BELOW-AMBIENT AND CRYOGENIC THERMAL TESTING

JAMES E. FESMIRE

NASA KENNEDY SPACE CENTER – CRYOGENICS TEST LABORATORY
OUTLINE

BELOW-AMBIENT / MOTIVATION FOR CRYOGENIC TESTING
STANDARDS FOR BOILOFF CALORIMETERY
THERMAL PERFORMANCE DATA
COLD PIPE TESTER
FUTURE PLANS
ENERGY MEASUREMENT

• ENERGY GOING = POWER = HEAT FLOW RATE
• JOULES PER SECOND = WATTS
• ENERGY (JOULES) IS AN ABSTRACTION, SO WE HAVE TO MEASURE SOMETHING ELSE
• ELECTRICAL RESISTANCE
• PHASE CHANGE OF A SUBSTANCE
BOILOFF CALORIMETRY

• CRYOGENIC BOILOFF CALORIMETRY
  • STATIC (FIXED VOLUME) NOT DYNAMIC (FLOW THROUGH)

• LIQUID NITROGEN (LN$_2$) AS THE “ENERGY METER”
  • SATURATED AT AMBIENT PRESSURE FOR STABILITY

• STEADY-STATE THERMAL EQUILIBRIUM
  • HEAT FLOW RATE IS THE SAME THROUGH ALL LAYERS

• TEMPERATURE RANGE FROM ABOUT 50 °C DOWN TO -196 °C
  • LARGE TEMPERATURE DIFFERENCE ($\Delta T$)
  • DIFFERENT MEAN TEMPERATURES ($T_M$)

• MULTIPLE TEST POINTS FROM A SINGLE TEST
CONFIGURATIONS

- FLAT PLATE OR CYLINDRICAL
- HORIZONTAL CYLINDRICAL FOR PIPELINE INSULATION
- COMPARATIVE OR ABSOLUTE

ASTM C1774 – STANDARD GUIDE TO THERMAL PERFORMANCE TESTING OF CRYOGENIC INSULATION SYSTEMS
- THREE DIFFERENT APPROACHES: BOILOFF OR ELECTRICAL POWER
- SIX DIFFERENT APPARATUSES: FOUR BOILOFF
- X1.2 The approaches, techniques, and methodologies given in this guide can be adapted for use in the cryogenic thermal performance testing of cryogenic pipelines: cryogen boiloff (static) or flow-through (dynamic).

ASTM C740 – STANDARD GUIDE FOR EVACUATED REFLECTIVE CRYOGENIC INSULATION
- THERMAL PERFORMANCE DATA FOR MULTILAYER INSULATION (MLI) AND OTHER CRYOGENIC INSULATION SYSTEMS, FOAMS, AEROGELS, AND BULK-FILL MATERIALS
DEFINITIONS

• FROM ASTM C1774 AND ASTM C740 (NEW IN 2014)

• Effective thermal conductivity \( (k_e) \) — the thermal conductivity through the total thickness of the insulation test specimen between the reported boundary temperatures and in a specified environment (mW/m-K). The insulation test specimen may be one material, homogeneous non-homogeneous, or a combination of materials.

• System thermal conductivity \( (k_s) \) — the thermal conductivity through the total thickness of the insulation test specimen and all ancillary elements such as packaging, supports, getter packages, enclosures, etc. (mW/m-K).

• Heat flow rate \( (Q) \) — quantity of heat energy transferred to a system in a unit of time (W).

• Heat flux \( (q) \) — heat flow rate, under steady-state conditions, through a unit area, in a direction perpendicular to the plane of the thermal insulation system (W/m\(^2\)).
By interposing different insulation layers on the cold boundary, the cryogenic boiloff method is suitable for a wide range of below-ambient temperature applications.
STEADY-STATE BOILOFF

• ESTABLISH A STEADY WARM BOUNDARY TEMPERATURE (WBT) ON AN OUTER SURFACE.

• ESTABLISH A STEADY COLD BOUNDARY TEMPERATURE (CBT) ON AN INNER SURFACE.

• AFTER THERMALIZATION, THE HEAT FLOW RATE (Q) THROUGH THE INSULATION IS CONSTANT AND THE SAME THROUGH ALL INTERIOR LAYERS OF THE INSULATION SYSTEM.

• BY INTERPOSING A PRIMARY INSULATION LAYER ON THE INNER COLD BOUNDARY, THE CRYOGENIC BOILOFF METHOD IS USED FOR A WIDE RANGE OF BELOW-AMBIENT TEMPERATURE APPLICATIONS.
Insulation test cryostat instruments: flat-plate configuration.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Type</th>
<th>Test Specimen Size</th>
<th>ASTM Test Standard</th>
<th>Environment</th>
<th>Heat Flux (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat-500 (3 units)</td>
<td>Absolute</td>
<td>203 mm diameter, up to 40 mm thick</td>
<td>C1774</td>
<td>Full range vacuum 77 K–353 K</td>
<td>0.4–400</td>
</tr>
<tr>
<td>Cryostat-600 (1 unit)</td>
<td>Absolute w/structural element option</td>
<td>305 mm diameter, up to any thickness</td>
<td>C1774</td>
<td>Full range vacuum 77 K–353 K</td>
<td>0.4–400</td>
</tr>
<tr>
<td>Cryostat-400 (2 units)</td>
<td>Comparative</td>
<td>203 mm diameter, up to 40 mm thick</td>
<td>C1774</td>
<td>Full range vacuum 77 K–353 K</td>
<td>4–400</td>
</tr>
<tr>
<td>Macroflash Cup Cryostat</td>
<td>Comparative</td>
<td>76 mm diameter, up to 7 mm thick</td>
<td>C1774</td>
<td>No vacuum 77 K–353 K</td>
<td>80–1000</td>
</tr>
</tbody>
</table>
FLAT PLATE BOILOFF TESTING – CRYOSTAT-500

The Cryostat-500 insulation test instrument provides:

- Testing 204-mm diameter, 25-mm thick specimens under representative-use conditions.
- Direct energy rate measurement by LN$_2$ boiloff calorimetry.
- Reliable testing of non-homogenous, non-isotropic thermal insulation systems.

- ASTM C1774, Annex A3
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.

Temperature profiles measured through the thickness of a six-layer stack of aerogel blankets and the resulting effective thermal conductivity, $k_e$, and local thermal conductivity distribution, $\lambda (T)$.

Boiloff flow rate for foam test specimen.
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Type</th>
<th>Test Specimen Size</th>
<th>ASTM Test Standard</th>
<th>Environment</th>
<th>Heat Flux (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat-100</td>
<td>Absolute</td>
<td>1 m long, 167 mm diameter, up to 50 mm thick</td>
<td>C1774 Annex A1</td>
<td>Full range vacuum 77 K–353 K</td>
<td>0.2–200</td>
</tr>
<tr>
<td></td>
<td>(1 unit)</td>
<td>0.5 m long,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Comparative</td>
<td>132 mm diameter, up to 50 mm thick</td>
<td>C1774 Annex A2</td>
<td>Full range vacuum 77 K–353 K</td>
<td>1–200</td>
</tr>
<tr>
<td>Cryostat-200</td>
<td>Absolute</td>
<td>12.2 m long, up to 200 mm OD</td>
<td>C335</td>
<td>No vacuum or vacuum-jacket 77 K–353 K</td>
<td>4–400</td>
</tr>
<tr>
<td></td>
<td>(2 units)</td>
<td>25 - 88 mm diameter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Comparative</td>
<td>1.8 m long,</td>
<td>C335</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryostat-P100</td>
<td>Absolute</td>
<td>33 mm diameter, up to 110 mm OD</td>
<td>C335</td>
<td>No vacuum 77 K–353 K</td>
<td>100–500</td>
</tr>
<tr>
<td></td>
<td>(1 unit)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryostat-P200</td>
<td>Comparative</td>
<td>1.8 m long,</td>
<td>C335</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(future)</td>
<td>33 mm diameter, up to 110 mm OD</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Cryostat-100 insulation test instrument provides:

- Testing 1-meter long, 218-mm diameter specimens under representative-use conditions.
- Direct energy rate measurement by LN$_2$ boiloff calorimetry.
- Reliable testing of non-homogenous, non-isotropic thermal insulation systems.
- ASTM C1774, Annex A1
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.

Baseline data for standards and benchmarks for comparison of thermal insulation materials.

Summary of test results for various thermal insulation systems and materials: variation of $k_e$ with vacuum pressure.

Notes:
1. Boundary Temperatures approximately 78 K & 293 K.
2. Residual gas nitrogen.
3. Legend data (25, 40, 55) means: 25 mm thickness, 40 layers, and 55 kg/m$^3$ bulk density [$x$, $n$, $\rho$].
BELOW-AMBIENT INSULATED PIPE TESTING

• REVISION OF ASTM C335 TO INCLUDE BELOW-AMBIENT METHOD BASED ON CRYOGENIC BOILOFF IS UNDER REVIEW BY C16 COMMITTEE OF ASTM INTERNATIONAL

• APPARATUS AND METHOD FOR THERMAL PERFORMANCE TESTING OF CRYOGENIC PIPING SYSTEMS HAS BEEN ESTABLISHED - CRYOSTAT-P100
  • ACCURATE HEAT LEAK DATA FOR FULL-SCALE PIPELINES UNDER “REAL WORLD” CONDITIONS
  • BASIS FOR STANDARDIZED HEAT TRANSFER TEST FOR LOW-TEMPERATURE PIPING SYSTEMS

• COMPARATIVE TYPE, BENCH-TOP COLD PIPE TESTER, CRYOSTAT-P200, IS UNDER DEVELOPMENT

• ENERGY-EFFICIENT TRANSFER LINES AND PIPING SYSTEMS FOR SPACE LAUNCH FACILITIES, EQUIPMENT, AND INDUSTRIAL INFRASTRUCTURE ARE THE TARGETS

• CURRENT WORK INCLUDES TESTING OF BELOW-AMBIENT THERMAL INSULATION MATERIALS/SYSTEMS

• EXAMPLE TEST DATA FOR DIFFERENT INSULATED PIPELINES (BOTH 18-M AND 12-M LENGTHS)
COLD PIPE TESTER - CRYOSTAT-P100
CURRENT 12-METER-LONG APPARATUS

• LN2 BOIL-OFF TEST APPARATUS, GUARDED, ABSOLUTE HEAT LEAK RATE
• 3 DEGREE UPWARD SLOPE TO PROVIDE HIGH POINT TAP FOR BOILOFF FLOW RATE
• EXTERNAL HEATER WRAP FOR WARM BOUNDARY TEMPERATURE CONTROL
• UPSTREAM AND DOWNSTREAM COLD BOXES FILLED WITH LN2
• TEST PIPES SUPPLIED WITH AMBIENT PRESSURE SATURATED LN2 VIA HEAT EXCHANGER COIL ROUTED THROUGH UPSTREAM COLD BOX

• TEMPERATURE MEASUREMENTS:
  • LENGTH-WISE: TOP, SIDE, AND BOTTOM
  • THROUGH THICKNESS OF INSULATION
  • TERMINATIONS

• TWO TEST ARTICLES (TYPICAL):
  • 12-M LONG (40-FEET)
  • UP TO 3-INCH DIAMETER PIPE SIZE (NPS)
  • TESTED IN PARALLEL

J. Fesmire
2/2/2016
COLD PIPE TESTER - CRYOSTAT-P100

Upstream Cold Box

- LN2 Supply (<20 psi)
- Insulated Test Pipe (3° slope)
- Thermal Guard & Pipe Interface
- Heat Exchanger Coil

Downstream Cold Box

- High Point Tap for Flow Meter
- LN2 Trickle Flow
- Wheels for Axial Compliance

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2/2/2016
COLD PIPE TESTER - CRYOSTAT-P100

Downstream Cold Box assembly showing insulated test pipe connection
COLD PIPE TESTER - CRYOSTAT-P100

Notes:

- Adaptable to any end connections.
- Terminations are thermally guarded.
- Built-in compliance for thermal contraction.
- Center line is used for downstream cold box supply.
COLD PIPE TESTER - CRYOSTAT-P100

PHASES:
✓ COOLDOWN
✓ FILL
✓ COLD SOAK
✓ TEST RUNS
✓ REFILL
✓ DRAIN

MULTIPLE TEST RUNS ARE PERFORMED AFTER COLD SOAK PHASE
### SUMMARY OF TEST RESULTS: 3” NOMINAL PIPE WITH 1.5” THICK INSULATION CLAM-SHELLS

<table>
<thead>
<tr>
<th></th>
<th>East Pipeline</th>
<th>West Pipeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total heat leakage rate</td>
<td>30.0 W</td>
<td>32.0 W</td>
</tr>
<tr>
<td>Heat leak per unit length</td>
<td>2.45 W/m</td>
<td>2.62 W/m</td>
</tr>
<tr>
<td>Overall k-value ($k_{oaf}$)</td>
<td>0.95 mW/m-K</td>
<td>1.1 mW/m-K</td>
</tr>
<tr>
<td>Boil-off flow rate</td>
<td>7.25 slpm</td>
<td>7.73 slpm</td>
</tr>
</tbody>
</table>

**Notes:**

- Boundary temperatures are approximately 293 K and 78 K.
- Cold soak phase of approximately 24 hours.
- Cold vacuum pressures verified.
- Wind and solar influences are negligible (vacuum jacketed insulation system).
COLD PIPE TESTER - CRYOSTAT-P100
ORIGINAL 18-METER-LONG APPARATUS
Example test results for cryogenic-vacuum pipelines: VIP (Pipe 2) and FJP (Pipe 3)
OTHER EXAMPLES OF COLD PIPE TESTING

NOT COMPLICATED

COMPLICATED
UNCERTAINTY ANALYSIS: CRYOSTAT-100

• 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 LN2 IS THE LARGEST SOURCE OF UNCERTAINTY AND IS TAKEN TO BE 2% ERROR.

• ALL HEAT FLOW IS ASSUMED TO GO INTO VAPORIZING THE LIQUID. THE VAPOR HEATING EFFECT CAN BE NEGLECTED FOR LN2 CALORIMETERS WITH SMALL ULLAGE SPACES (ERROR IS LESS THAN 0.1%).

• REPEATABILITY FOR MOST TESTS IS DEMONSTRATED TO BE WITHIN 2%.
**UNCERTAINTY ANALYSIS: CRYOSTAT-100**

$$Q = V_{STP} \, h_{fg} \, \frac{f}{f_{fg}}$$

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

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

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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V$</td>
<td>Volumetric flow rate (boiloff) at STP</td>
<td>m$^3$/s</td>
<td>0.500</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of GN$_2$ (boiloff) [0.0012502 g/cm$^3$]</td>
<td>kg/m$^3$</td>
<td>n/a</td>
</tr>
<tr>
<td>$h_{fg}$</td>
<td>Heat of vaporization</td>
<td>J/g</td>
<td>2.37</td>
</tr>
<tr>
<td>$d_o$ &amp; $d_i$</td>
<td>Outer and inner diameters of insulation specimen</td>
<td>m</td>
<td>1.53 &amp; 1.23</td>
</tr>
<tr>
<td>$x$</td>
<td>Thickness of insulation specimen</td>
<td>m</td>
<td>n/a</td>
</tr>
<tr>
<td>$L_e$</td>
<td>Length, effective heat transfer</td>
<td>m</td>
<td>0.730</td>
</tr>
<tr>
<td>$A_e$</td>
<td>Area, effective heat transfer area</td>
<td>m$^2$</td>
<td>n/a</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature difference (WBT – CBT)</td>
<td>K</td>
<td>0.894</td>
</tr>
</tbody>
</table>

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).
FUTURE PLANS

• CONTINUE WORK WITH INDUSTRY PARTNERS FOR TECHNICAL CONSENSUS STANDARD FOR BELOW-AMBIENT THERMAL PERFORMANCE TESTING OF INSULATED PIPING
  • ABOVE-AMBIENT TEST STANDARD COMPATIBILITY
  • REVISE ASTM C335 OR NEW STANDARD?

• DEVELOP COMPARATIVE, BENCH-TOP CRYOSTAT-P200 FOR 1.5-METER LONG 25-MM DIAMETER (NOMINAL) TEST PIPE

• VERIFY CONSISTENT TECHNIQUES FOR COLD BOUNDARY TEMPERATURES UP TO APPROXIMATELY 0°C

• ROUND ROBIN TESTING OF SELECT INSULATION MATERIAL(S)
CONCLUSION

BELOW-AMBIENT / MOTIVATION FOR CRYOGENIC TESTING
STANDARDS FOR BOILOFF CALORIMETERY
THERMAL PERFORMANCE DATA
COLD PIPELINE TESTER
FUTURE PLANS
REFERENCE PUBLICATIONS


• ASTM C1774 - STANDARD GUIDE FOR THERMAL PERFORMANCE TESTING OF CRYOGENIC INSULATION SYSTEMS. ASTM INTERNATIONAL, WEST CONSHOHOCKEN, PA, USA (2013).

• ASTM C740 - STANDARD GUIDE FOR EVACUATED REFLECTIVE CRYOGENIC INSULATION. ASTM INTERNATIONAL, WEST CONSHOHOCKEN, PA, USA (2013).

• ASTM C335 STANDARD TEST METHOD FOR STEADY-STATE HEAT TRANSFER PROPERTIES OF PIPE INSULATION. ASTM INTERNATIONAL, WEST CONSHOHOCKEN, PA, USA.


• US PATENT 6,715,914 “APPARATUS AND METHOD FOR THERMAL PERFORMANCE TESTING OF PIPELINES AND PIPING SYSTEMS.”

JAMES E. FESMIRE
SR. PRINCIPAL INVESTIGATOR  1.321.867.7557  JAMES.E.FESMIRE@NASA.GOV

CRYOGENICS TEST LABORATORY

EXPLORATION RESEARCH & TECHNOLOGY, UB-R1  NASA KENNEDY SPACE CENTER, FL 32899  USA