Cylindrical Boiloff Calorimeters for Testing of Thermal Insulation Systems

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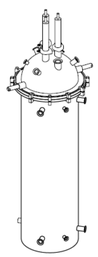
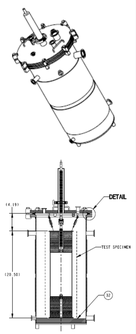
Introduction

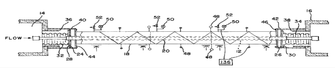
- Three types of cryostat instruments for the testing of thermal insulation systems in a cylindrical configuration have been developed and standardized for laboratory operation.
- The measurement principal is boiloff calorimetry for the determination of the effective thermal conductivity (k_e) and heat flux (q) of a test specimen at a fixed environmental condition (boundary temperatures, cold vacuum pressure, and residual gas composition).
- Through its heat of vaporization property, liquid nitrogen (LN_2) is the energy meter but the designs are adaptable for different cryogens.
- The main instrument, Cryostat-100, is guarded on top and bottom to provide direct, absolute thermal performance measurement.
- Cryostat-200 is a cylindrical instrument for comparative data.
- The Cold Pipeline Test Apparatus provides absolute data for insulated pipelines.



Insulation test cryostat instruments: cylindrical configurations.

Instrument	Type	Test Specimen Size	ASTM Test Standard	Environment	Heat Flux (W/m²)
Cryostat-100 (2 units)	Absolute	1 m long, 167 mm diameter, up to 50 mm thick	C1774 Annex A1	Full range vacuum 77 K–353 K	0.2–200
Cryostat-200 (2 units)	Comparative	0.5 m long, 132 mm diameter, up to 50 mm thick	C1774 Annex A2	Full range vacuum 77 K–353 K	1–200
Cold Pipeline Test Apparatus (1 unit)	Absolute	12 m long, 25 mm to 88 mm diameter	C335	No vacuum or vacuum-jacket 77 K–353 K	4–400



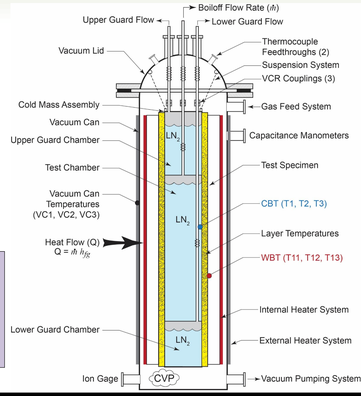


Testing Methodology

- Steady-state heat flow rate (Q) is the basis for calculating thermal properties: effective thermal conductivity (k_e), or system thermal conductivity (k_s), and heat flux (q) per ASTM C1774, Annex A1.
- Thicknesses from zero (bare cold mass) to approximately 50-mm can be tested.
- Materials can be multilayer, blanket, clam-shell, molded, or bulk-fill type.
- The warm boundary temperature (WBT) is typically set to 293 K for a test (or up to 353 K).
- The cold vacuum pressure (CVP) within the vacuum chamber is maintained in the range of 10^{-6} torr (high vacuum - HV) to 760 torr (no vacuum – NV) by active vacuum pumping plus GN_2 supply system.

Funnel Filling Tubes in operation during cooldown

Boiloff flow rate stability is affected by regional variations and twice-daily fluctuations in atmospheric pressure. For very low heat flux rates this fluctuation can cause periodic and substantial variation unless systematic controls are implemented to counteract this effect. The cryostat systems include an optional backpressure control system to provide a more even ambient pressure.



Cooldown and LN_2 filling of Cryostat-100

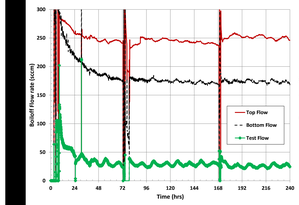
Example Test Results: Cryostat-100

- For all cylindrical calorimeters: grand total of 174 materials specimens tested through approximately 1,500 individual tests representing roughly 5 years of continuous boiloff run time. Many of these results have provided the baseline data for ASTM C740 and ASTM C1774 and continue to establish the benchmark of comparison for both new and old thermal insulation materials.
- Boiloff technology to measure ultra-low heat flow is at the heart developing and proving out advancements such as future MLI systems that will push the envelope toward the theoretical limits in thermal insulation performance (<0.01 mW/m-K and/or <0.1 W/m² for typical boundary conditions of 300 K / 77 K in vacuum).

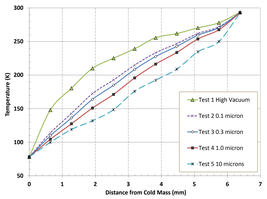
Summary of cylindrical cryostat testing by number of material specimens and tests.

Apparatus	Number of specimens	Number of tests	Hours of run time[a]
Cryostat-100	132	~1,188	~35,640
Cryostat-200	42	~378	~7,560
Total	174	~1,566	~43,200

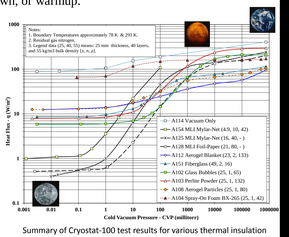
[a]Time does not include that required for evacuation and heating, purging, cooldown, or warmup.



Test result for A138 MLI (60 layers: Mylar/polyester net) at HV: boiloff flow rates over 10 days. Periodic oscillation of test chamber flow rate, induced by atmospheric tides, is indicated by the regular 12-hour peaks.



Temperature profile for A145 MLI (10 layers: Mylar and polyester fabric) for various CVPs. Boundary temperatures: 293 K/78 K; residual gas: nitrogen.

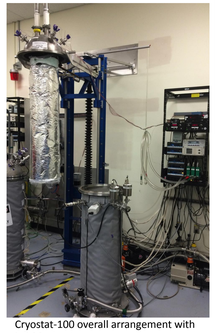


Summary of Cryostat-100 test results for various thermal insulation systems and materials: variation of heat flux with CVP. Boundary temperatures: 293 K/78 K; residual gas: nitrogen.

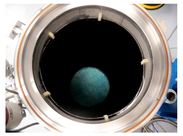
Cryostat-100 Design & Setup

- Cold mass assembly, including upper and lower guard chambers and test vessel, is suspended from vacuum canister lid.
- Unique thermal break design precludes direct solid conduction heat transfer (other than vessel outer wall) between liquid volumes.
- Each of the three chambers is filled and vented through a single feedthrough for minimum heat leak and simplified operation.
- Fluid & instrumentation feedthroughs are mounted and suspended from domed lid for easy removal.
- Lift mechanism allows manipulation of cold mass assembly and test specimen.
- External and internal heating systems for bakeout and fine control of warm boundary temperature.
- Custom design funnel filling tubes (5/16" OD) interface with the three LN_2 feedthroughs (1/2" OD) providing means for cooldown and filling.
- Gaseous nitrogen supply system provides purging and residual gas pressure control.

Model views of Cryostat-100: overall isometric with Vacuum Can (left) and Cold Mass assembly (right)



Cryostat-100 overall arrangement with Lift Mechanism



View inside Vacuum Can showing internal heater assembly

Uncertainty Analysis

- Total uncertainty in k_e is calculated to be 3.4% for the Cryostat-100:
  - ✓ Uncertainty in heat flux q is 3.2% (temperatures are not part of the heat flux calculation).
  - ✓ Physical measurement of test specimen is "robust" because only the outer diameter, not thickness, is part of the calculation.
- Overall error of k_e estimated for the worst-case situation. Heat of vaporization of the cryogen is the largest source of uncertainty and is typically taken to be a 2% uncertainty error for LN_2.
- All heat flow is assumed to go into vaporizing the liquid (none of it sensibly heating the vapor or liquid). This vapor heating effect can be neglected for LN_2 calorimeters with small ullage spaces (less than 20% of the total volume).
- Error due to vapor heating in nitrogen is estimated to be less than 0.1%.
- Overall repeatability for most test series is demonstrated to be within 2%.

$$Q = V_{STP}\rho_{STP}h_{fg}\left(\frac{\rho_f}{\rho_{fg}}\right)$$

$$k_e = \frac{Qx}{A_e \Delta T} = \frac{Q\ln\left(\frac{d_o}{d_i}\right)}{2\pi L_e \Delta T}$$

$$q = \frac{Q}{A_e}$$

Symbols and sources of error for the cylindrical calorimeter, Cryostat-100.

Symbol	Description	Unit	% Error
V	Volumetric flow rate (boiloff) at STP	m³/s	0.500
ρ	Density of GN_2 (boiloff) [0.0012502 g/cm³]	kg/m³	n/a
h_{fg}	Heat of vaporization	J/g	2.37
d_o & d_i	Outer and inner diameters of insulation specimen	m	1.53 & 1.23
x	Thickness of insulation specimen	m	n/a
L_e	Length, effective heat transfer	m	0.730
A_e	Area, effective heat transfer area	m²	n/a
ΔT	Temperature difference *(WBT – CBT)*	K	0.894

Measurement of the boiloff flow rate is made using a mass flow meter that automatically compensates for gas densities in the range of 273 K to 323 K. The mass flow meter output is in terms of a volumetric flow rate at STP (0 °C and 760 torr).

Conclusion

- Cylindrical cryostats and methods for testing thermal insulation systems have been developed over the last 20 years in support of a wide range of aerospace, industry, and research projects.
- These 3 different boiloff instruments (3 patents and 2 patents-pending) are applicable to a wide range of different materials and conditions.
- Measurements are generally obtained for large ΔT and over the full CVP range.
- Results are reported in effective thermal conductivity (k_e) and mean heat flux (q).
- The Cryostat-100 instrument is an absolute calorimeter that has provided baseline data for dozens of materials and a foundation for current and future standards for thermal insulation systems.

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