Flat Plate Boiloff Calorimeters for Testing of Thermal Insulation Systems

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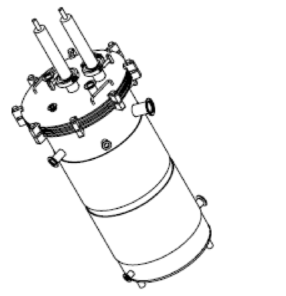
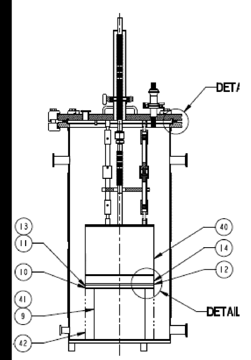
Introduction

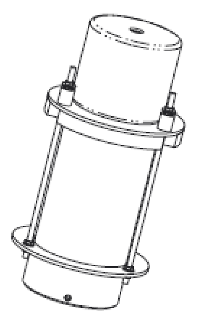
- Four types of cryostat instruments for the testing of thermal insulation systems in a flat plate configuration have been developed and standardized for laboratory operation.
- Measurement principle is boiloff calorimetry for the determining effective thermal conductivity (k_e) and heat flux (q) of a test specimen under a wide range of real-world conditions.
- Cryostat-500 is thermally guarded (by separate cryogen chamber) to provide absolute thermal performance data when properly calibrated with a known reference material.
- Cryostat-600 (larger size) includes a structural element option (for example, MLI + struts).
- Cryostat-400 is a comparative type instrument without a separate cryogen guard chamber.
- The Macroflash Cup Cryostat is bench-top size comparative instrument for thermal conductivity testing of materials from aerogel insulation to carbon composites.

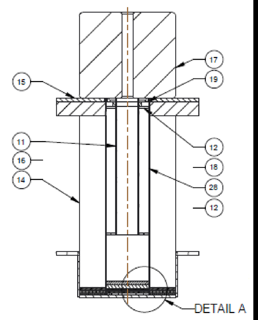




Insulation test cryostat instruments: flat-plate configuration.

Instrument	Type	Test Specimen Size	ASTM Test Standard	Environment	Heat Flux (W/m^2)
Cryostat-500 (3 units)	Absolute	203 mm diameter, up to 40 mm thick	C1774 Annex A3	Full range vacuum 77 K–353 K	0.4–400
Cryostat-600 (1 unit)	Absolute w/structural element option	305 mm diameter, up to any thickness	C1774 Annex A3	Full range vacuum 77 K–353 K	0.4–400
Cryostat-400 (2 units)	Comparative	203 mm diameter, up to 40 mm thick	C1774 Annex A4	Full range vacuum 77 K–353 K	4–400
Macroflash Cup Cryostat (3 units)	Comparative	76 mm diameter, up to 7 mm thick	C1774 Annex A4	No vacuum 77 K–353 K	80–1000





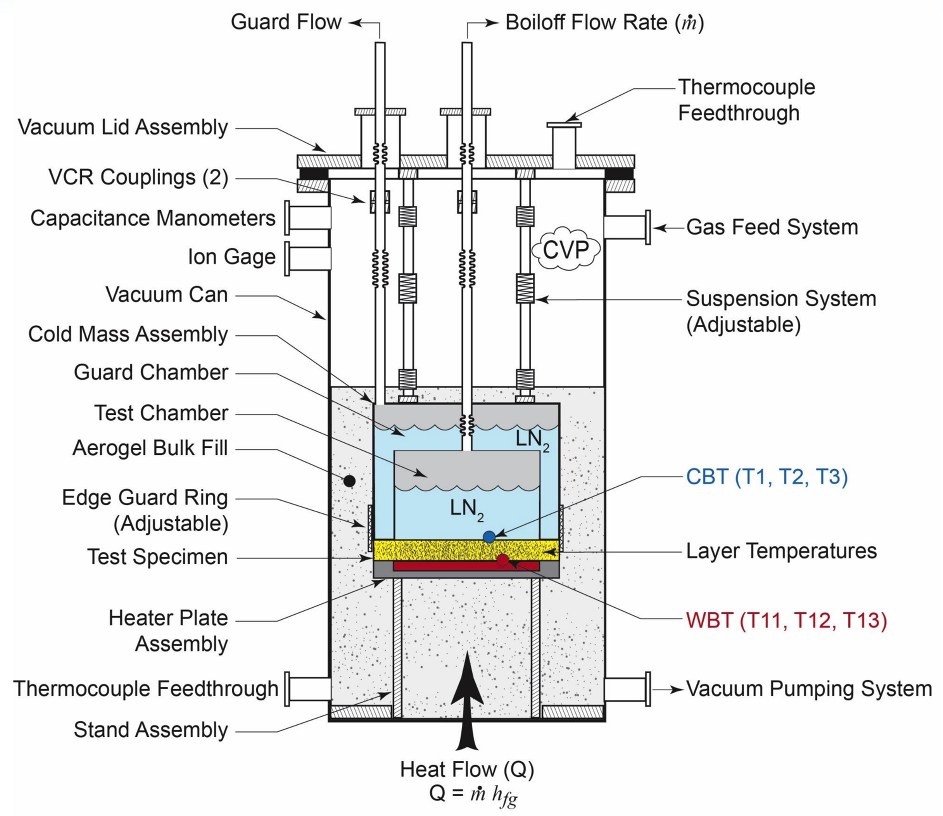
Cylindrical is best in limiting lateral heat transfer but the flat plate design gives a number of advantages:
- ✓ Size and availability of test specimen (only a small piece can be obtained),
- ✓ Compression loading capability,
- ✓ Specialized ambient pressure testing with different purge gases,
- ✓ Relevance to end-use application, and
- ✓ Easier in adjustment for different boundary temperatures by placement of an intermediary material.

Testing Methodology

- Principle of heat flow measurement: boiloff calorimetry (ASTM C1774, Annex A3).
- Test specimen: single material or specialized combination of different materials.
- Materials: monolithic, composites, blanket, layered blanket, MLI, or bulk-fill type.
- Thickness: critical measurement for k_e calculation. Fit-up for good thermal contact is also crucial for rigid materials.
- Adjustable edge guard ring assembly provides calibration capability.
- Steady-state condition: boiloff flow rates from both chambers stabilized + temperature profile through thickness stabilized + liquid level in guard >50% full.
- Thermal measurement capability is more than 3 orders of magnitude over the full CVP range.

✓ Multiple data points can be obtained from a single test by using intermediately placed temperature sensors through the thickness of the test specimen. Any two temperatures between 78 K and about 353 K can be set up.
✓ The heat transfer principle remains the same: heat flows as a function of the temperature difference, not as a function of temperature.

Funnel Filling Tubes in operation during cooldown



Example Test Results: Cryostat-500

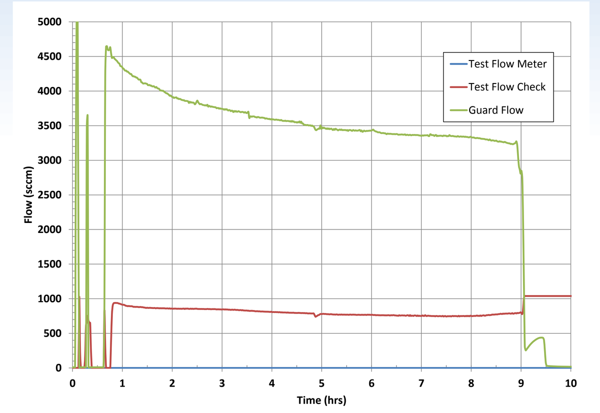
- For all flat plate calorimeters: over 500 materials specimens tested through approximately 2,100 individual tests representing over 6 years of continuous boiloff run time.
- Materials include, for example, composite panels, foams, aerogels, and MLI systems.
- The large database of thermal performance data can provide a foundation for the development of future standards in insulation materials specifications and installation practices.

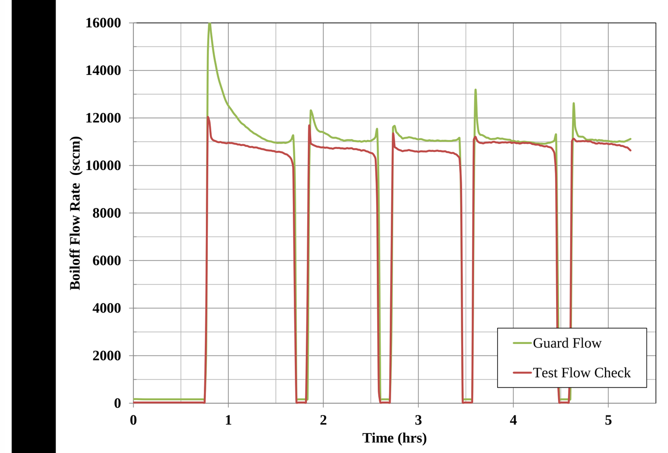
Summary of flat-plate cryostat testing by number of material specimens and tests.

Apparatus	Number of specimens	Number of tests	Hours of run time[a]
Cryostat-500	81	~729	~21,870
Cryostat-600	44	~88	~7,040
Cryostat-400	142	~1,056	~25,344
Macroflash	253	~263	~1,052
Total	520	~2,136	~55,306

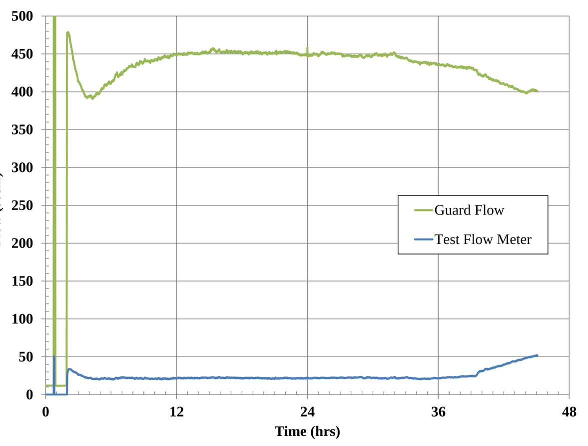
[a]Time does not include that required for evacuation and heating, purging, cooldown, or warmup.

A set of cellular glass specimens (203-mm diameter by 25-mm thick, 20 each) is available for industry round robin testing and future precision and bias studies (recent program of 45 tests of 14 cellular glass disks using two Cryostat-400 units showed variability of ~ 3.0%).

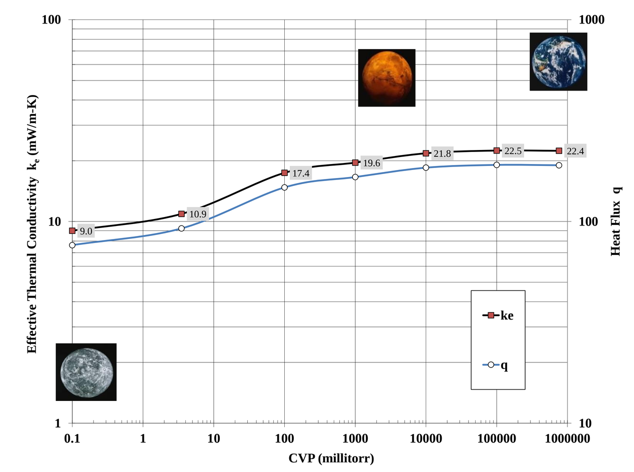




Composite panel test series G139 at 760 torr CVP: boiloff flow rates. Test specimen: six-stack of carbon fiber panels; 13 mm thick. Boundary temperatures 293 K/78 K; residual gas nitrogen.



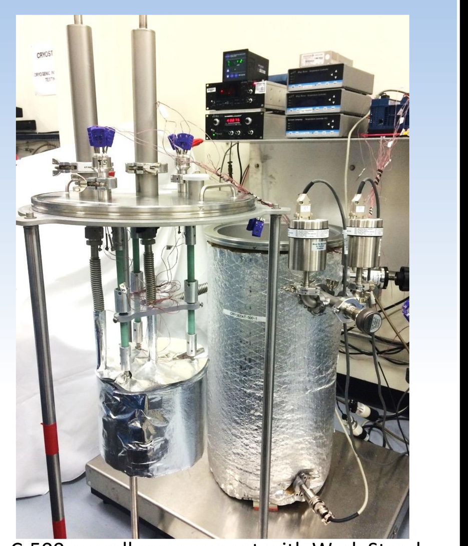
MLI test series G143 at 1×10^{-5} torr CVP: boiloff flow rates. Test specimen: 11 layers Mylar and polyester net, 3 mm thick. Boundary temperatures 293 K/78 K; residual gas nitrogen.



Foam material test series G157: Boiloff flow rate for 760 torr CVP test (top); variation of k_e and q with CVP (bottom). Test specimen: SOFI BX-265; 25 mm thick. Boundary temps 293 K/78 K; residual gas GN2.

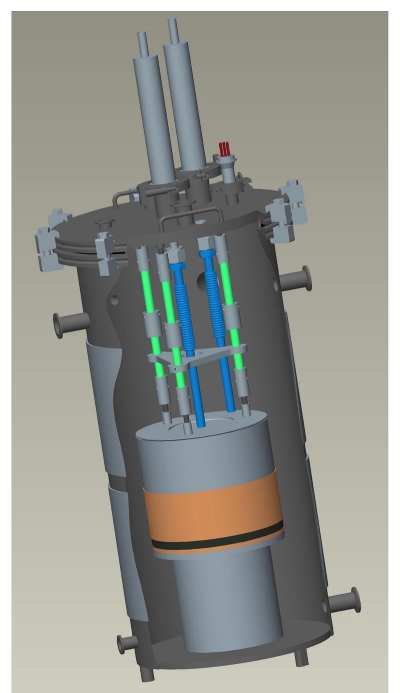
Cryostat-500 Design & Setup

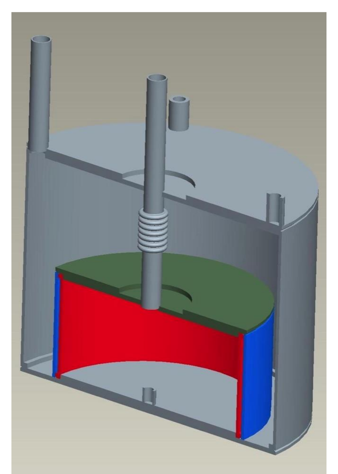
- Cold mass assembly, comprised of the heat measurement vessel and thermal guard vessel, is suspended from the vacuum chamber lid.
- Unique thermal break design precludes direct solid conduction heat transfer between the two liquid volumes.
- Low thermal conductivity suspension system includes adjustable compliance rod assemblies for a given test specimen.
- Thicknesses in the range of approximately 3 mm to 40 mm can be tested.
- The suspension system can be readily configured for rigid or fully compressible materials with compression loading from zero to approximately 100 kPa (15 psi).
- External heating system for bakeout; internal heater plate system for control of warm boundary temp.
- Two custom designed funnel filling tubes (5/16” OD) interface with two LN_2 feedthroughs (1/2” OD) for cooldown, filling, and replenishment.
- Full range vacuum pressure control: 10^{-6} to 760 torr.



C-500 overall arrangement with Work Stand

Two Cryostat-500 units in the laboratory setting





Model views of Cryostat-500: Overall isometric with Vacuum Can (l) and Cold Mass Assembly (r)

Uncertainty Analysis

- Total uncertainty in k_e is calculated to be 4.8 % for the Cryostat-500.
  - ✓ Uncertainty in heat flux q is 3.2 % (temperatures are not part of heat flux calculation).
  - ✓ Thickness measurement is by far the largest source of uncertainty and must be handled with care, particularly for test specimens under 10-mm.
  - ✓ For flat-plate geometries, the effective heat transfer area (A_e) is the area defined by the median line of the test chamber side wall.
- Overall error of k_e is estimated for the worst-case situation. With the test specimen positioned at the bottom of the chamber, ullage vapor heating is not an issue.
- Test specimen fit-up is crucial for good thermal contact to be maintained through the usual thermal cycles and shrinkage associated with testing.
- Overall repeatability for most test series is demonstrated to be within 2%.

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

$$k_e = \frac{Qx}{A_e \Delta T} = \frac{4Qx}{\pi d_e^2 \Delta T}$$

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

Symbols and sources of error for the flat plate calorimeter, Cryostat-500.

Symbol	Description	Unit	% Error
V	Volumetric flow rate (boiloff) at STP	m^3/s	0.500
ρ	Density of GN_2 (boiloff) [0.0012502 g/cm^3]	kg/m^3	n/a
h_{fg}	Heat of vaporization	J/g	2.00
x	Thickness of insulation specimen	m	3.94
d_e	Diameter, effective heat transfer	m	1.60
A_e	Area, effective heat transfer area	m^2	n/a
ΔT	Temperature difference (WBT – CBT)	K	0.981

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

- Based on boiloff calorimetry, new flat plate cryostats and methods for testing thermal insulation systems are working for a wide range of different materials and conditions.
- Four different and complementary instruments developed over the last 15 years.
- 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 new cryostat instruments provide an effective and reliable way to characterize the thermal performance of materials (insulation, polymers, composites, etc.) under sub-ambient conditions.
- Proven through thousands of tests of hundreds of different material specimens, these flat plate cryostats have supported a wide range of aerospace, industry, and research projects.

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