLI	5	295	77	2.0	—	ε* not reported
IMLI (tested@K SC)	20	295	77	0.405	0.061	ε* = 0.00095
LDMLI (@KSC)	60	295	77	0.332	0.093	ε* = 0.00080
Dacron net (@GRC)	61	250	93	0.342	0.187	ε* = 0.0016; NASA GRC MLSTC
Perforated MLI (@KSC)	30	230	77	0.87	0.040	ε* = 0.0055; perforated Dacron net

(Sources: Quest/Ball Aerospace; Quest Thermal IMLI Product Sheet v3, 2024)

5.3.2 IMLI Complete Configuration Table (295 K / 77 K)

Layers	Thickness (cm)	Heat Flux (W/m²)	Areal Density (g/m²)	ε*	k* (W/m·K)
5	0.72	2.162	209	0.0051	0.1565
10	1.63	1.039	430	0.0024	0.1688
15	2.53	0.683	650	0.0016	0.1727
20	3.43	0.509	870	0.0012	0.1746
30	5.23	0.337	1311	0.0008	0.1764
40	7.04	0.252	1751	0.0006	0.1773

(Source: Quest Thermal Group IMLI Product Sheet v3, 2024. Test conditions: TH = 295 K, TC = 77 K, spacing = 5.08 cm (2 in), aluminized Mylar + polymer spacers, high vacuum)

5.3.3 IMLI Complete Configuration Table (295 K / 20 K)

Layers	Thickness (cm)	Heat Flux (W/m²)	Areal Density (g/m²)	ε*	k* (W/m·K)
5	0.72	2.218	209	0.0052	0.1606
10	1.63	1.064	430	0.0025	0.1730
15	2.53	0.700	650	0.0016	0.1769
20	3.43	0.522	870	0.0012	0.1789
30	5.23	0.345	1311	0.0008	0.1807
40	7.04	0.258	1751	0.0006	0.1816

(Source: Quest Thermal Group IMLI Product Sheet v3, 2024. Test conditions: TH = 295 K, TC = 20 K, spacing = 5.08 cm (2 in), aluminized Mylar + polymer spacers, high vacuum)

5.3.4 IMLI at LH_2 Temperature Range (90 K / 20 K)

Layers	TH (K)	TC (K)	Heat Flux (W/ m²)	Notes
5	90	20	0.36	—
10	90	20	0.18	—
20	90	20	0.081	—
10	293	20	1.032	—
20	293	20	0.52	—

(Source: Quest Thermal Group IMLI Product Sheet v3, 2024)

Key Findings:

IMLI demonstrates 16–37% lower heat flux compared to conventional MLI at the same layer count (10 layers, 295 K / 77 K), with the improvement being more pronounced on cylindrical geometries (37%) than flat plates (16%).

At 40 layers, modeled IMLI conductance is only 60% of conventional MLI conductance (0.16 W/m² vs. higher for conventional), indicating that the IMLI advantage scales with layer count.

The complete IMLI configuration tables (5–40 layers) provide a comprehensive performance map for both 77 K and 20 K cold boundaries, enabling precise system design optimization.

The improved performance is attributed to controlled, uniform layer spacing that minimizes compression-induced solid conduction hot spots.

IMLI's structural design also enables load-bearing and load-responsive capabilities, opening new application domains such as structural insulation for cryogenic tanks.

5.4 FSU/GE MRI Tests (National High Magnetic Field Lab)

(Source: AIP Conference Proceedings 1573 [7])

Florida State University (FSU), in collaboration with General Electric (GE), conducted a systematic study of MLI blanket performance for MRI (Magnetic Resonance Imaging) cryostat applications. The tests were performed at the National High Magnetic Field Laboratory using the MIkE (Multilayer Insulation Kinetic Experiment) apparatus.

The study focused on variable-density MLI—configurations where layer density is non-uniform across the blanket thickness. The hypothesis is that optimizing the density distribution between cold and warm sides can reduce overall heat flux by better matching the local conduction-radiation balance to the local temperature gradient.

Blanke t	Type	Reflect or	Spacer	Layers	Layer Densit y (cold/ warm)	TC (K)	TH (K)	Heat Flux (W/m^2)
A	Consta nt density	DAM	Polyest er	66 total	33/33 layers/ cm	60.9	295.8	0.833
B	Variabl e density	DAM	Polyest er	66 total	28/33 layers/ cm	61.1	298.4	0.889
C0	Variabl e density	DAM	Polyest er	66 total	21/33 layers/ cm	60.3	299.6	0.648
C1	Compr essed	DAM	Polyest er	66 total	24/38 layers/ cm	60.7	300.3	0.855
C2	Compr essed	DAM	Polyest er	66 total	28/43 layers/ cm	—	—	—
Cracke d Ice	New design	DAM	Embos sed polyest er	—	—	—	—	12% better than baselin e

(Source: FSU/GE, AIP Conf. Proc. 1573 [7])

Key Findings:

Blanket C0, with the most aggressive variable-density distribution (21 layers/cm on the cold side vs. 33 layers/cm on the warm side), achieves the lowest heat flux (0.648 W/m^2)—a 22% improvement over constant-density blanket A (0.833 W/m^2).

The optimal strategy is to decrease density on the cold side (where conduction dominates and fewer contact points are beneficial) and maintain or increase density on the warm side (where more layers are needed for radiation suppression).

Compression (C1, C2) degrades performance, with C1 showing 0.855 W/m^2 vs. 0.648 W/m^2 for uncompressed C0 at similar density distribution—a 32% penalty.

The "Cracked Ice" design using embossed polyester spacers achieves 12% better performance than the baseline, demonstrating the potential of textured spacer materials.

5.5 WUT + IUAC Tests (Poland + India)

(Source: AIP Conference Proceedings 985 [8])

The Warsaw University of Technology (WUT, Poland) and the Inter-University Accelerator Centre (IUAC, India) conducted a collaborative MLI testing program focusing on cryogenic performance across multiple temperature regimes. This Indo-Polish cooperation produced valuable data on MLI behavior at liquid helium temperatures (4.2 K), where the physics of heat transfer differ fundamentally from highertemperature regimes.

Test	Reflecto r	Spacer	Layers	TH (K)	TC (K)	Vacuum (Pa)	Heat Flux
30-layer	DAM	Dacron net	30	300	77.3	$< 10^{-4}$	—
30-layer	DAM	Dacron net	30	300	4.2	$< 10^{-4}$	—
30-layer	DAM	Dacron net	30	77.3	4.2	$< 10^{-4}$	~10 mW/m^2
Variable N	DAM	—	0–100	300	77.3	$< 10^{-4}$	See curves
Variable N	DAM	—	0–100	300	4.2	$< 10^{-4}$	See curves
Variable N	DAM	—	0–100	77.3	4.2	$< 10^{-4}$	See curves

(Source: WUT/IUAC, AIP Conf. Proc. 985 [8])

Key Finding:

In the 4.2 K–77.3 K temperature range with good vacuum ($< 10^{-4}$ Pa), heat flux exhibits a nonmonotonic dependence on layer count: it first increases with N (reaching a peak around N ≈ 25 layers)

and then decreases back to approximately 10 mW/m^2 at N ≈ 100 layers. This counterintuitive behavior is attributed to the $T^{0.67}$ emissivity dependence: at very low temperatures, the emissivity of reflective shields becomes so low that adding layers (which also add conduction paths) initially increases total heat flux. Only at sufficiently high layer counts does the additional radiation suppression overcome the conduction penalty.

This finding has profound implications for MLI design at liquid helium temperatures: simply adding more layers is not always beneficial, and careful optimization is required.

5.6 Chinese Research Institution Tests

Chinese research institutions have made significant contributions to MLI technology, particularly in areas of novel material combinations, manufacturing processes, layer density optimization, and application-specific testing. The following subsections present test data from seven major Chinese institutions.

5.6.1 Shanghai Jiao Tong University – Institute of Refrigeration and Cryogenics Engineering

(Source: 低温工程 2026)

Shanghai Jiao Tong University (SJTU) developed a GM cryocooler-based dry calorimetry system for MLI testing in the liquid hydrogen temperature range (20–315 K). This system uses a closed test chamber with a GM cryocooler as the cold source, enabling non-evaporative (dry) heat flux measurement—a significant advantage over traditional LN_2 boil-off methods for liquid hydrogen temperature testing.

Configur ation	Reflecto r	Spacer	Layers	TC (K)	TH (K)	Vacuum	Key Results
DAM + Dacron net	DAM	Dacron net (polyest er)	12	20	285– 315	< 5×10⁻⁵ Pa	Baseline; perform ance drops ~29.1% when TH rises from 285 K to 315 K

Configur ation	Reflecto r	Spacer	Layers	TC (K)	TH (K)	Vacuum	Key Results
DAM + Hollow Glass Microsp heres	DAM	Hollow Glass Microsp heres (HGMs)	12	20	285–315	< 5×10⁻⁵ Pa	HGM MLI insulatio n perform ance 14.1% lower than Dacron net MLI
DAM + Hollow Glass Microsp heres	DAM	Hollow Glass Microsp heres (HGMs)	36	20	285–315	< 5×10⁻⁵ Pa	21.8% improve ment over 12- layer HGM configur ation

(Source: 低温工程 2026)

Key Findings:

The GM cryocooler dry calorimetry system enables accurate MLI testing at liquid hydrogen temperatures (20 K) without the complexity and cost of LH_2 boil-off methods.

Hollow Glass Microspheres (HGMs) as spacer material show 14.1% lower insulation performance than Dacron net at the same layer count (12 layers), but offer significant structural weight advantages— making them attractive for mass-critical applications.

Increasing HGM layers from 12 to 36 improves performance by 21.8%, demonstrating that the layer count effect applies to novel spacer materials as well.

Heat boundary temperature increase from 285 K to 315 K causes approximately 29.1% performance degradation, consistent with the T^4 radiation scaling.

5.6.2 Chinese Academy of Sciences – Technical Institute of Physics and Chemistry

(Source: ICEC 2024)

The CAS Institute of Technical Physics and Chemistry (中科院理化所) conducted MLI testing using a GM cryocooler measurement system with steady-state axial heat flow method, covering the 20–120 K temperature range. This is one of the few publicly available datasets for MLI performance across the full 20–120 K range.

Config uration	Reflect or	Spacer	Layers	Layer Densit y	TC (K)	TH (K)	Vacuu m	Key Results
DAM + fibergl ass paper	DAM	Fibergl ass paper	30	28.5 layers/ cm	20–120	~298	~10⁻⁴ Pa	CBT from 120 K to 20 K: heat flux increas es 39.0%; from 77 K to 20 K: increas es 17.7%

(Source: ICEC 2024)

Key Findings:

When the cold boundary temperature (CBT) decreases from 120 K to 20 K, the heat flux increases by 39.0%—a counterintuitive result that reflects the shift from radiation-dominated to conductiondominated heat transfer at very low temperatures.

From 77 K to 20 K, the heat flux increase is more moderate at 17.7%, as the system is already partially in the conduction-dominated regime.

These findings complement the WUT/IUAC data (Section 5.5) and confirm that MLI optimization at liquid hydrogen temperatures requires careful balancing of conduction and radiation components.

5.6.3 China Special Equipment Inspection and Research Institute (中国特种设备检测研究院)

(Source: 低温与超导 2023)

This institution conducted large-scale MLI testing using a 135 L cryogenic calorimeter, systematically evaluating the effect of layer count on thermal performance for different cryogenic fluids. The study covered LNG, LO_2, LN_2, and LH_2 storage applications.

Fluid	Tested Layers	Optimal Layer Count	Calorimeter Volume	Method
LNG	25, 50, 75, 100	60	135 L	LN_2 evaporation calorimetry
LO_2	25, 50, 75, 100	65	135 L	LN_2 evaporation calorimetry
LN_2	25, 50, 75, 100	68	135 L	LN_2 evaporation calorimetry
LH_2	25, 50, 75, 100	80	135 L	LN_2 evaporation calorimetry

(Source: 低温与超导 2023)

Key Findings:

The optimal layer count varies significantly by stored fluid: LNG (60), LO_2 (65), LN_2 (68), LH_2 (80). Lowertemperature fluids require more layers because the conduction-to-radiation balance shifts further toward conduction dominance.

The 135 L calorimeter provides a practical, vessel-scale test platform that better represents real-world installation conditions than small-scale coupon tests.

Beyond the optimal layer count, additional layers provide diminishing returns while increasing cost, weight, and assembly complexity.

5.6.4 Aerospace Materials and Processes Research Institute (航天材料及工艺研究所)

(Source: 有色金属工程 [13])

This institute operates a high-vacuum test platform (vacuum chamber ≤ 1 mPa) equipped with Φ6–16 mm penetration tube fittings and an ALICAT mass flow meter. The facility is specifically designed to test MLI performance with realistic penetration thermal bridges.

Config uration	Reflect or	Spacer	Layers	TC (K)	TH (K)	Vacuu m	k- value	Notes
DAM (variou s configs)	DAM	Variou s	—	77	~305	HV (≤1 mPa)	1.1 mW/ m•K	Penetr ation tube testing
Pin- type (nylon + glue gun)	DAM	Nylon velcro + glue pins	30	77 (LN_2)	—	HV	1.1 mW/ m•K	Pin- type constr uction
Pin- type (nylon + glue gun)	DAM	Nylon velcro + glue pins	30	20 (LH_2)	—	HV	—	—
Bundle d	DAM	—	—	77 (LN_2)	—	HV	3.253 mW/ m•K	—
Bonde d	DAM	—	—	77 (LN_2)	—	HV	2.56 mW/ m•K	—
Nylon velcro	DAM	—	—	77 (LN_2)	—	HV	4.7 mW/ m•K	Worst perfor mer
Bonde d	DAM	—	—	20 (LH_2)	—	HV	0.98 mW/ m•K	—
New seamle ss	DAM	—	—	77 (LN_2)	—	HV	1.1 mW/ m•K	Seam elimina tion

(Source: 有色金属工程 [13])

Key Findings:

The pin-type construction (k = 1.1 mW/m•K at 77 K) significantly outperforms bundled (3.253 mW/ m•K), nylon velcro (4.7 mW/m•K), and bonded (2.56 mW/m•K) configurations, demonstrating the importance of controlled layer spacing.

The new seamless construction achieves the same k-value as pin-type (1.1 mW/m•K), suggesting that seam elimination is as important as spacer optimization.

At LH_2 temperature (20 K), the bonded configuration achieves k = 0.98 mW/m•K, showing that performance improves at lower cold-side temperatures where radiation is further suppressed.

The high-vacuum test platform (≤1mPa) withΦ6–16 mm penetration tube fittings enables realistic assessment of MLI performance including thermal bridge effects from penetrations—a critical real-world factor often missing from laboratory coupon tests.

5.6.5 Vacuum & Cryogenics Journal – Layer Density Study

(Source: 真空与低温 [12])

This study systematically investigated the effects of layer count and layer density on MLI thermal performance under controlled vacuum conditions, providing valuable quantitative data for design optimization.

Layers	Layer Density	TH (K)	TC (K)	Vacuum (Pa)	Heat Flux (W/m^2)
10	18.1/cm	300	77	7×10^{-4}	6.93
20	18.1/cm	300	77	7×10^{-4}	3.72
30	18.1/cm	300	77	7×10^{-4}	~2.11
60	18.1/cm	300	77	7×10^{-4}	1.30
70	18.1/cm	300	77	7×10^{-4}	1.12
30	10/cm	300	77	7×10^{-4}	~1.0
30	40/cm	300	77	7×10^{-4}	~3.0
30	18.1/cm	240	77	7×10^{-4}	1.21
30	18.1/cm	360	77	7×10^{-4}	2.86

(Source: 真空与低温 [12])

Key Findings:

Layer count effect (at 18.1 layers/cm, 300 K / 77 K): Heat flux decreases from 6.93 W/m^2 (10 layers) to 1.12 W/m^2 (70 layers)—an 84% reduction. However, the rate of improvement diminishes significantly: from 10→20 layers the reduction is 46.3%, while from 60→70 layers it is only 13.8%.

Layer density effect (at 30 layers, 300 K / 77 K): Heat flux increases dramatically with density—from ~1.0 W/m^2 at 10/cm to ~3.0 W/m^2 at 40/cm, a 3× degradation. This confirms that compression-induced solid conduction is a dominant factor.

Temperature effect (at 30 layers, 18.1/cm): Reducing TH from 360 K to 240 K decreases heat flux from 2.86 to 1.21 W/m^2 (58% reduction), consistent with the T^4 radiation scaling.

5.6.6 Chinese Academy of Sciences – Institute of Plasma Physics (ASIPP)

(Source: 真空与低温 [16])

ASIPP developed variable-density MLI (VD-MLI) for the ITER (International Thermonuclear Experimental Reactor) cold shield application. The ITER cold shield operates at ~138 K and must limit total heat leak to below 1 kW.

Configurat ion	Reflector	Spacer	Layers	TH (K)	TC (K)	Result
VD-MLI	Aluminize d polyester	Polyester fiber	50	300	~138	< 1 kW total heat leak

(Source: 真空与低温 [16])

Notes: The VD-MLI configuration with 50 layers successfully meets the ITER requirement of < 1 kW total heat leak at the cold shield boundary (300 K / ~138 K), demonstrating the effectiveness of variabledensity optimization for large-scale applications.

5.6.7 Chinese Simulation Study – Variable Density Optimization

(Source: 真空与低温 2024)

A simulation study investigated variable-density MLI configurations using polyester film and dry paper as spacer materials, with DAM reflectors at 50 layers.

Group	Spacer Material	Configuration	Layer Density	Heat Flux (W/ m²)
A	Polyester film	Uniform density	10/cm	0.3596
B	Dry paper	Uniform density	10/cm	0.3642
C	Inner 15 dry paper + outer 35 polyester	Mixed	10/cm	0.3292
Optimal	Variable density (sparse→dense, cold→hot)	Variable	10/cm	0.3213

(Source: 真空与低温 2024. Test conditions: 50 layers, TC = 20 K, TH = 300 K, vacuum = 0.01 Pa)

Key Findings:

The optimal variable-density configuration achieves 0.3213 W/m², a 10.7% improvement over uniform polyester film (0.3596 W/m²) and 11.8% over uniform dry paper (0.3642 W/m²).

The mixed configuration (Group C: inner dry paper + outer polyester film) performs better than either uniform configuration, confirming the benefit of matching spacer material to the local temperature regime.

These simulation results align with the FSU/GE experimental findings (Section 5.4) on the superiority of decreasing-density (cold-to-hot) configurations.

5.6.8 Shanghai Institute of Technical Physics

This institution investigated aerogel-based composite insulation as an alternative to traditional MLI spacer materials. The configuration combines aluminum plates with aerogel pads, creating a hybrid system that leverages aerogel's extremely low thermal conductivity.

Configuratio n	Reflector	Spacer	Layers	TC (K)	k-value
Aerogel composite	Al plates (5 × 1mm)	Aerogel pads (13× 2mm)	5 Al + 13 aerogel	—	~10^{-4}mW/ m•K

Notes: The reported k-value of ~10^{-4} mW/m·K is exceptionally low, approaching the theoretical limit for vacuum insulation. This likely reflects idealized test conditions; real-world performance would be higher due to edge effects and thermal bridging.

5.6.9 State Key Laboratory of Aerospace Cryogenic Propellant Technology

(Source: 真空与低温 [16])

This laboratory investigated multi-metal reflective coatings and variable-density optimization for enhanced MLI performance.

Configurat ion	Reflector	Spacer	Layers	TH (K)	TC (K)	Heat Flux
Al coating	Al	—	—	300	77	0.4007 W/ m²
Multi- metal (Al + Au + Cu)	Al + Au + Cu	—	—	300	77	0.3903 W/ m² (↓ 33.54%)
Variable density (↓)	Multi- metal	—	—	300	77	0.3903 W/ m²
Variable density (↑)	Multi- metal	—	—	300	77	0.4109 W/ m²
Optimized 3-zone	Multi- metal	—	—	300	77	0.3916 W/ m²

(Source: 真空与低温 [16])

Key Findings:

The multi-metal coating (Al + Au + Cu) achieves a 33.54% reduction in heat flux compared to pure aluminum (0.3903 vs. 0.4007 W/m²).

Decreasing density (cold-to-hot: high-to-low) performs better than increasing density (0.3903 vs. 0.4109 W/m²), consistent with the FSU/GE findings (Section 5.4).

5.7 High Temperature MLI Tests

High-temperature MLI is essential for applications such as radioisotope thermoelectric generators (RTGs), nuclear power systems (e.g., JPL SP-100), hypersonic vehicles, and spacecraft operating near

the sun. Traditional aluminum-based MLI is limited to ~600 °C; this section presents data on specialized high-temperature MLI systems.

5.7.1 Beijing Spacecraft Design Institute – Mo Foil + ZrO_2

(Source: Deep Space Exploration Journal [15])

Configuration	Reflector	Spacer	Layers	TH (°C)	TC (°C)	Notes
Traditional high-temp	Ni foil	—	—	1050	20	Baseline
New high-temp	Mo foil (0.1 mm) + ZrO_2 particles	ZrO_2 ceramic (0.075–0.1 mm height, Φ0.5–2 mm, 15 mm spacing)	10 units	1050	20	29 °C lower at equilibrium
Mo foil + ZrO_2 (PVD)	Mo foil	ZrO_2 coating	—	—	—	Dense but poor high-temp adhesion
Mo foil + ZrO_2 (sintered)	Mo foil	ZrO_2	—	—	—	Weak adhesion, easy detachment
Mo foil + ZrO_2 (plasma spray)	Mo foil	ZrO_2 + Ni alloy bond coat	—	—	—	Best method; good adhesion + thermal match

(Source: 深空探测学报 [15])

Key Findings:

The new high-temperature MLI configuration (Mo foil + ZrO_2 ceramic particles as spacers) achieves a 29 °C reduction in equilibrium temperature compared to the traditional nickel foil baseline at 1050 °C hot boundary.

Plasma spray with Ni alloy bond coat is the recommended ZrO_2 spacer manufacturing method, providing good adhesion and thermal expansion matching.

5.7.2 NASA – Gold Reflective Foil + Alumina Fiber (High-Temp MLI)

(Source: NASA NTRS 2006)

Configuration	Reflector	Spacer	Layers	TH (K)	TC (K)	Pressure Range	Result
Gold reflective foil + Saffil	Gold-coated reflective foil	Alumina fibrous insulation (Saffil)	1–4	300–1300	—	1.33×10^{-5}–101.32 kPa	Reflective foil significantly reduces effective thermal conductivity (RMS deviation 9.5%)

(Source: NASA NTRS 2006)

5.7.3 NASA – Europa Clipper High-Temp MLI

(Source: NASA TFAWS 2023)

Configuration	Reflector	Layers	Tested Temp (°C)	Notes
Copper layer	Copper foil	—	273	Solar testing; high oxidation risk
Titanium layer	Titanium	—	241	Solar testing
Nextel 312	Nextel 312 fabric	—	149	Solar testing; ceramic fiber fabric
Aluminum	Al	—	—	Baseline comparison

(Source: NASA TFAWS 2023)

5.7.4 Arthur D. Little – Goldized Mylar Early Test

(Source: NASA NTRS 1968)

Configuration	Reflector	Spacer	Layers	TH (K)	TC (K)	Vacuum	Result
Double goldized Mylar	Goldized Mylar (double-sided)	Silk net (2 layers/interval)	5	LN_2/LH_2 range	LN_2/LH_2 range	High vacuum	0.33 Btu/hr•ft² (stable after 1 year storage)

(Source: NASA NTRS 1968)

5.7.5 Convair/NASA – Goldized Kapton + Dacron Tufts

(Source: NASA NTRS 1972)

Configuration	Reflector	Spacer	Layer Density	TH (K)	TC (K)	Vacuum	Result
Goldized Kapton + Dacron fiber tufts	Goldized Kapton	Dacron fiber tufts (Superfloc)	30 layers/in	LN_2 range	LN_2 range	High vacuum	$k = 1.37$–1.5×10^{-5} Btu/hr•ft•°F

(Source: NASA NTRS 1972)

5.7.6 Mo Foil + Quartz Fiber Cloth (Materials 2025)

(Source: Materials 2025)

Configur ation	Reflecto r	Spacer	Layers	TH (°C)	Vacuum	Total Thicknes s	Result
Mo foil + quartz fiber cloth	Molybde num foil	Quartz fiber cloth (~0.3 mm/ layer)	60	≤1000	High vacuum	~18 mm	k = 10^{-2}– 10^{-3}W/ (m•K); long- term temp resistanc e ~1050 °C

(Source: Materials 2025)

5.7.7 NASA Ames – Stainless Steel Foil + Borosilicate Aluminum Cloth

(Source: Materials 2025)

Configuratio n	Reflector	Spacer	Layers	TH (°C)	Notes
Stainless steel foil + borosilicate aluminum fine yarn cloth	Stainless steel foil (10–20 μm)	Borosilicate aluminum fine yarn cloth	10	500–1000	Flexible high-temp TPS structure; includes silicon fiber felt + alumina fiber insulation

(Source: Materials 2025)

5.7.8 JPL SP-100 – High-Temp Foil Evaluation

(Source: Materials 2025)

Baseline	Candidate Materials	Weight Reduction	Temperature Range	Notes
8μmMo foil	Carbon foil	44–85%	≤1000°C+	Extreme temperature resistance
8μmMo foil	Niobium foil	44–85%	High temp	Reacts with ZrO_2 near 1000°C
8μmMo foil	Titanium foil	44–85%	≤500 °C	Also tested in Europa Clipper
8μmMo foil	Zirconium foil	44–85%	High temp	BIPS system compatibility

(Source: Materials 2025)

Key Findings for High-Temperature MLI:

Two distinct technical routes exist for high-temperature MLI: (1) Gold-coated foil + alumina fiber (NASA, 300–1300 K) and (2) Mo foil + ZrO_2 ceramic / quartz fiber cloth (Chinese institutions, ≤1000°C).

The JPL SP-100 project demonstrated that carbon, niobium, titanium, and zirconium foils can achieve 44–85% weight reduction compared to the 8μmMo foil baseline, though specific MLI thermal performance data requires consulting the original SP-100 reports.

The Mo foil + quartz fiber cloth system (60 layers, ~18 mm thick) achieves k = 10^{-2}–10^{-3}W/(m•K) at 1000°C in high vacuum—the best reported high-temperature MLI performance.

NASA Ames' stainless steel foil + borosilicate aluminum cloth system offers a flexible TPS solution for 500–1000°C applications.

5.8 Fermilab MLI Calorimeter Tests

(Source: Fermilab FN-0423)

Fermi National Accelerator Laboratory (Fermilab) conducted MLI thermal performance testing using a copper cylindrical calorimeter with two surface treatments: aluminum tape-faced copper and blackpainted copper. The tests were performed at 1.5 × 10^{-5} torr vacuum with LN_2 evaporation calorimetry.

Configur ation	Reflecto r	Spacer	Layers	TC (K)	TH (K)	Vacuum (torr)	Heat Flux (W/ m²)
Al tape- faced copper	DAM (Al tape on Cu surface)	Standar d MLI spacer	90	77	~300	1.5× 10^{-5}	0.20
Al tape- faced copper	DAM (Al tape on Cu surface)	Standar d MLI spacer	30	77	~300	1.5× 10^{-5}	0.52
Black- painted copper	DAM (black paint on Cu surface)	Standar d MLI spacer	30	77	~300	1.5× 10^{-5}	0.64

(Source: Fermilab FN-0423)

Key Findings:

The 90-layer configuration achieves 0.20 W/m²—excellent performance consistent with the diminishingreturns behavior documented in other datasets.

At 30 layers, the aluminum tape-faced surface (0.52 W/m²) outperforms the black-painted surface (0.64 W/m²) by 23%, demonstrating the importance of the cold-boundary surface emissivity on overall MLI performance.

The Fermilab data provides a valuable intermediate layer count (30 layers) between the NASA KSC data points, helping to fill gaps in the layer-count performance curve.

5.9 CERN Flow Cryostat Tests

(Source: Venturi et al. 2020)

CERN (European Organization for Nuclear Research) conducted MLI testing using a flow cryostat with a 4.2 K cold boundary and 20–60 K shield temperatures. This testing is particularly relevant for particle accelerator cryogenic systems where MLI must perform across the 4.2–60 K range.

Configur ation	Reflecto r	Spacer	Layers	TC (K)	TH (K)	Vacuum	Notes
DAM (various configs)	DAM	Various	—	4.2	20–60	HV (10^{-6}– 10^{-4} mbar)	Testing in progress ; detailed heat flux and thermal conducti vity values pending full publicati on

(Source: Venturi et al. 2020)

Notes: CERN's MLI testing program is particularly valuable for its coverage of the 4.2–60 K range, which is critical for superconducting magnet and particle accelerator applications. The flow cryostat methodology enables precise measurement of heat loads at very low temperatures. Specific numerical results require consulting the complete publication.

5.10 Variable-Density MLI (VD-MLI) Tests

(Sources: NASA NTRS 2002; NASA TFAWS 2024)

Variable-density MLI (VD-MLI) is an advanced concept where layer density is intentionally varied across the blanket thickness to optimize the local conduction-radiation balance. NASAMarshall Space Flight Center's Multipurpose Hydrogen Test Bed (MHTB) is the primary test facility for VD-MLI evaluation.

No.	Reflect or	Spacer	Total Layers	Layer Densit y Config uration	TC (K)	TH (K)	Perfor mance	Source
1	DAM	Dacron net	45	8/12/1 6 layers/ cm (3 zones)	20	164–305	Heat leak reduce d ~50% vs. standa rd MLI; weight reduce d 74%	NASA NTRS 2002
2	DAM	Dacron net	45	7.1/11. 8/14.8 layers/ cm (5-zone model)	77→261	209→298	Inter- layer temper ature predict ion error < 5%	NASA TFAWS 2024

(Sources: NASA NTRS 2002; NASA TFAWS 2024)

Key Findings:

VD-MLI with a three-zone density configuration (8/12/16 layers/cm) achieves approximately 50% heat leak reduction compared to standard uniform-density MLI, while simultaneously reducing weight by 74% [Source: NASA NTRS 2002].

The five-zone model achieves inter-layer temperature prediction accuracy within 5%, validating the VDMLI optimization methodology [Source: NASA TFAWS 2024].

The optimal strategy is to use lower density on the cold side (where conduction dominates) and higher density on the warm side (where radiation suppression is needed)—consistent with the FSU/GE findings (Section 5.4) and the Chinese simulation study (Section 5.6.7).

The ITER cold shield application (Section 5.6.6) further validates VD-MLI at scale, with 50 layers meeting the < 1 kW total heat leak requirement.

5.11 Special MLI Systems

This section presents test data for specialized MLI systems that deviate from conventional DAM + net/ paper configurations, including hybrid aerogel-MLI systems, multi-layer aerogel insulation (MLAI), dualblanket designs, zero-stitch designs, and commercial products.

No.	Syste m Type	Reflec tor	Space r	Layer s	TC (K)	TH (K)	Heat Flux / k-value	Instit ution	Sourc e
1	Aerog el + MLI hybri d	Al foil + MLI	Aerog el blank et + SI	15 SI + aerog el	~80	~293	k = 0.15 mW/ m•K (HV)	NASA KSC (A113)	NASA NTRS 1999
2	Layer ed aerog el	—	Aerog el blank et	—	~80	~293	k = 0.15 mW/ m•K (HV)	NASA KSC (A112)	NASA NTRS 1999
3	MLAI (aero gel- based)	—	C40 space r posts + aerog el	4	—	—	2.2 W/m^2	NASA SBIR	NASA NTRS 2018
4	MLAI (aero gel- based)	—	C40 space r posts + aerog el	40 (50 mm)		250	0.25 W/m^2	NASA SBIR	NASA NTRS 2018
5	TFAW S dual- blank et desig n	DAM/ AM	CK (EAK)/ Dacro n	5 + 15 (dual blank et)		~298	ε^* = 0.006 8– 0.015	NASA (TFA WS 2018)	NASA TFAW S 2018
6	JAXA zero- stitch MLI	Alumi nized film	Plasti c pins	—		~298	ε_{eff} < 0.005 0	JAXA	JAXA 2014
7	Com merci al MLI (Frako - Term)	Al foil	Fiber glass	~40		293	k≈ 0.03 mW/ m•K	Frako - Term	Frako - Term
8	Com merci al MLI (Frako - Term)	DAM	Fiber glass	~40		293	k≈ 0.03 mW/ m•K	Frako - Term	Frako - Term

(Sources: NASA NTRS 1999; NASA NTRS 2018; NASA TFAWS 2018; JAXA 2014; Frako-Term)

Key Findings:

Aerogel + MLI hybrid systems achieve k = 0.15 mW/m•K in high vacuum and provide the best ambientpressure insulation, making them ideal for applications where vacuum degradation is a concern.

MLAI (Multi-Layer Aerogel Insulation) with 40 layers (50 mm thick) achieves 0.25 W/m² at 250 K hot boundary, demonstrating the viability of aerogel-based structured insulation.

The TFAWS dual-blanket design (5-layer inner + 15-layer outer) achieves ε* = 0.0068–0.015, comparable to conventional single-blanket MLI while offering improved installation flexibility.

JAXA's zero-stitch MLI uses plastic pins instead of sewing, achievingεeff < 0.0050—eliminating stitch thermal bridges that can degrade conventional MLI performance by 10–30%.

Commercial MLI (Frako-Term, ~40 layers) achieves k≈ 0.03 mW/m•K, demonstrating that commercial products can match laboratory-grade performance when properly manufactured.

5.12 LB-MLI Tank Applied Tests (NASA/KSC + Quest Thermal)

(Source: AIAA, NASA KSC [20])

Load-Bearing Multilayer Insulation (LB-MLI) is an advanced MLI concept developed by Quest Thermal Systems in collaboration with NASA KSC. LB-MLI is designed to serve as both thermal insulation and structural support, enabling its use as an outer shell for cryogenic propellant tanks.

Configuratio n	Layers	TH (K)	TC (K)	Heat Flux (W/m²)	Notes
LB-MLI coupon	—	293	77	—	KSC testing
	—	90	20	—	

Configuratio n	Layers	TH (K)	TC (K)	Heat Flux (W/m²)	Notes
LB-MLI coupon					LH_2 temp range
LB-MLI tank (VATA)	19 inner + BAC + 30 outer	293	20	—	VATA tank, LH_2 boil-off
LB-MLI with 56 nylon tags	10	—	—	0.92→ 1.04	Tag heat load: 0.16 W total

(Source: NASA KSC / Quest Thermal [20])

Key Findings:

The LB-MLI tank configuration uses a bifurcated architecture: 19 inner layers + BAC (Bulkhead Attachment Collar) + 30 outer layers, providing both insulation and structural load path.

Testing was conducted across both LN_2 range (293 K / 77 K) and LH_2 range (90 K / 20 K), demonstrating operability across the full cryogenic propellant temperature spectrum.

The addition of 56 nylon spacer tags to a 10-layer LB-MLI blanket increases heat flux from 0.92 to 1.04 W/ m² (a 13% increase), with the tags contributing an additional 0.16 W of total heat load.

The VATA (Vacuum-Insulated Test Article) tank test represents a full-scale validation of LB-MLI technology using LH_2 boil-off calorimetry.

6. Key Performance Trends & Engineering Insights

This section synthesizes the test data from Section 5 into actionable engineering insights for MLI system design and selection.

6.1 Layer Count Effect

The relationship between layer count and thermal performance follows a law of diminishing returns:

10→ 20 layers: 46.3% heat flux reduction (from 6.93 to 3.72 W/m² at 300 K / 77 K, 18.1 layers/cm) [Source: 真空与低温]

20 → 30 layers: ~43.3% reduction (from 3.72 to ~2.11 W/m²)

30 → 60 layers: ~38.4% reduction (from ~2.11 to 1.30 W/m²)

60 → 70 layers: only 13.8% reduction (from 1.30 to 1.12 W/m²)

The optimal practical range is 30–60 layers for most applications, where the majority of thermal benefit is captured while material cost, weight, and assembly complexity remain manageable. Beyond ~60 layers, additional thermal benefit is marginal and may be offset by increased solid conduction from additional spacer contact points.

The Chinese 135 L calorimeter study provides fluid-specific optimal layer counts [Source: 低温与超导 2023]:

Stored Fluid	Boiling Point (K)	Optimal Layer Count
LNG	~111	60
LO_2	90	65
LN_2	77	68
LH_2	20	80

Lower-temperature fluids require more layers because the conduction-to-radiation balance shifts further toward conduction dominance, requiring more radiation-suppressing layers to compensate.

Exception: At liquid helium temperatures (4.2 K cold boundary), the WUT/IUAC data (Section 5.5) shows that heat flux can initially increase with layer count due to the $T^{0.67}$ emissivity dependence. In this regime, careful optimization—not simply maximizing layers—is essential.

6.2 Layer Density Effect

Layer density (layers per unit thickness) directly controls the degree of compression between reflective shields and, consequently, the magnitude of solid conduction:

Lower layer density → lower heat flux: At 30 layers (300 K / 77 K), reducing density from 40/cm to 10/cm decreases heat flux from ~3.0 to ~1.0 W/m²—a 3× improvement [Source: 真空与低温].

But too low density → blanket instability: Extremely low densities compromise mechanical integrity, making the blanket susceptible to handling damage and gravity-induced compression in vertical orientations.

Optimal density: NASA Cryostat-100 testing indicates the optimal range is 1.5–2.6 layers/mm (15–26 layers/cm), with the practical optimum approximately 2× the theoretical prediction [Source: NASA NTRS 2011].

Variable density is superior: FSU/GE data (Section 5.4) demonstrates that non-uniform density distributions—specifically, lower density on the cold side and higher density on the warm side— outperform uniform configurations by up to 22%. NASA MSFC VD-MLI testing (Section 5.10) confirms that variable-density configurations reduce heat leak by approximately 50%while reducing weight by 74% [Source: NASA NTRS 2002]. The Chinese simulation study (Section 5.6.7) further validates this with a 10.7% improvement for the optimal sparse-to-dense configuration.

6.3 Temperature Dependence

The balance between radiation and conduction in MLI shifts dramatically with temperature:

At 300 K→ 77 K: Radiation is the dominant heat transfer mechanism. The T^4 (more precisely, $T^{4.67}$) dependence means radiation scales strongly with the hot boundary temperature.

At 77 K→ 4 K: Solid conduction becomes dominant. At these temperatures, radiation is negligible (scaling as $T^{4.67}$), and heat transfer is governed by spacer thermal conductivity.

At < 50 K (hot side): MLI can perform worse than a bare low-emittance surface. This is because the emissivity at such low temperatures is so low ($\varepsilon \propto T^{0.67}$) that the radiation suppression provided by additional shields is offset by the conduction introduced by additional spacers.

CAS Institute of Physics and Chemistry data (Section 5.6.2): When CBT decreases from 120 K to 20 K, heat flux increases by 39.0%; from 77 K to 20 K, it increases by 17.7% [Source: ICEC 2024].

Emissivity scaling: The relationship$\varepsilon = 6.8\times 10^{-4}\times T^{0.67}$ predicts $\varepsilon \approx 0.031$ at 300 K, $\varepsilon \approx 0.011$ at 77 K, and $\varepsilon \approx 0.0036$ at 20 K—each order-of-magnitude reduction in temperature yields approximately a 5× reduction in emissivity.

6.4 Vacuum Level Effect

The vacuum level within the MLI blanket is one of the most critical performance determinants:

Vacuum Level	Pressure Range	k-value Range (mW/ m·K)	Notes
High Vacuum (HV)	< 10^{-4} torr	0.03–0.1	Optimal; gas conduction negligible
Soft Vacuum (SV)	~1 torr (133 Pa)	1.6–10	6–10× degradation; gas conduction significant
No Vacuum	1 atm (760 torr)	~30	MLI essentially ineffective; gas conduction dominates

The benchmark MLI system (C108/C123) degrades from k = 0.086 mW/m•K (HV) to k = 10.0 mW/m•K (SV)—a 110× degradation [Source: NASA NTRS 2013].

The LCI configuration with fumed silica achieves k = 1.6 mW/m•K at 1 torr—6.25× better than conventional MLI (10.0 mW/m•K) at the same pressure [Source: NASA KSC].

Gas type matters: At the same pressure, helium interstitial gas produces 3.3× higher gas conduction than nitrogen (Cg = 48,900 vs. 14,600), due to helium's higher molecular velocity and thermal conductivity.

Aerogel + MLI hybrid systems provide the best coverage across the full vacuum range, with aerogel dominating at ambient pressure and MLI dominating at high vacuum [Source: NASA NTRS 1999].

6.5 Spacer Type Impact

The choice of spacer material significantly affects both thermal performance and practical usability:

Charac teristic	Dacron Net	Fibergl ass Paper/ Cloth	Single Silk Net	Triple Silk Net	IMLI Polym er Posts	Embos sed/ Dimple d	Hollow Glass Micros pheres	Quartz Fiber Cloth
Gas evacua tion	Excelle nt (open mesh)	Poor (contin uous barrier)	Good (open mesh)	Moder ate (dense r)	Excelle nt	Good	Moder ate	Poor
Gas conduc tion at SV	Higher	Lower	Higher	Higher	Lower	Moder ate	Moder ate	Lower
Solid conduc tion	Low	Moder ate	Higher	Very low	Very low	Minim al	Low	Low
Best vacuu m regime	HV	HV + SV	HV	HV (cryog enic)	HV	HV	HV	HV (high- temp)
Max temper ature	~150 °C	~500 °C	~150 °C	~150 °C	~200 °C	~150 °C	—	~1050 °C
Assem bly comple xity	Low	Low	Low	Moder ate	Mediu m	Lowest	Mediu m	Mediu m

Dacron net (open structure) excels at gas evacuation, making it ideal for high-vacuum applications. However, the open mesh allows gas molecules to traverse the blanket freely, increasing gas conduction at soft-vacuum levels.

Fiberglass/silk paper (continuous barrier) impedes gas movement, reducing gas conduction at soft vacuum—but also slowing pump-down time.

Triple silk net achieves 10× lower conductance than single silk net (1.5 vs. 25 $mW/m^2 \cdot K$), making it the gold standard for liquid helium temperature applications [Source: JPL CEC2015].

IMLI polymer spacers achieve 50% lower per-layer heat leak than conventional net spacers, with 16– 37% better overall performance at equivalent layer counts [Source: Quest Thermal 2024].

Quartz fiber cloth is the premier high-temperature spacer, achieving $k = 10^{-2}$–10^{-3}W/(m•K) at 1000 °C when paired with Mo foil [Source: Materials 2025].

Hollow Glass Microspheres offer a lightweight alternative to Dacron net, with 14.1% lower insulation performance but significant weight savings [Source: 低温工程2026].

Embossed/dimpled self-spacing films eliminate the spacer entirely, minimizing blanket thickness and assembly complexity. Performance is moderate—suitable for applications where space and weight constraints outweigh thermal optimization.

6.6 Material Comparison Summary

The following summary provides a quick-reference guide for material selection based on application requirements:

Material System	Best Application	Key Advantage	Key Limitation	Relative Cost
DAM + Dacron net	Cryogenic (77– 300 K)	Best cost- performance; industry standard; most test data available	Max temp ~150 °C	Low
Al foil + fiberglass paper	Cryogenic (77– 300 K)	Higher temp tolerance (~500 °C); ASTM C740 baseline	Heavier; less flexible	Low–Medium
DAK (aluminized Kapton)	Elevated cryogenic (77–400°C)	Extended temp range vs. DAM; 9–15% lower ε* than PET	Higher cost than DAM	Medium
Mo foil + ZrO_2 ceramic	Ultra-high temp (≤1000°C)	Only practical option for >1000 °C; 29°C improvement vs. Ni baseline	Higher emissivity (~0.10); expensive; complex manufacturing	High
Mo foil + quartz fiber cloth	Ultra-high temp (≤1050°C)	$k = 10^{-2}$–10^{-3} W/(m•K) at 1000°C; long-term stability	Expensive; 60 layers required	High
Stainless steel foil + borosilicate Al cloth	High temp (500–1000°C)	Flexible TPS structure; NASA Ames validated	Moderate thermal performance	Medium–High
Gold-coated foil + Saffil	High temp (300–1300 K)	Extremely high IR reflectance; oxidation resistant	Very high cost; limited availability	Very High
Gold/silver coatings	Specialized optical/thermal	Marginal emissivity		Very High

Material System	Best Application	Key Advantage	Key Limitation	Relative Cost
		improvement (ε≈ 0.02)	Very high cost; limited availability	
Multi-metal (Al + Au + Cu)	Research; advanced cryogenic	33.5% improvement (research setting)	Manufacturing complexity; cost	High
IMLI (structured polymer spacers)	Precision cryogenic; load-bearing	16–37% better than conventional; predictable; load-bearing	Higher manufacturing cost	Medium–High
LCI (fumed silica composite)	Soft-vacuum cryogenic	6.25× better at soft vacuum	Heavier; more complex	Medium
VD-MLI (variable density)	All cryogenic; mass-critical	50% heat leak reduction; 74% weight reduction	Design complexity; requires optimization	Medium–High
Aerogel + MLI hybrid	Full vacuum range	Best ambient- pressure insulation; k = 0.15 mW/m•K (HV)	Heavy; expensive	High
JPL SP-100 foils (C/Nb/Ti/Zr)	Ultra-high temp; mass-critical	44–85% weight reduction vs. Mo foil	Limited test data; manufacturing challenges	High

7. Research Institutions Directory

The following table provides a comprehensive directory of all research institutions mentioned in this document, organized by country. Each entry includes the institution's test equipment, methodology,

temperature range, and vacuum capability. This directory serves as a resource for identifying potential collaboration partners, test facilities, and subject-matter experts.

7.1 United States

Institution	Key Contribution s	Equipment / Model	Test Method	Temperature Range	Vacuum Range
NASA KSC Cryogenics Test Laboratory	Cryostat-1/1 00/2/3, LCI, robust MLI, LB-MLI	Cryostat-100 (1 m× 168 mm dia.); Cryostat-1; Cryostat-2/3 (0.5 m× 132 mm); Cryostat- P100 (12.2 m pipe)	LN_2 evaporation calorimetry (absolute/ comparative)	77–353 K	760–10^{-4} torr (full range)
NASA GRC (Glenn Research Center)	CFM, LH_2 storage, VD- MLI, MLSTC	SMiRF (Small Multipurpose Research Facility)	Evaporation calorimetry	LH_2 temperature range	High vacuum
NASA MSFC (Marshall Space Flight Center)	VD-MLI analysis, MHTB	MHTB (Multipurpos e Hydrogen Test Bed)	Large-scale LH_2 evaporation calorimetry	20 K	High vacuum
NASA Lewis Research Center (LeRC)	LH_2 tank MLI	Tank calorimeter (4 ft dia. tank)	LN_2/LH_2 evaporation calorimetry	20–300 K	High vacuum
NASA JPL (Jet Propulsion Laboratory)	SP-100, spacecraft MLI, Cassini	Various	Calorimetry / analysis	87–328 K; ≤1000°C+	High vacuum
					Vacuum

Institution	Key Contribution s	Equipment / Model	Test Method	Temperature Range	Vacuum Range
NASA Ames Research Center	FRCI ceramic tiles, flexible high-temp TPS	Flexible TPS test bed	Thermal vacuum / thermal equilibrium	500–1000 °C	
Lockheed Martin (Palo Alto)	Lockheed equation, cryo dewar MLI	Custom cryogenic dewar MLI test stand	Calorimetry	4–300 K	High vacuum
Ball Aerospace	IMLI, LB-MLI	Cylindrical calorimeter	LN_2 evaporation calorimetry	77–295 K	High vacuum
Quest Thermal Systems	IMLI, LRMLI, LB-MLI	Flat/ cylindrical LN_2 calorimeter	LN_2 evaporation calorimetry	77–295 K	< 10^{-4} Pa
GE (General Electric)	MRI cryostat MLI	—	—	Cryogenic	—
Thermo Fisher Scientific	SP-100 oxide coatings	High-temp testing	—	High temp	—
A.D. Little, Inc.	Early MLI characterizati on (1960s)	Tank calorimeter (4 ft dia.)	LN_2/LH_2 evaporation calorimetry	20–300 K	High vacuum
Convair Aerospace (General Dynamics)	Goldized Kapton + Dacron tufts (Superfloc)	—	Calorimetry	LN_2 temperature range	High vacuum
Sierra Lobo	LCI development	—	—	Cryogenic	—
				60–300 K	High vacuum

Institution	Key Contribution s	Equipment / Model	Test Method	Temperature Range	Vacuum Range
FSU (Florida State University)	MIkE apparatus, MRI blankets, VD-MLI	MIkE (Multilayer Insulation Kinetic Experiment)	Steady-state calorimetry		
Fermi National Accelerator Laboratory (Fermilab)	MLI calorimeter, Cu surface comparison	MLI calorimeter (Cu cylinder, Al tape / black paint)	LN_2 evaporation calorimetry	77–300 K	10^{-5} torr
Texas Tech University	MLI for spacecraft instruments, embossed DAK	Radiation heat source test bed	Steady-state thermal equilibrium	200–300 K	High vacuum

7.2 Japan

Institution	Key Contributions	Equipment / Model	Test Method	Temperature Range
JAXA	Pin-controlled MLI, zero-stitch design	Evaporation calorimeter (3 cylindrical LN_2 tanks; measurement tank area 0.2826 m²)	LN_2 evaporation calorimetry	77–300 K
Ohmori T. / Teikyo University (IHI)	Ideal MLI k- value ~0.05 mW/ m•K	Evaporation calorimeter	LN_2 evaporation calorimetry	77–300 K
KEK (High Energy		Calorimeter	LN_2 evaporation calorimetry	77–300 K

Institution	Key Contributions	Equipment / Model	Test Method	Temperature Range
Accelerator Research Organization)	MLI for accelerator cryogenics			

7.3 Europe

Institution	Key Contributions	Equipment / Model	Test Method	Temperature Range
TU Dresden (Dresden University of Technology)	Flow calorimetry MLI testing	Flow cryostat (0.9 m² cylindrical surface, LHe/ cold He gas)	Flow calorimetry	20–300 K
ESA/ESTEC Mechanical Systems Laboratory	MLI thermal efficiency, Pyrogel aerogel R&D	Thermal vacuum chamber	Thermal cycling / thermal equilibrium	Variable
Cracow University of Technology	MLI cryogenic testing	—	—	Cryogenic
CERN (European Organization for Nuclear Research)	Flow cryostat, 4.2 K MLI testing	Flow cryostat (4.2 K cold boundary, 20–60 K shield)	Flow calorimetry	4.2–60 K

7.4 China

Institution	Key Contributions	Equipment / Model	Test Method	Temperature Range
Shanghai Jiao Tong University – Institute of	LH_2 temp dry calorimetry, HGM spacer, GM	GM cryocooler dry calorimetry system (closed test chamber);	Dry calorimetry (GM cryocooler); LN_2 evaporation	20–315 K

Institution	Key Contributions	Equipment / Model	Test Method	Temperature Range
Refrigeration and Cryogenics	cryocooler system	LN_2 evaporation calorimeter		
CAS – Technical Institute of Physics and Chemistry (中科 院理化所)	20–120 K MLI testing, CBT effect study	G-M cryocooler measurement system	Steady-state axial heat flow	20–120 K
China Special Equipment Inspection and Research Institute (中国特 种设备检测研究 院)	135 L calorimeter, fluid-specific optimal layers	135 L cryogenic calorimeter	LN_2 evaporation calorimetry	77–300 K
Aerospace Materials and Processes Research Institute (航天材 料及工艺研究所)	High-vacuum platform, penetration tube testing, pin-type MLI	High-vacuum test platform (vacuum chamber ≤ 1 mPa, Φ6–16 mm penetration tubes, ALICAT mass flow meter)	LN_2 evaporation calorimetry	77–305 K
Shanghai Institute of Space Propulsion (上海 空间推进研究 所)	Pin-type MLI, new seamless construction	High vacuum test platform	LN_2 evaporation calorimetry	77–305 K
Shanghai Institute of Technical	Aerogel + Al composite	—	High vacuum testing	Cryogenic

Institution	Key Contributions	Equipment / Model	Test Method	Temperature Range
Physics (上海技 术物理研究所)				
Shanghai Astronautical Systems Engineering Research Institute (上海宇 航系统工程研究 所)	Cryogenic MLI applications	—	—	Cryogenic
CAS – Institute of Plasma Physics (ASIPP, 中科院等离子体 物理研究所)	ITER cold shield VD-MLI	—	—	138–300 K
Beijing Spacecraft Design Institute	High-temp MLI (Mo + ZrO_2)	—	Calorimetry	≤1050 °C
State Key Lab of Aerospace Cryogenic Propellant Technology	Multi-metal coatings, VD optimization	—	—	77–300 K
Lanzhou University of Technology (兰 州理工大学)	Cryogenic MLI research	—	—	Cryogenic
Zhejiang Normal University	Layer density optimization	—	—	Cryogenic
NPU (Northwestern Polytechnical University)	ZrO_2 preparation methods	—	—	High temp

7.5 India

Institution	Key Contributions	Equipment / Model	Test Method	Temperature Range
IUAC (Inter- University Accelerator Centre)	MLI testing, Indo-Polish cooperation	IUAC cryostat	Calorimetry	4.2–300 K

7.6 Poland

Institution	Key Contributions	Equipment / Model	Test Method	Temperature Range
WUT (Warsaw University of Technology)	MLI modeling, non-monotonic layer effect	WUT cryostat	Calorimetry	4.2–300 K

Total: 32 institutions across 6 countries/regions.

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9. Product Brochure Selection Recommendations

This chapter provides practical guidance for MLI material selection and system design, synthesizing the comprehensive data presented in this document into actionable recommendations for engineers and procurement decision-makers.

9.1 DAM + Dacron Net as Baseline Configuration

Recommendation: Use DAM (Double Aluminized Mylar) + Dacron net as the baseline MLI configuration for general cryogenic applications (77–300 K).

Rationale:

Most extensively tested material combination, with data from NASA KSC Cryostat-100, JPL, Ball Aerospace, Fermilab, WUT/IUAC, and multiple Chinese institutions—providing unparalleled design confidence.

Lowest cost of any viable MLI system, with widely available commercial sources (e.g., Frako-Term, Dunmore).

Excellent high-vacuum performance: k = 0.03–0.09 mW/m•K, heat flux = 0.25–0.87 W/m² (300 K / 77 K, HV).

Full vacuum range data available: from HV (< 10^{-4} torr) through SV (1 torr) to ambient pressure, enabling performance prediction across all operating conditions.

ASTM C740 baseline: Al foil + fiberglass paper is the ASTM standard reference, but DAM + Dacron net offers comparable performance with easier handling and lower weight.

Compatible with variable-density optimization: Both FSU/GE and Chinese studies validate VD configurations with Dacron net spacers.

Limitations: Maximum operating temperature ~150 °C (Mylar substrate). For applications above 150 °C, use DAK (Kapton, up to 400 °C) or metal foil systems.

9.2 IMLI as High-Performance Benchmark

Recommendation: Use IMLI (Integrated Multilayer Insulation) as the high-performance comparison benchmark for precision cryogenic and load-bearing applications.

Rationale:

16–37% better than conventional MLI at equivalent layer counts (10 layers, 295 K / 77 K).

Complete performance tables available for 5–40 layers at both 77 K and 20 K cold boundaries (Section 5.3), enabling precise system design.

Predictable performance: Controlled polymer spacer positioning eliminates the variability inherent in blanket-style MLI, enabling reliable model-based design.

Load-bearing capability: IMLI can serve as structural insulation, enabling dual-function designs that reduce system mass and complexity.

Lowest per-layer heat leak: Each IMLI layer's heat leak is only 50% of conventional net-spaced MLI.

A 20-layer IMLI configuration achieves 0.45 W/m² (77 K–295 K) with an areal density of only 0.87 kg/m².

Limitations: Higher manufacturing cost; limited to ~200 °C maximum temperature; requires Quest Thermal Systems as supplier.

9.3 High-Temperature MLI: Two Technical Routes

High-temperature MLI (> 500 °C) should be evaluated as a separate category with two distinct technical routes:

Route 1: Gold-Coated Foil + Alumina Fiber (NASA, 300–1300 K)

Materials: Gold-coated reflective foil (1 μm Au) + alumina fibrous insulation (Saffil)

Temperature range: 300–1300 K (27–1027°C)

Performance: Reflective foil significantly reduces effective thermal conductivity (RMS deviation 9.5%)

Advantages: Extremely high IR reflectance; oxidation resistant; broad temperature range

Limitations: Very high cost (gold); limited availability

Historical validation: Arthur D. Little (1968, goldized Mylar + silk net, 0.33 Btu/hr•ft²); Convair (1972, goldized Kapton + Dacron tufts, k = 1.37–1.5× 10^{-5} Btu/hr•ft•°F)

Route 2: Mo Foil + ZrO_2 Ceramic / Quartz Fiber Cloth (Chinese Institutions, ≤1000–1050 °C)

Materials: Molybdenum foil (8–100μm) + ZrO_2 ceramic particles or quartz fiber cloth

Temperature range:≤1000–1050°C

Performance: Mo + ZrO_2 achieves 29°C improvement vs. Ni baseline at 1050°C; Mo + quartz fiber cloth (60 layers) achieves k = 10^{-2}–10^{-3}W/(m•K) at 1000°C

Advantages:More cost-effective than gold; proven manufacturing methods (plasma spray); long-term stability (~1050°C)

Limitations: Higher emissivity (~0.10 vs. ~0.02 for gold); requires many layers (60); complex manufacturing

Weight optimization: JPL SP-100 project demonstrated that carbon, niobium, titanium, and zirconium foils can achieve 44–85% weight reduction vs. Mo foil baseline

Additional high-temp option: NASAAmes' stainless steel foil (10–20 μm) + borosilicate aluminum fine yarn cloth offers a flexible TPS solution for 500–1000 °C applications.

9.4 Variable-Density Design: Principle and Effect

Recommendation: Consider variable-density MLI (VD-MLI) for mass-critical applications where weight reduction is as important as thermal performance.

Principle:

The optimal MLI layer density is not uniform across the blanket thickness. The local conductionradiation balance varies with temperature:

Cold side (low T): Radiation is negligible (scales as T^4); conduction dominates. Lower layer density reduces contact points and minimizes solid conduction.

Warm side (high T): Radiation is significant. Higher layer density provides more radiation-suppressing shields.

Effect:

Metric	Standard Uniform MLI	Variable-Density MLI	Improvement
Heat leak	Baseline	~50% reduction	2× better
Weight	Baseline	~74% reduction	3.8× lighter
Optimal density distribution	Uniform	Low cold / High warm	—
Validated by	—	NASA MSFC MHTB, FSU/GE, Chinese simulation	Multiple sources

Implementation: Three-zone configuration (e.g., 8/12/16 layers/cm from cold to hot) is sufficient; fivezone models provide < 5% additional improvement. The Chinese 135 L calorimeter study provides fluidspecific optimal total layer counts (LNG: 60, LO_2: 65, LN_2: 68, LH_2: 80).

9.5 Chinese Research Data: Supplementary Value

Chinese research institutions have produced increasingly valuable MLI test data that complements international datasets, particularly in the following areas:

Liquid hydrogen temperature range (20 K): SJTU's GM cryocooler dry calorimetry system enables nonevaporative testing at 20 K, avoiding the complexity of LH_2 boil-off methods. CAS Institute of Physics and Chemistry provides the only publicly available 20–120 K MLI performance curve, quantifying the 39.0% heat flux increase when CBT drops from 120 K to 20 K. 1.

Fluid-specific optimal layer counts: The 135 L calorimeter study (中国特种设备检测研究院) provides the only available dataset comparing optimal MLI layer counts for different cryogenic fluids (LNG, LO_2, LN_2, LH_2), directly applicable to storage vessel design. 2.

Novel spacer materials: Hollow Glass Microspheres (SJTU) offer a lightweight alternative to Dacron net, with quantified performance trade-offs (14.1% lower insulation, significant weight savings). 3.

Variable-density simulation validation: Chinese simulation studies independently confirm the superiority of decreasing-density (cold-to-hot) configurations, with a 10.7% improvement quantified for the optimal case. 4.

High-temperature MLI manufacturing: The Beijing Spacecraft Design Institute's systematic evaluation of three ZrO_2 application methods (PVD, sintering, plasma spray) provides practical manufacturing guidance unavailable fromWestern sources. 5.

Penetration thermal bridge effects: The Aerospace Materials and Processes Research Institute's highvacuum test platform withΦ6–16 mm penetration tube fittings enables realistic assessment of MLI 6.

performance including thermal bridges—a critical real-world factor often missing from laboratory coupon tests.

9.6 Selection Decision Matrix

Application	Recommended System	Key Parameter	Source
Cryogenic storage (LN_2, 77 K)	DAM + Dacron net, 30–68 layers	k = 0.03–0.09 mW/ m•K (HV)	NASA KSC, ASTM C740
Cryogenic storage (LH_2, 20 K)	DAM + Dacron net or IMLI, 60–80 layers	Heat flux < 1 W/m²	SJTU, CAS, Quest Thermal
Liquid helium (4.2 K)	DAM + triple silk net, 9–37 layers	k_0 = 1.5 mW/m²•K	Lockheed/JPL
Spacecraft thermal control	DAM, 20–40 layers	Radiation-dominated	JPL Cassini
MRI cryostat	DAM + polyester, VD configuration	22% improvement with VD	FSU/GE
Soft vacuum / degraded vacuum	LCI (fumed silica) or aerogel + MLI	k = 1.6 mW/m•K (SV)	NASA KSC
High temperature (500–1000°C)	Mo foil + quartz fiber cloth or SS foil + borosilicate Al cloth	k = 10^{-2}–10^{-3}W/ (m•K)	Materials 2025, NASA Ames
Ultra-high temperature (1000–1300°C)	Gold-coated foil + Saffil	RMS deviation 9.5%	NASA NTRS 2006
Mass-critical cryogenic	VD-MLI, 45 layers	50% heat leak reduction, 74% weight reduction	NASA MSFC
Load-bearing insulation	LB-MLI or IMLI	Dual structural + thermal function	Quest Thermal, NASA KSC
Commercial/industrial	Frako-Term MLI (~40 layers)	k ≈ 0.03 mW/m•K	Frako-Term

Application	Recommended System	Key Parameter	Source
Particle accelerator (4.2–60 K)	DAM (various configs)	Testing in progress	CERN
Penetration-heavy systems	DAM + Dacron net with penetration testing	k = 1.1 mW/m•K (with penetrations)	航天材料及工艺研究 所

Document compiled as a comprehensive technical reference for engineering and procurement decisionmaking. All data is sourced from publicly available technical literature and test reports. Users should consult primary sources for detailed test conditions and methodology before making design decisions.