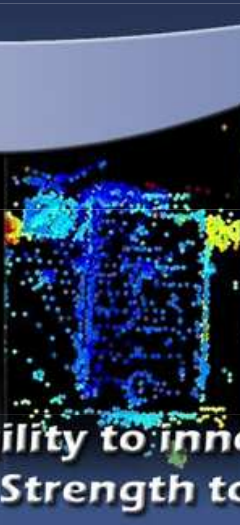
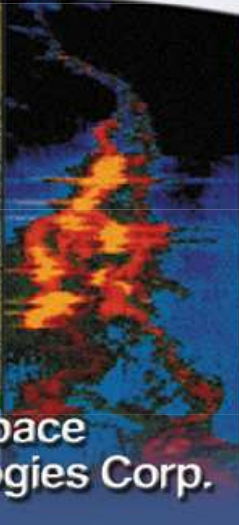


Modeling and Testing of Integrated and Load Responsive Multilayer Insulation

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Spacecraft Thermal Control Workshop
March 20, 2012



**Agility to innovate,
Strength to deliver.**



What is Multilayer Insulation?

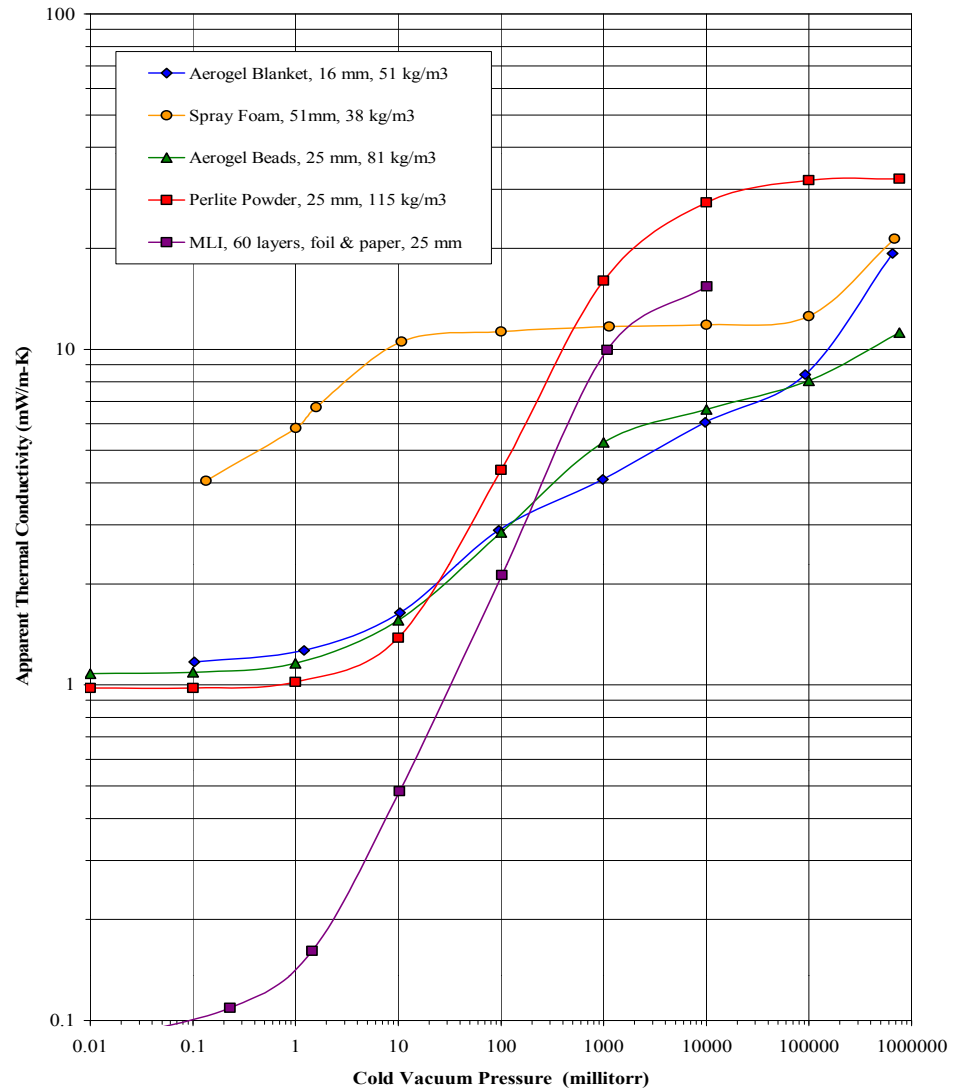
- Current technology consists of metalized polymer films (Mylar or Kapton) separated by polyester or silk netting.
- Used where high thermal performance insulation is needed
 - Spacecraft
 - Cryogenic systems
 - Space instruments
- Technology is over 50 years old
 - First version was aluminum foil with paper spacers
 - Has been done at Ball Aerospace since very early days
- From 3 to 100 layers are used
- Typically installed in quilts or sub-blankets of 3 to 5 layers





MLI is the Best Insulation, but Requires a Vacuum

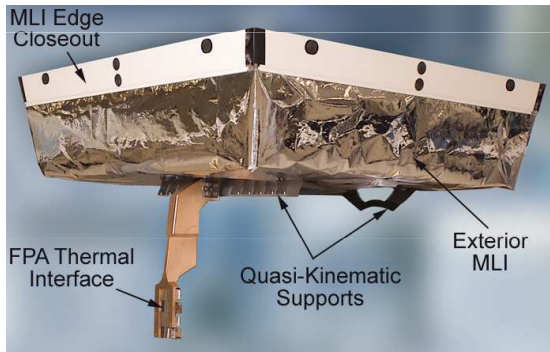
- In a vacuum of less than a millitorr, MLI has an apparent thermal conductivity ~ 10 X less than other insulations





Ball has Over Half Century Supporting JPL, NASA, and DOD with Cryogenics Using MLI

SBIRS HEO TCS



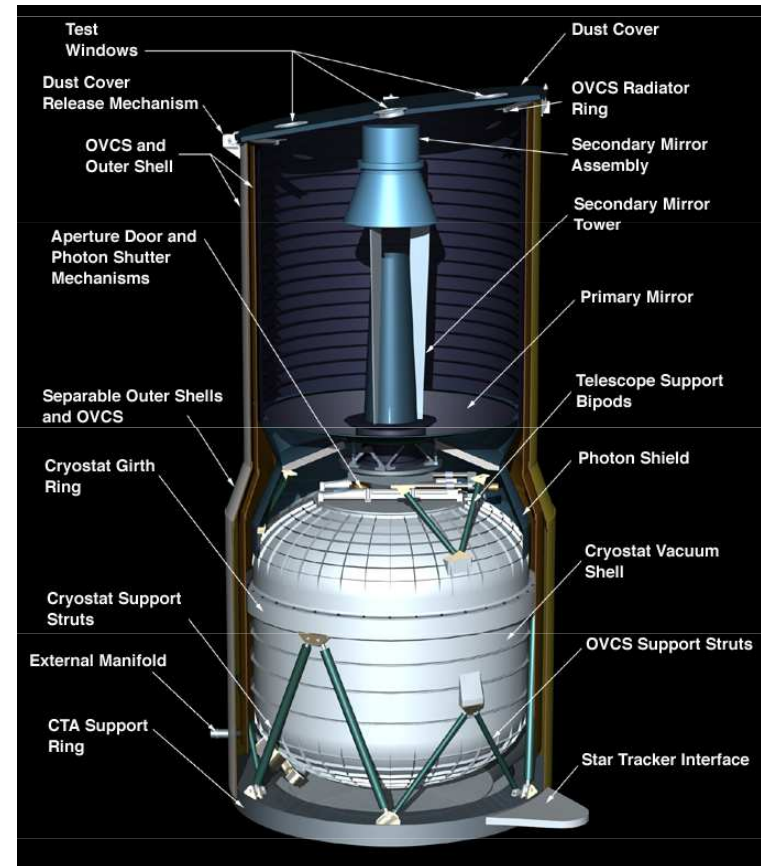
IRAS



PRSA



SPITZER





Ball MLI Center Provides Complete Range of MLI Services to Internal and External Customers

- **Extensive MLI Product Line**
 - High Performance (Cryogenics)
 - Standard Performance (Satellites)
 - High Temperature (Stirling Cycle Engines, Solar Thermal Propulsion Systems)
- **Industry Experts in Cryogenic MLI**
 - State-of-the-art, proprietary high performance MLI design techniques
 - Proven performance on dewars, cryo-coolers, cryo-radiators, and optical instruments
- **Delivers Consistent, Repeatable, and Efficient End-to-End Performance on Programs**
 - Effective management of cost, schedule and technical commitments
 - Integrate, optimize and standardize end-to-end capabilities and processes
 - Leverage commonality and reuse

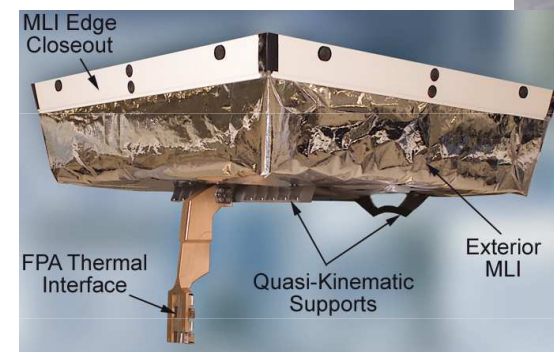
WorldView



Kepler



SBIRS HEO TCS



Ball MLI Center – We Gotcha Covered!



Full-up MLI Fabrication Capability

- **Controlled Facilities, Clean Rooms**
 - Capacity: 80 feet of lay-up tables, 5 sewing stations, 8 fabrication stations
 - Mylar templates
- **Cutting Techniques**
 - Hot knife
 - Laser cutter (for high quantity)
- **Capable of Processing All Insulation Materials**
 - Including Mylar, Kapton, Teflon, beta-cloth, net/mesh films with all metalized finishes such as aluminum, gold, silver, and inconel
- **Processes used include stitching, venting, attachment (snaps, grommet, Velcro, bonding), and ground strap installation**

John W. Fisher Manufacturing and Environmental Test Facilities



MLI Processing Center





Advanced Multilayer Insulation



Motivation for Advanced MLI

- MLI Performance is highly dependent on layer density (compression), which is only loosely controlled.
 - Layer density affected by the number of layers, gravity
 - All performance models contain significant empirical corrections
 - Ball Low Density MLI technique is a major step in improving density control but still requires empirical based modeling

$$Q_{\text{leak}} := \frac{2.11 \cdot 10^{-9} \cdot \rho_{\text{MLI}}^{3.56} \cdot T_{\text{med}} \cdot (T_{\text{h}} - T_{\text{c}})}{N_{\text{layers}} + 1} + \frac{5.39 \cdot 10^{-10} \cdot .031 \left(T_{\text{h}}^{4.67} - T_{\text{c}}^{4.67} \right)}{N_{\text{layers}}}$$

Layer density

Semi-empirical equation for MLI performance developed by Lockheed
under NASA contract



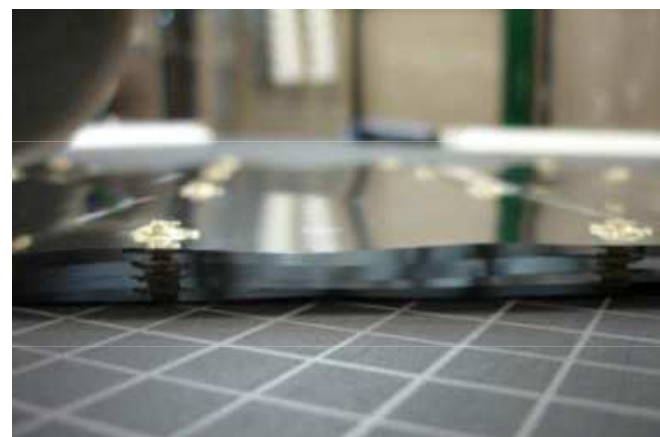
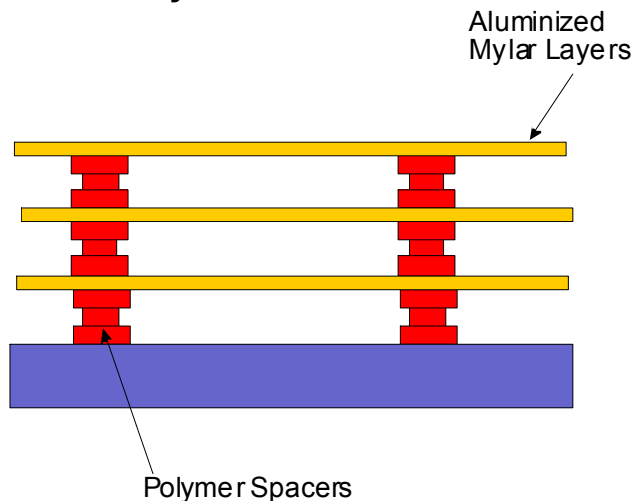
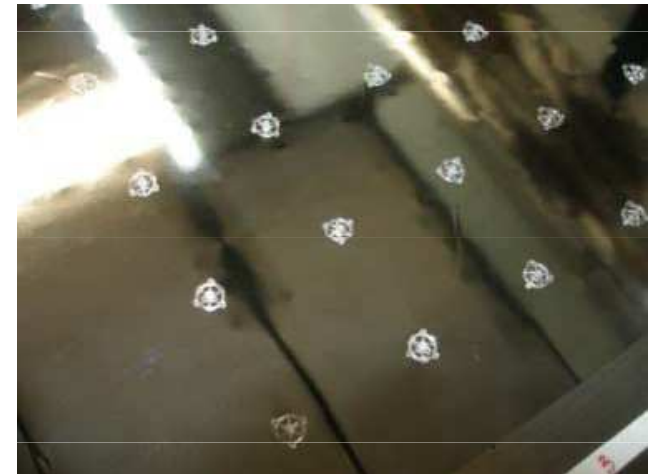
More Motivations for Advanced MLI

- Performance is dependent on design and installation workmanship
- High performance MLI is not structurally robust, layers are loosely tied together
- Netting generates particulates
- Labor intensive to fabricate and install properly
- Vacuum shells are required for operation in the atmosphere and are heavy
 - ~ 0.1" thick aluminum
 - ~ 10 kg/m²



Integrated Multilayer Insulation (IMLI), US patent 7,954,301

- Advanced MLI developed Insulation by Ball and Quest Product Development
- Successfully completed a Phase II SBIR, TRL 6 achieved.
- Uses polymer spacers instead of netting
 - Performance can be accurately predicted
 - Not affected by gravity
- IMLI is a replacement for conventional MLI
 - More robust, layers bonded together
 - Lower heat leak or fewer layers and less mass
 - Potentially lower cost



Integrated MLI Concept



IMLI compared to conventional MLI



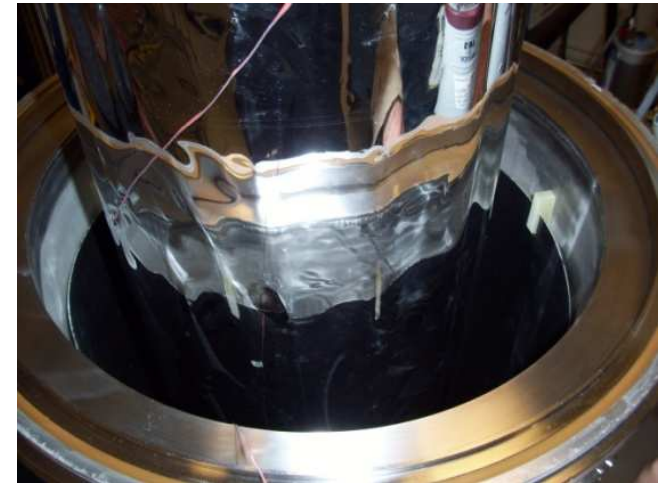
- IMLI 20-layer blanket on left, conventional MLI 20-layer sample on right





Results of Testing of IMLI at NASA KSC Cryogenic Test Lab

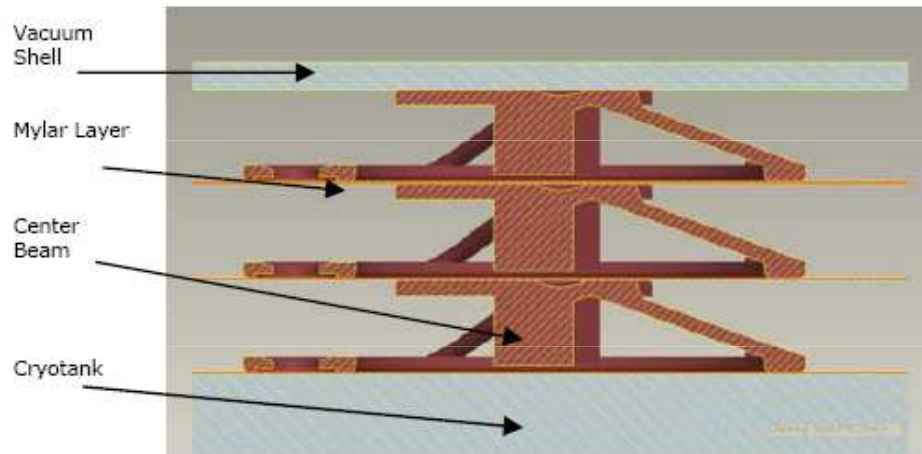
- Testing on KSC Cryostat-100 calorimeter
 - LN2 boil off calorimeter
 - Has guard chambers to isolate heat leak to insulation
 - Low density MLI tested recently
- Heat leak 27% less than conventional, low density MLI per layer.
- Vacuum pump down significantly faster than MLI with netting
- Soft vacuum ($> 10^{-4}$ torr) performance not as good as other MLI , probably due to layer spacing.





Load Responsive MLI (LRMLI), US Patent 7,954,301

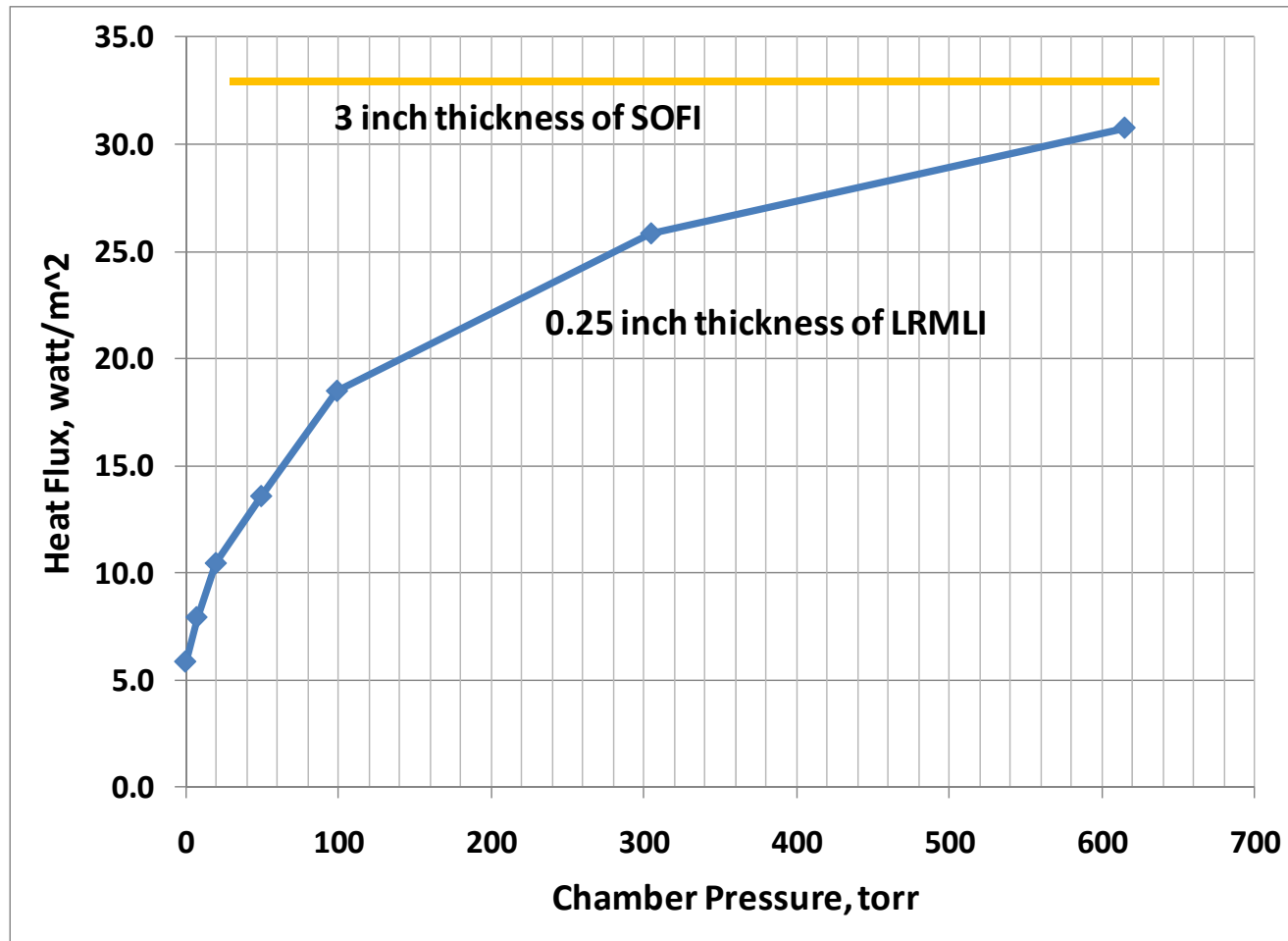
- Uses polymer spacers to support a thin vacuum shell
- Spacers elastically compress with atmospheric load and disconnect with low pressure
- Being developed by Ball and Quest Product Development
- Successfully demonstrated in a Phase I SBIR, TRL 4 achieved.
- Development continuing in a Phase II SBIR.





The Measured Conductivity and Heat Flux of Load Responsive MLI is Significantly Lower than SOFI (Spray on Foam Insulation)

- Performance on a liquid nitrogen cylindrical calorimeter (77 to 294 K)





Some Applications



Launch Vehicle External Insulation

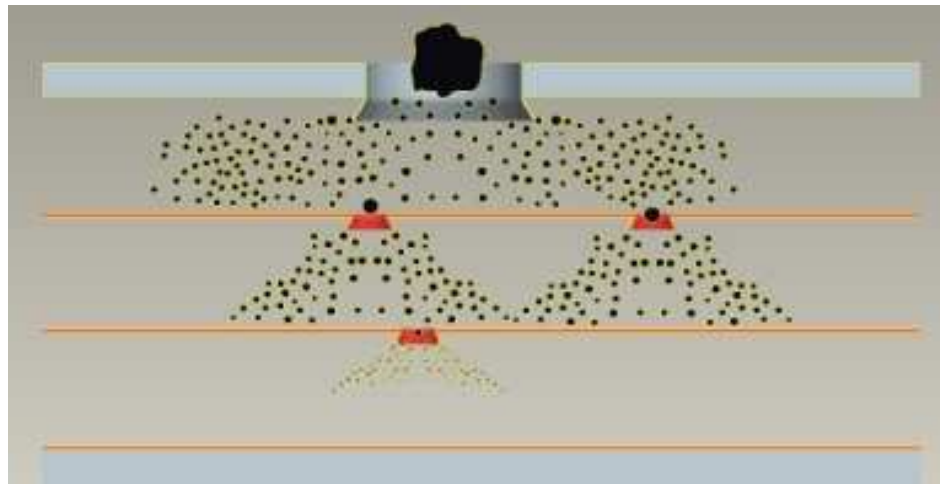
- Launch vehicles with cryogenic upper stages could benefit from reduced LH₂ boil off on-orbit
 - Centaur
 - Delta IV
- IMLI/LRMLI would have to be developed that would be robust enough to survive on outside of launch vehicle
- Feasibility demonstrated in a NASA SBIR phase 1 program, now at TRL 5
- Prototype of a 3 layer system survive aerodynamic loading equivalent to a launch





Micrometeoroid/Orbital Debris Protection

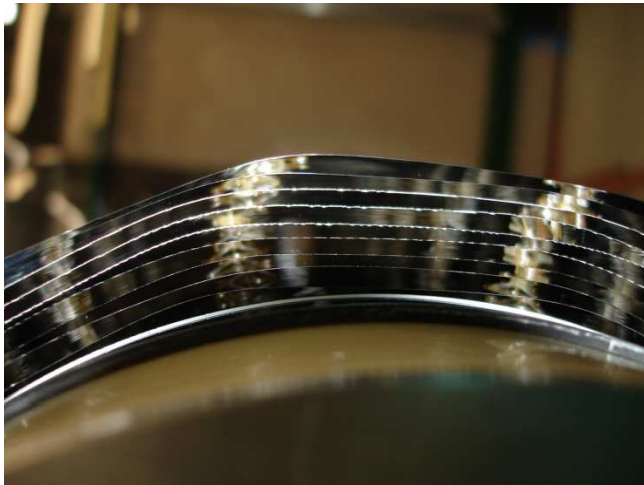
- MMOD-IMLI uses engineered polymer spacers to provide precise layer spacing and combinations of layer materials to provide excellent MMOD protection combined with thermal insulation
- MMOD-IMLI with 0.070" inter-layer spacing has a modeled energy dissipation that predict 9-fold fewer layers than conventional MLI to stop particle penetration
- Prototype have stopped a 5.5 mm projectile at 7 km/sec in testing at White Sands Test Facility
- Feasibility demonstrated in an SBIR phase 1 program, now at TRL 4





Wrapped MLI for Cryo-feed Line Insulation

- Cryogenic feed lines are difficult to well insulate
- Current feed line MLI performance is 3 – 10x worse than tank insulation
- Prototypes have provided 4 X lower heat leak than spiral wrapped netting MLI
- Wrapped MLI is a NASA Phase II SBIR contract to develop improved feed line insulation
- Currently at TRL 3





Testing of Multilayer Insulations



Heat Flux Measurement by Liquid Nitrogen Boil-off Calorimeter

- Tank is insulated by MLI test sample
- Tank and sample placed in vacuum chamber
- Chamber pumped to high vacuum
- Tank filled with LN2
- Steady state boil off gas flow rate measured with flow meter
- Insulation heat flux calculated from heat of vaporization and tank area
- Accuracies of better than 5% are possible





Important details in testing

- **Minimize parasitic heat leaks**
 - Suspend test tank with vent line to negate any support heat load with vent gas
 - LN₂ guard tanks at each end of the test tank; NASA KSC approach
- **Control absolute pressure of liquid nitrogen**
 - Variations in atmospheric pressure can cause steady state boil off rate to vary
 - Absolute pressure controller used to regulate absolute pressure above ambient



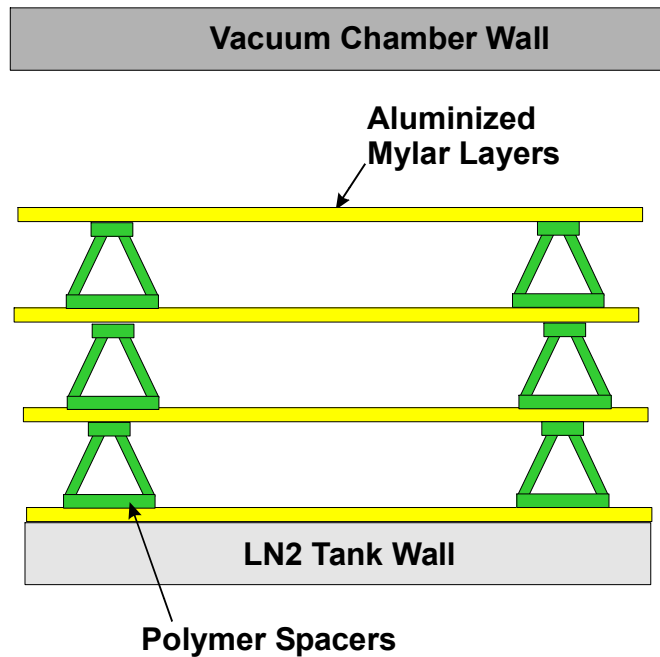


Modeling of IMLI/LRMLI

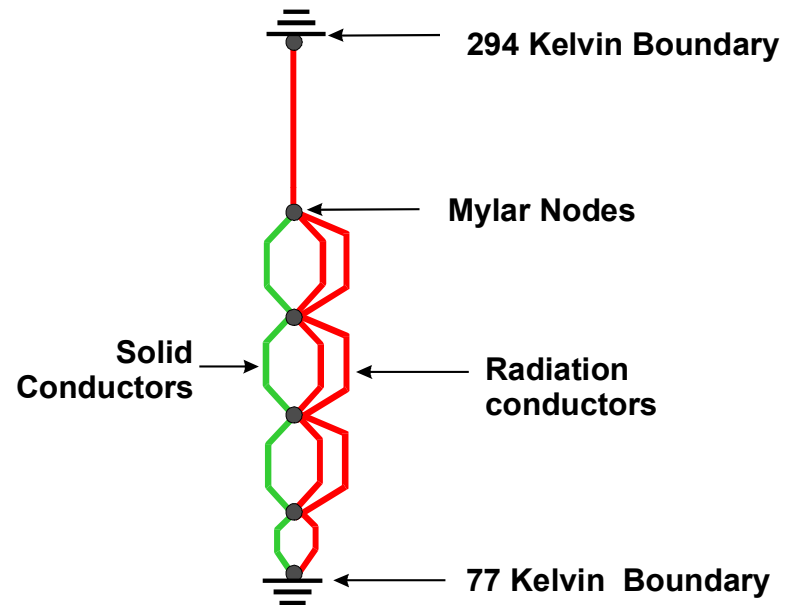


Modeling of IMLI and LRMLI uses standard network thermal modeling techniques

- TAK 2000 was used but SINDA could also be used.
- Layer by layer model: each metalized Mylar layer is a node
- The conductors between layers are modeled
 - Solid conductors are modeled based on conductivity*area/length of the spacer post
 - Radiation conductors from Mylar to Mylar and spacer post top to bottom



IMLI test configuration



IMLI Network Thermal Model



Results of Modeling and Test Show Good Correlation

Apparatus	Number and Type of Layers	Hot Bound, K	Cold Bound, K	Heat flux modeled watts/m ²	Heat flux measured watts/m ²	% Δ
Ball	10, IMLI	296	76	1.06	0.95	-11.6
KSC cryostat 100	20, IMLI	305	78	0.58	0.57	-1.8
KSC cryostat 100	20, IMLI	292	78	0.49	0.41	-19.5
Ball	2, IMLI	296	76	3.92	3.62	-8.3
Ball	8, IMLI, 2 ballistic cloth layers	296	76	1.43	1.58	9.5
Ball	3, unloaded LRMLI	296	76	5.42	5.87	7.7
Ball	3, loaded LRMLI	296	76	22.4	29.6*	32.1

*small vacuum leak in LRMLI

■ Model assumptions:

- Mylar emissivity of 0.031
- Polymer emissivity 0.82
- Published data on spacer polymer conductivity
- Measured spacer post area/length times the number of posts in a given area
- High conductance between tank and first layer of Mylar, because of direct contact interface



Conclusions

- **IMLI and LRMLI advanced multilayer insulations have been developed and have several advantages**
 - **Structurally robust; the layers are bonded together**
 - **Lower heat leak per layer**
 - **Potentially lower cost thru more automation**
 - **Less particulates due to no netting**
 - **LRMLI is much lighter and thinner than competing technologies such as SOFI**
- **Layer by layer network thermal models of IMLI and LRMLI correlate well with measured heat fluxes**
 - **Average difference between model and measurement is around 10%**
 - **Discrepancy between netting based MLI and models is often much higher than this.**
 - **No empirical correction factors are used in IMLI model**