BELOW-AMBIENT AND CRYOGENIC THERMAL TESTING

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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 (ΔT)
  - DIFFERENT MEAN TEMPERATURES (T_M)
- MULTIPLE TEST POINTS FROM A SINGLE TEST

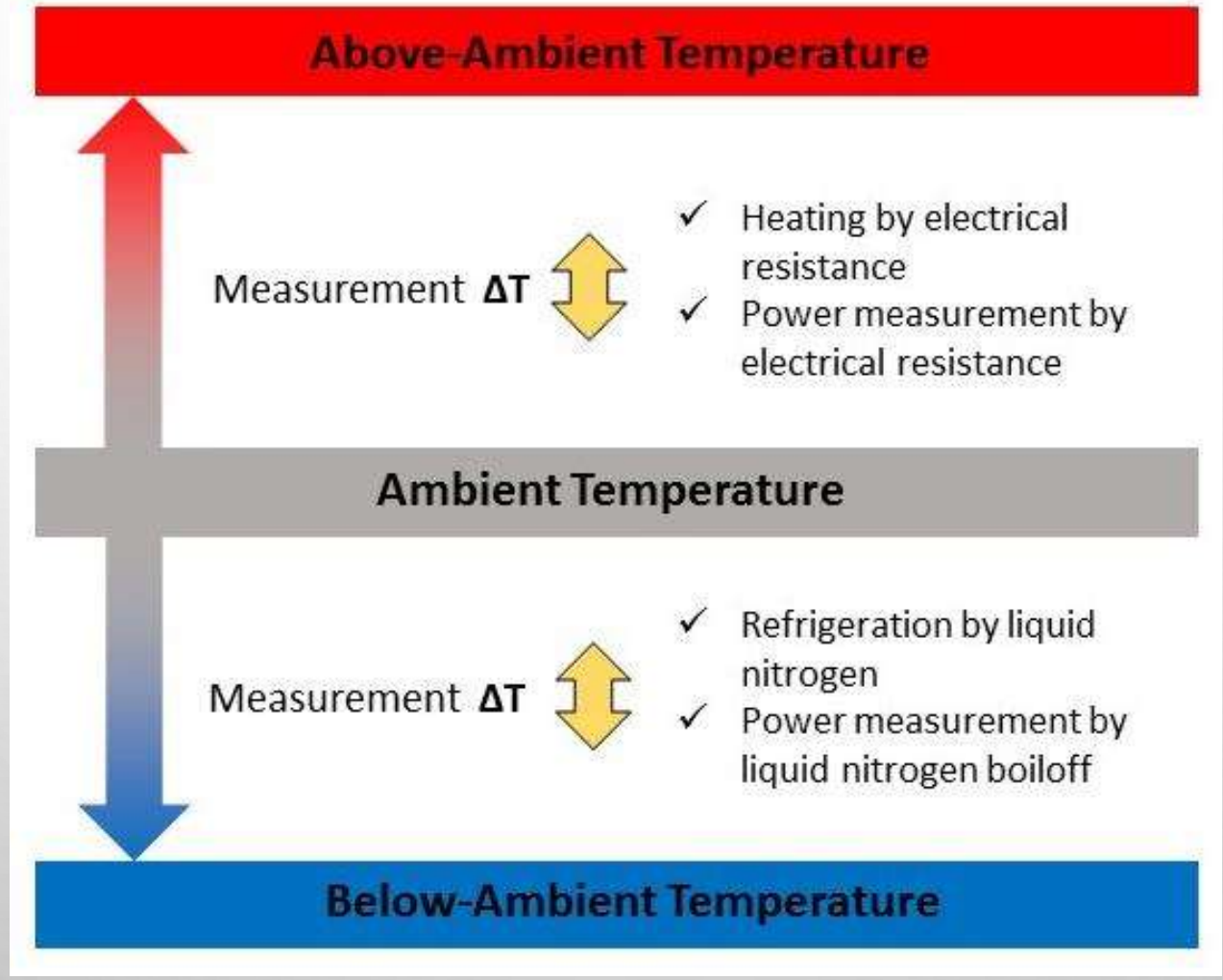
CONFIGURATIONS

- 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).

AMBIENT TEMPERATURE = 20 °C (±)

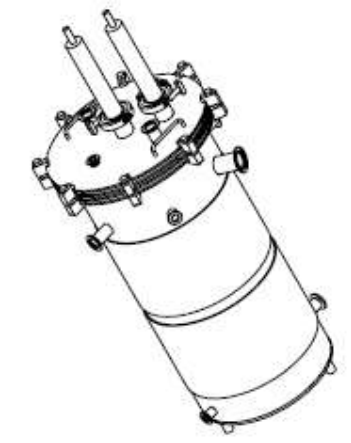


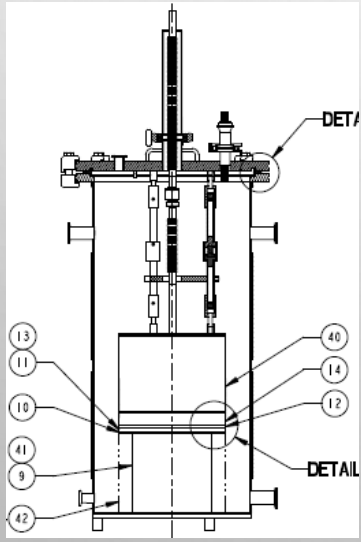
By interposing different insulation layers on the cold boundary, the cryogenic boiloff method is suitable for a wide range of below-ambient temperature applications.

STEADY-STATE BOILOFF

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

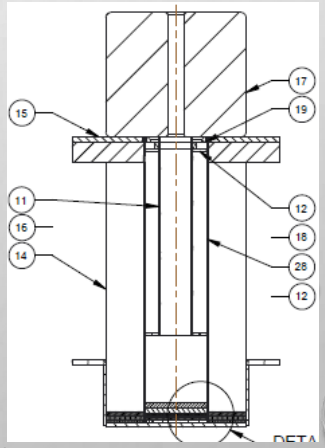
FLAT PLATE BOILOFF TESTING – CONFIGURATIONS





Insulation test cryostat instruments: flat-plate configuration.

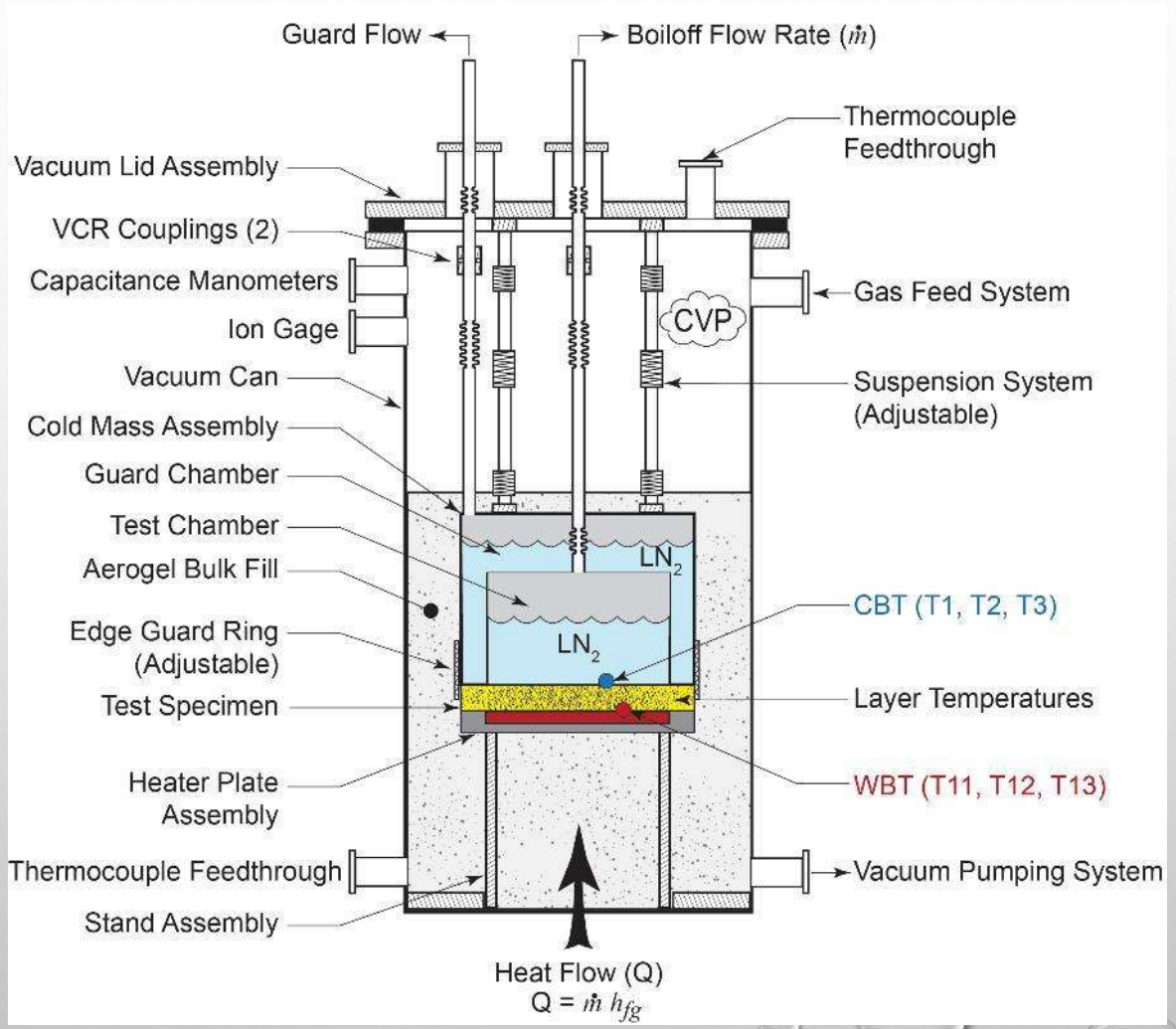
Instrument	Type	Test Specimen Size	ASTM Test Standard	Environment	Heat Flux (W/m^2)
Cryostat-500 (3 units)	Absolute	203 mm diameter, up to 40 mm thick	C1774 Annex A3	Full range vacuum 77 K–353 K	0.4–400
Cryostat-600 (1 unit)	Absolute w/structural element option	305 mm diameter, up to any thickness	C1774 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



FLAT PLATE BOILOFF TESTING – CRYOSTAT-500

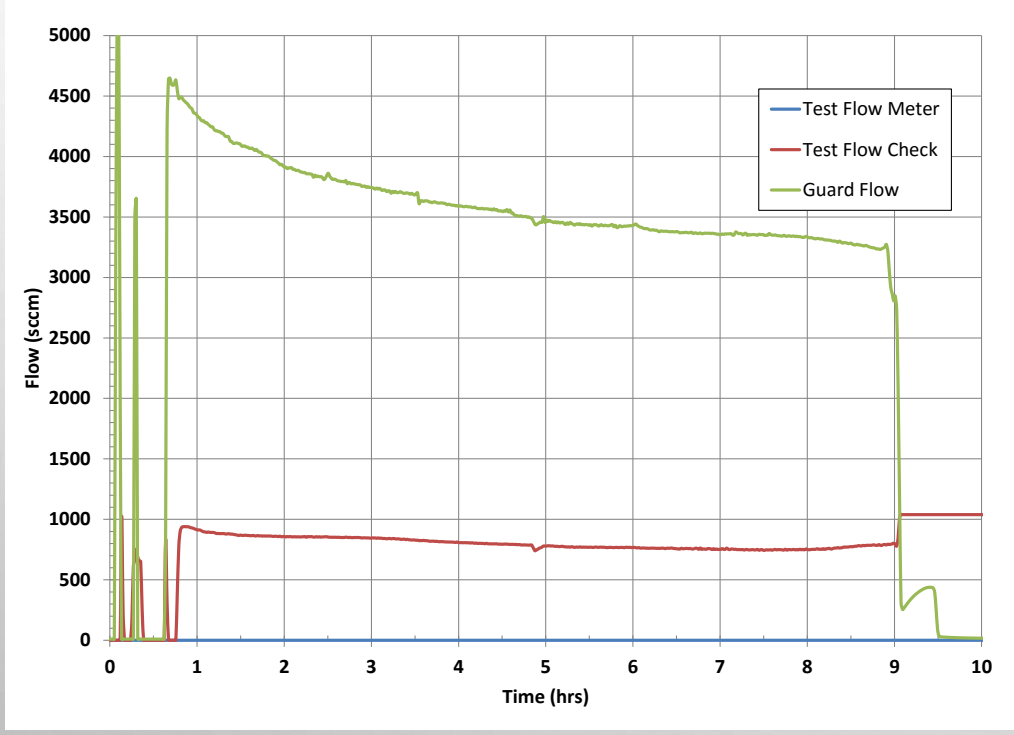
The Cryostat-500 insulation test instrument provides:

- ✓ 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**

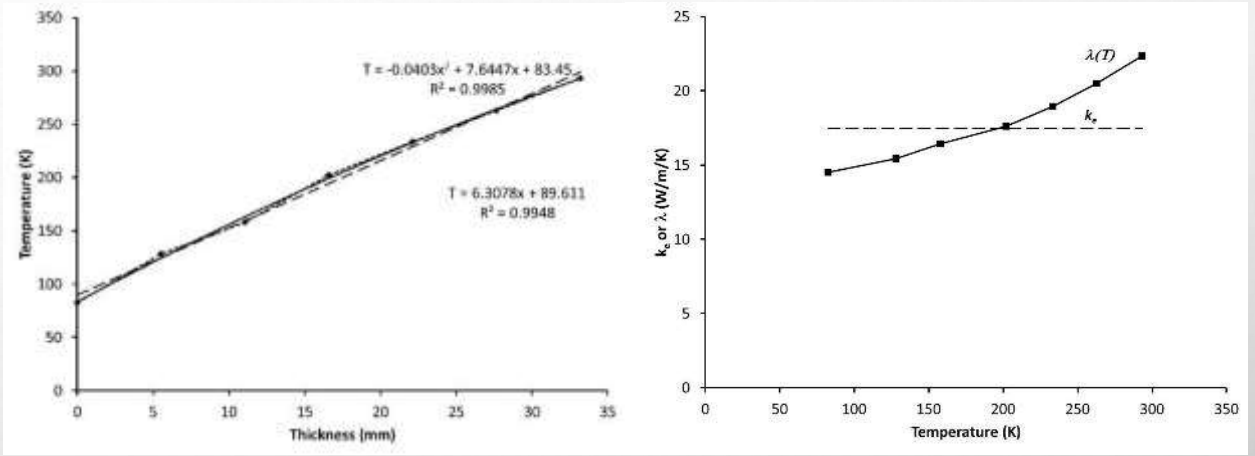


FLAT PLATE BOILOFF TESTING – EXAMPLE DATA

- ✓ 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.

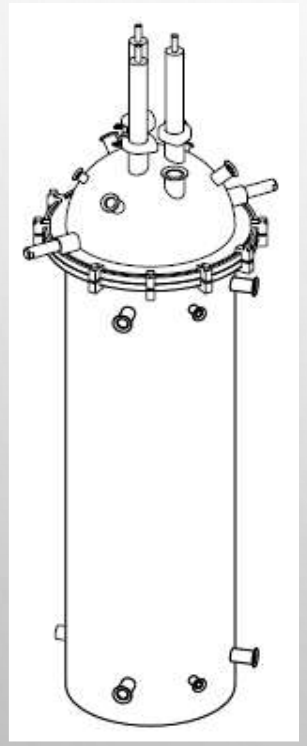


Boiloff flow rate for foam test specimen.



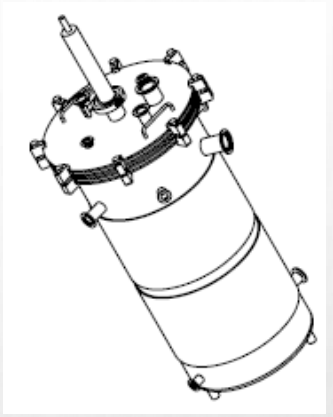
Temperature profiles measured through the thickness of a six-layer stack of aerogel blankets and the resulting effective thermal conductivity, $k_{e,}$ and local thermal conductivity distribution, $\lambda\ (T)$.

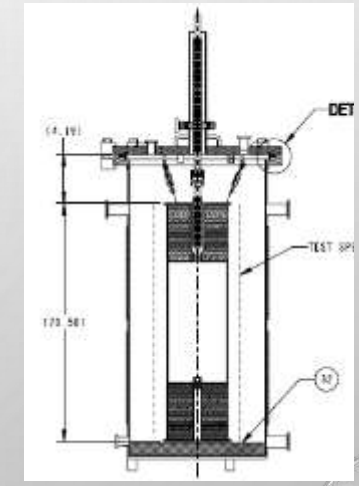
CYLINDRICAL BOILOFF TESTING – CONFIGURATIONS

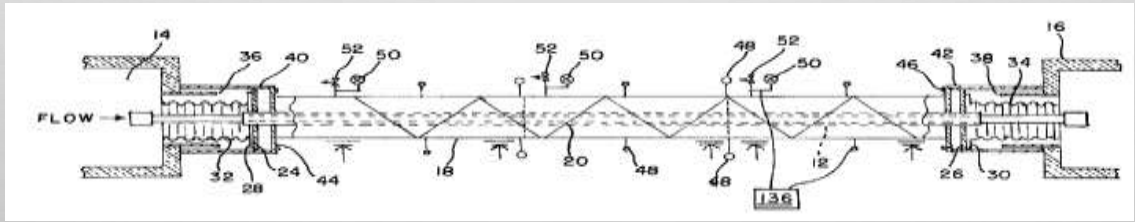


Insulation test cryostat instruments: cylindrical configurations.

Instrument	Type	Test Specimen Size	ASTM Test Standard	Environment	Heat Flux (W/m^2)
Cryostat-100 (1 unit)	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
Cryostat-P100 (1 unit)	Absolute	12.2 m long, 25 - 88 mm diameter up to 200 mm OD	C335	No vacuum or vacuum-jacket 77 K–353 K	4–400
Cryostat-P200 (future)	Comparative	1.8 m long, 33 mm diameter, up to 110 mm OD	C335	No vacuum 77 K–353 K	100–500



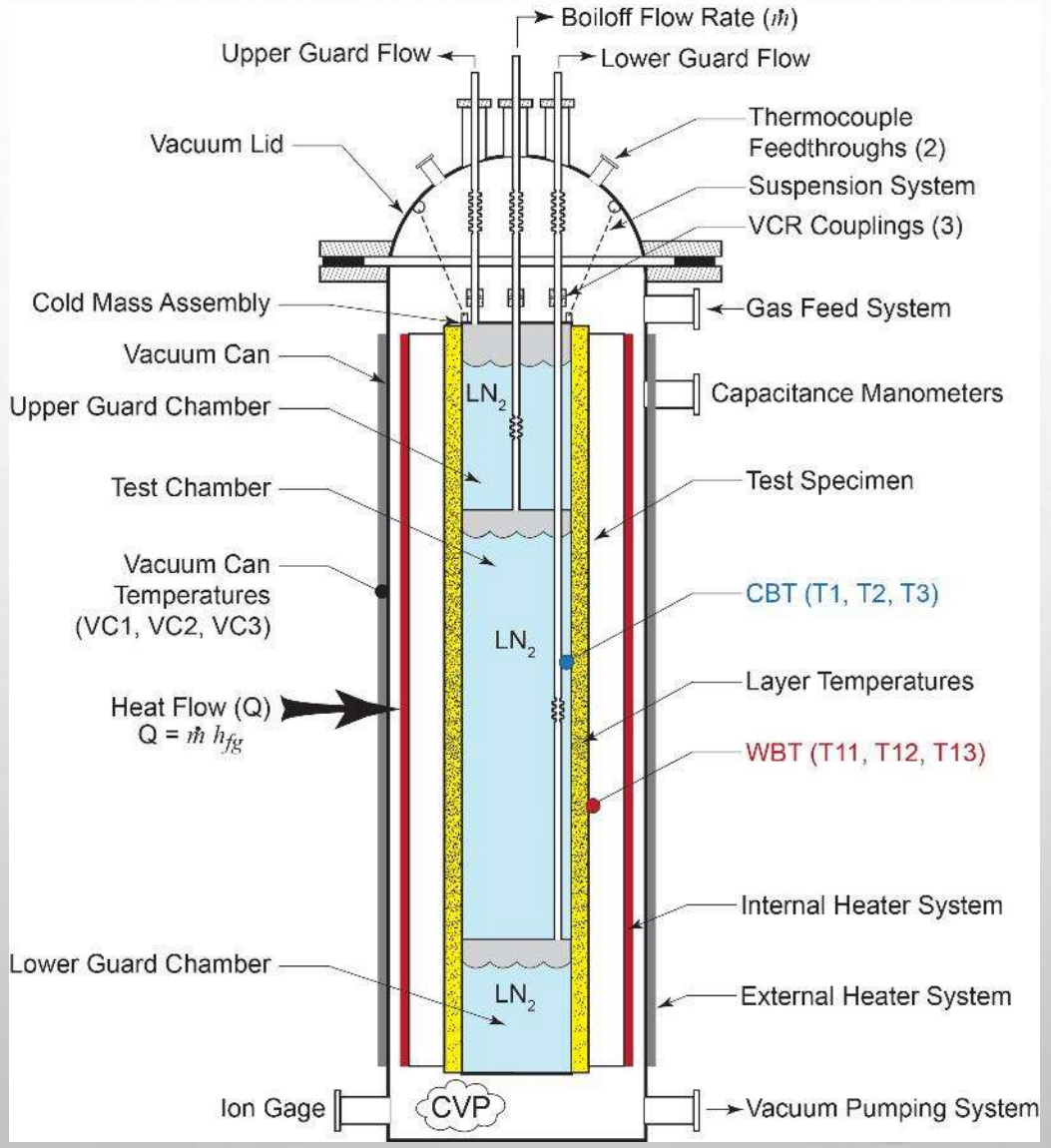


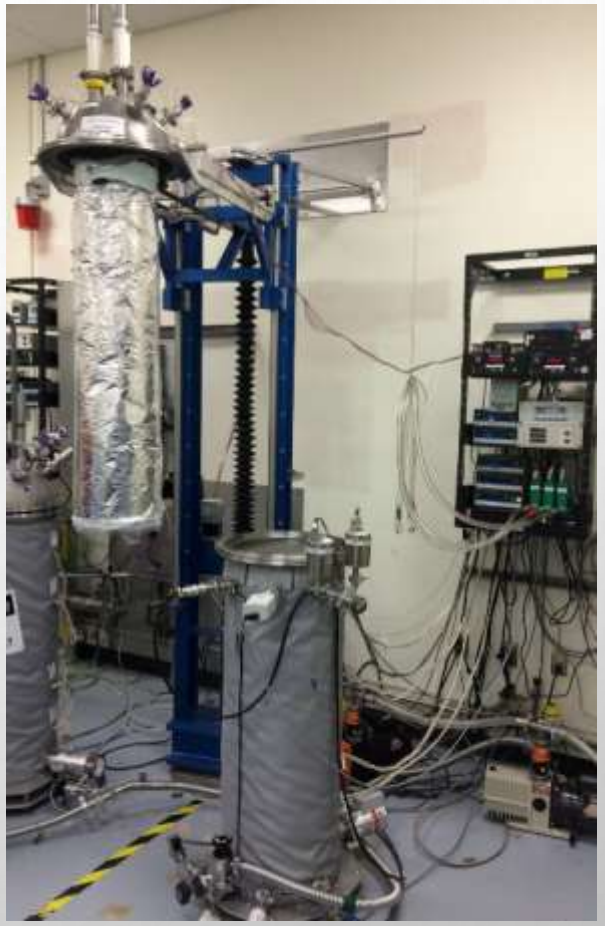


CYLINDRICAL BOILOFF TESTING – CRYOSTAT-100

The Cryostat-100 insulation test instrument provides:

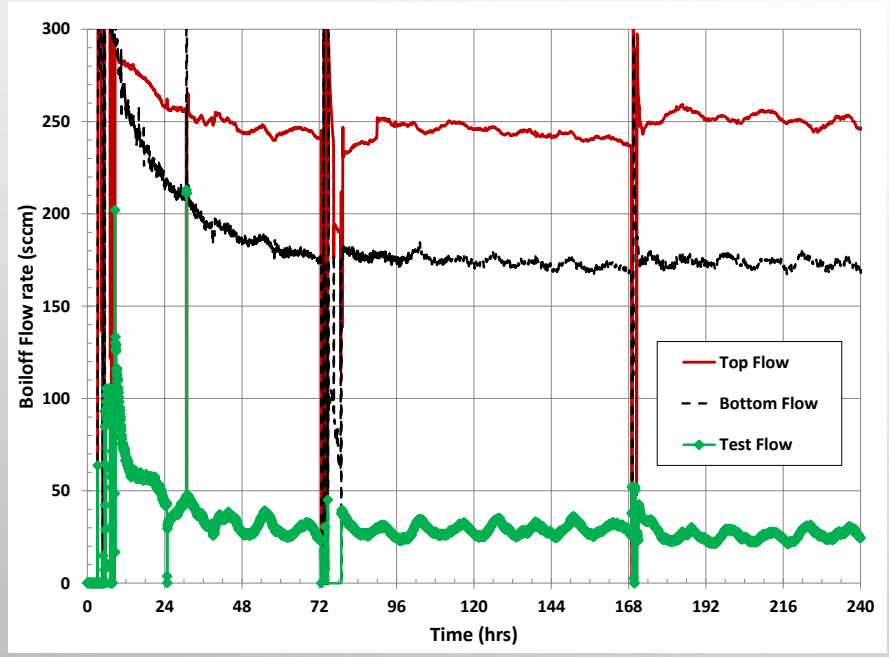
- ✓ Testing 1-meter long, 218-mm diameter specimens under representative-use conditions.
- ✓ Direct energy rate measurement by LN_2 boiloff calorimetry.
- ✓ Reliable testing of non-homogenous, non-isotropic thermal insulation systems.
- ✓ **ASTM C1774, Annex A1**





CYLINDRICAL BOILOFF TESTING – EXAMPLE DATA

- ✓ 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.



Boiloff flow rate for MLI test specimen at high vacuum.

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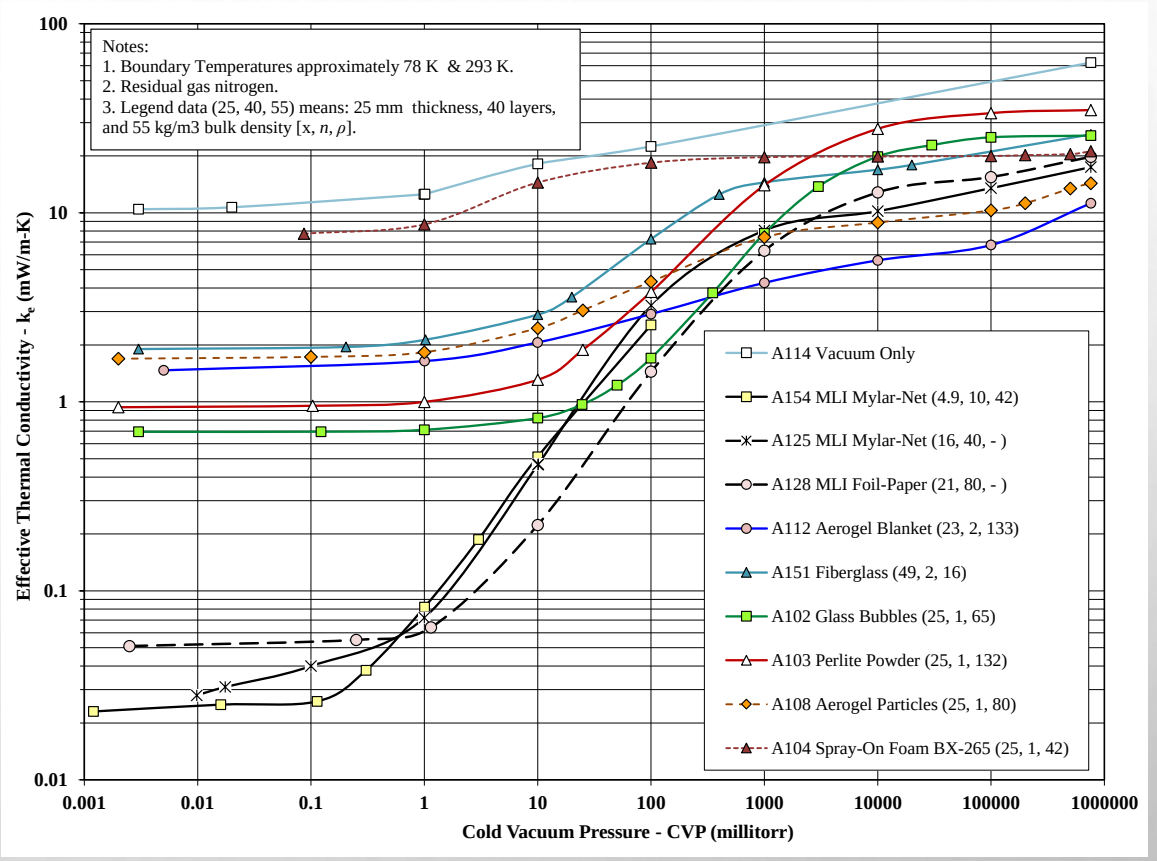


Summary of test results for various thermal insulation systems and materials: variation of k_e with vacuum pressure.

BELOW-AMBIENT INSULATED PIPE TESTING

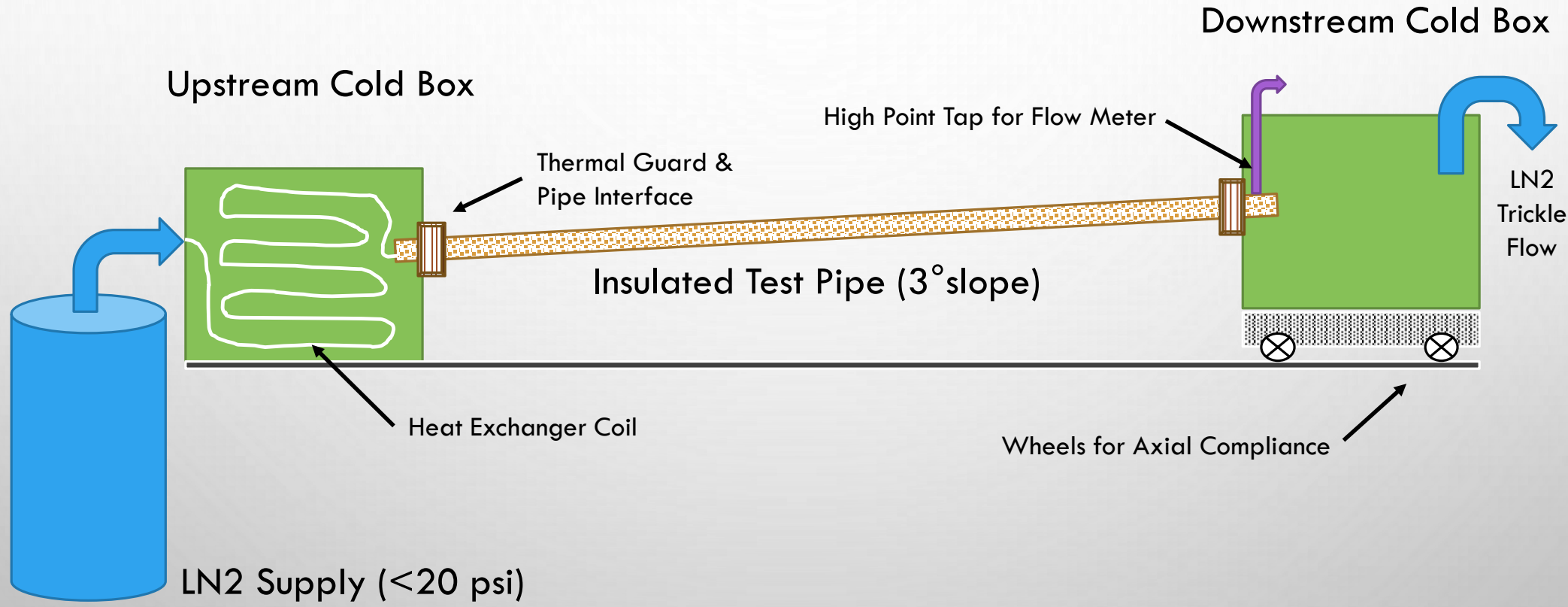
- REVISION OF ASTM C335 TO INCLUDE BELOW-AMBIENT METHOD BASED ON CRYOGENIC BOILOFF IS UNDER REVIEW BY C16 COMMITTEE OF ASTM INTERNATIONAL
- APPARATUS AND METHOD FOR THERMAL PERFORMANCE TESTING OF CRYOGENIC PIPING SYSTEMS HAS BEEN ESTABLISHED - CRYOSTAT-P100
  - ACCURATE HEAT LEAK DATA FOR FULL-SCALE 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

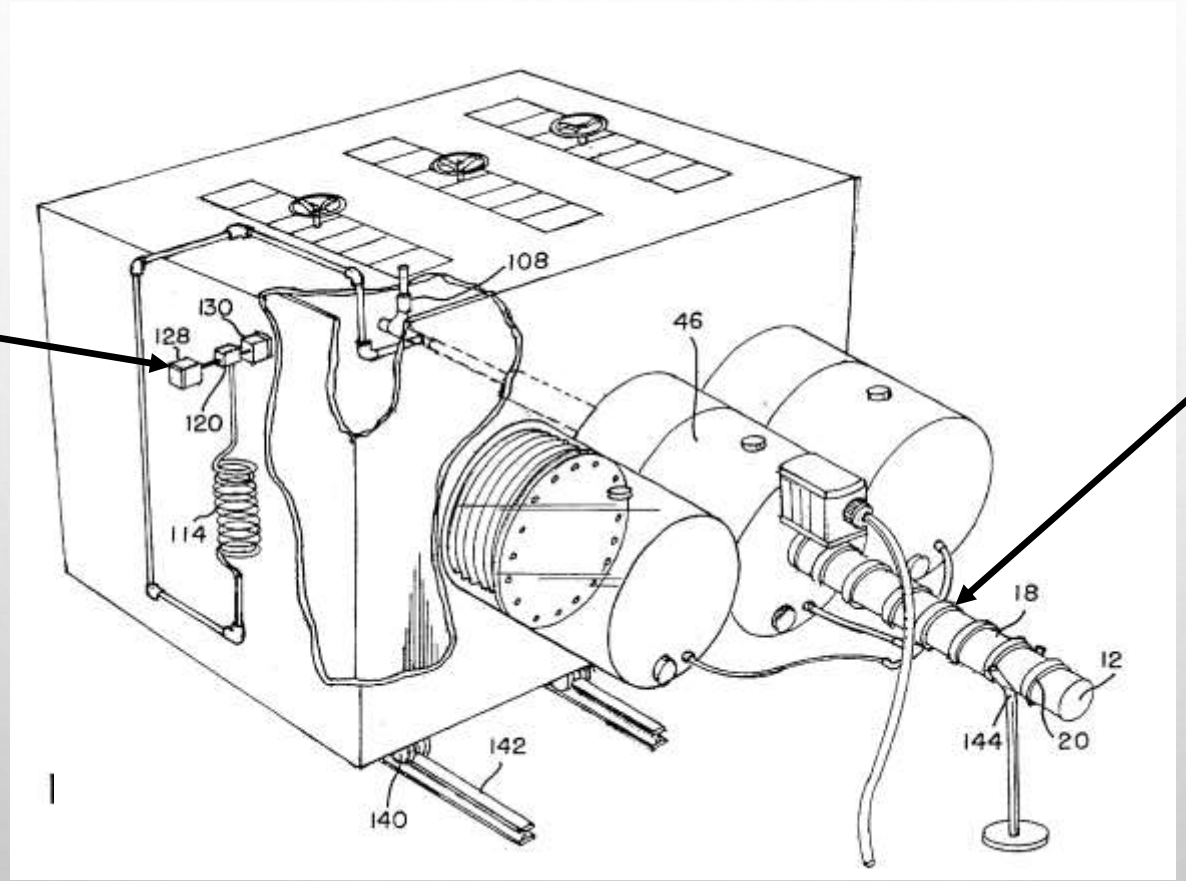
COLD PIPE TESTER - CRYOSTAT-P100



COLD PIPE TESTER - CRYOSTAT-P100

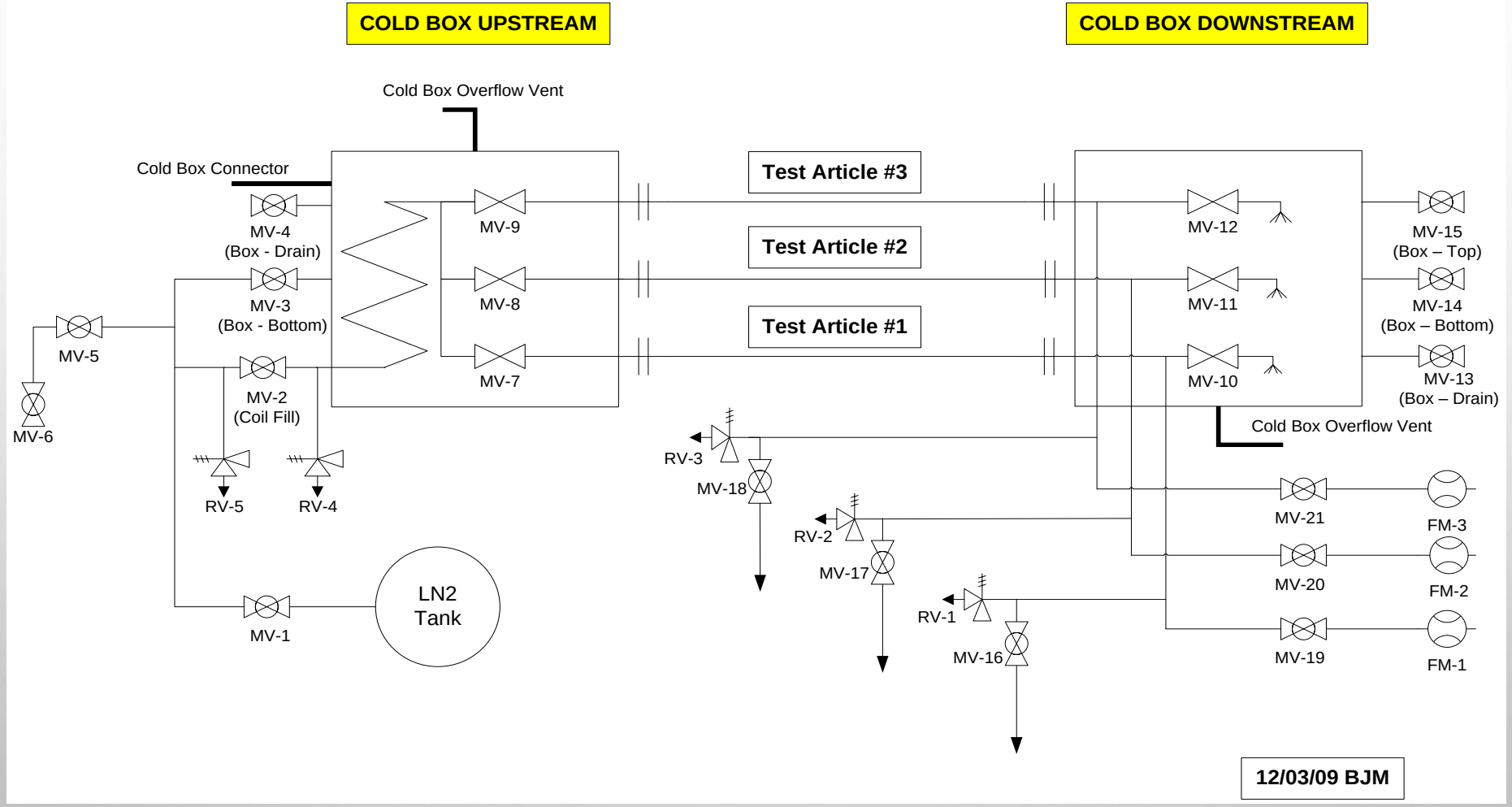
Downstream Cold Box assembly showing insulated test pipe connection

Boiloff Flow Meter connection



External Heater Wrap

COLD PIPE TESTER - CRYOSTAT-P100



COLD PIPE TESTER - CRYOSTAT-P100

Thermal End Guards & Test Pipe Termination

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

COLD PIPE TESTER - CRYOSTAT-P100

SUMMARY OF TEST RESULTS: 3" NOMINAL PIPE WITH 1.5" THICK INSULATION CLAM-SHELLS

	East Pipeline	West Pipeline
Total heat leakage rate	30.0 W	32.0 W
Heat leak per unit length	2.45 W/m	2.62 W/m
Overall k-value (k_{oafi})	0.95 mW/m-K	1.1 mW/m-K
Boil-off flow rate	7.25 slpm	7.73 slpm

Notes:

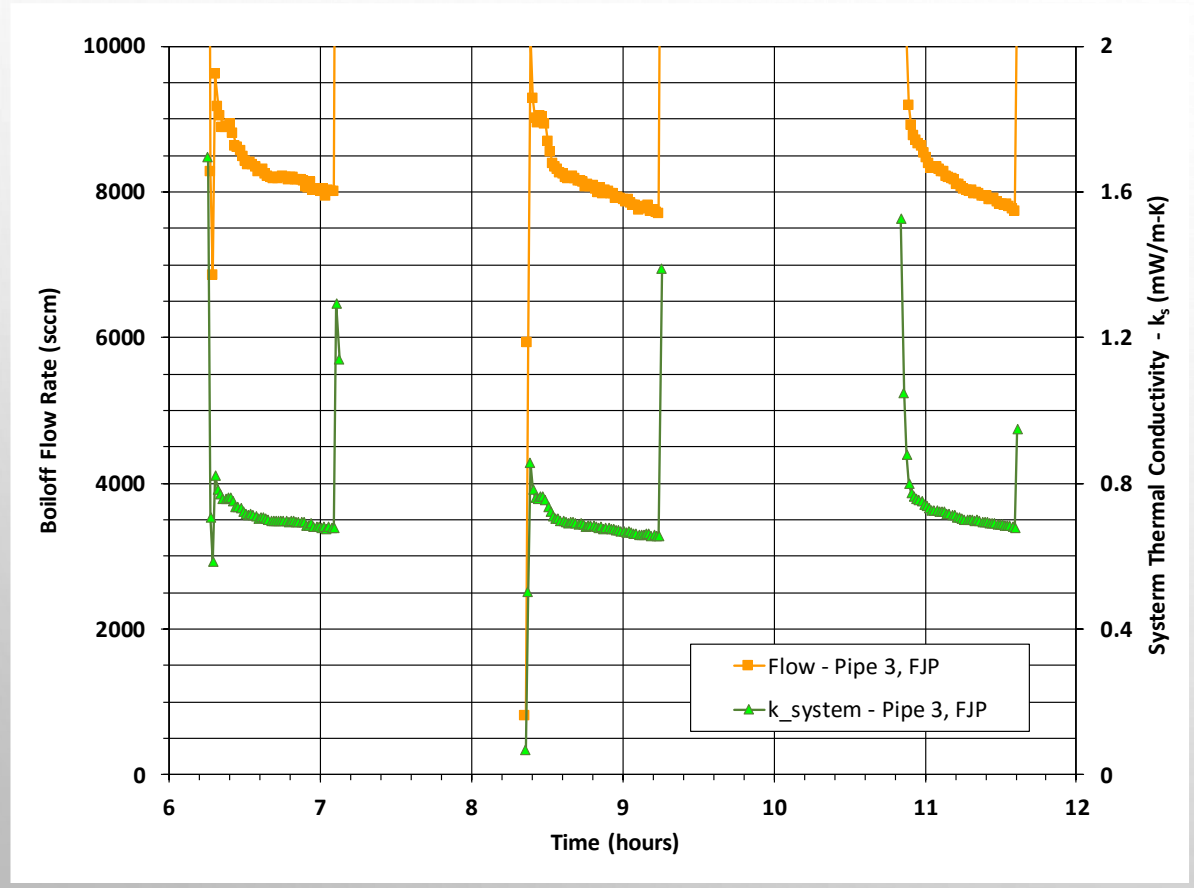
- ✓Boundary temperatures are approximately 293 K and 78 K.
- ✓Cold soak phase of approximately 24 hours.
- ✓Cold vacuum pressures verified.
- ✓Wind and solar influences are negligible (vacuum jacketed insulation system).

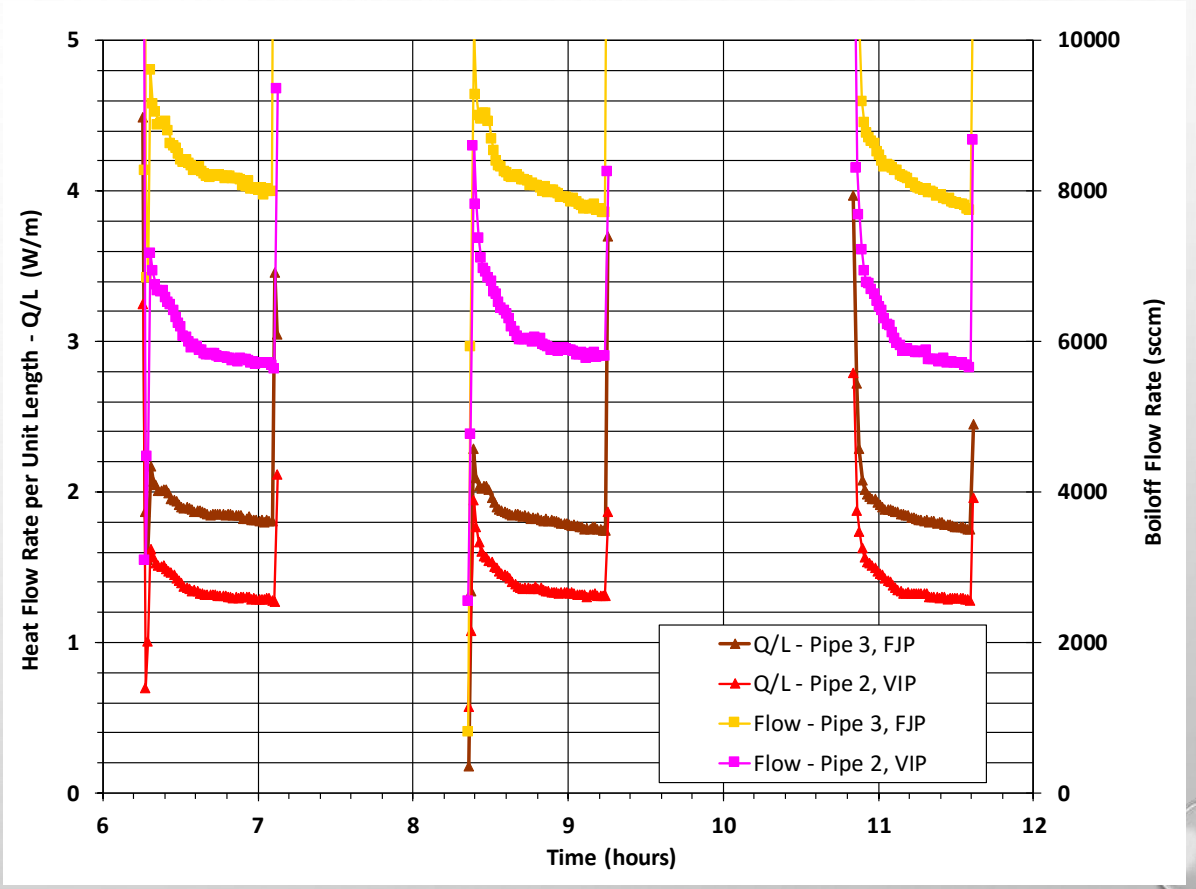
COLD PIPE TESTER - CRYOSTAT-P100

ORIGINAL 18-METER-LONG APPARATUS

COLD PIPE TESTER - CRYOSTAT-P100

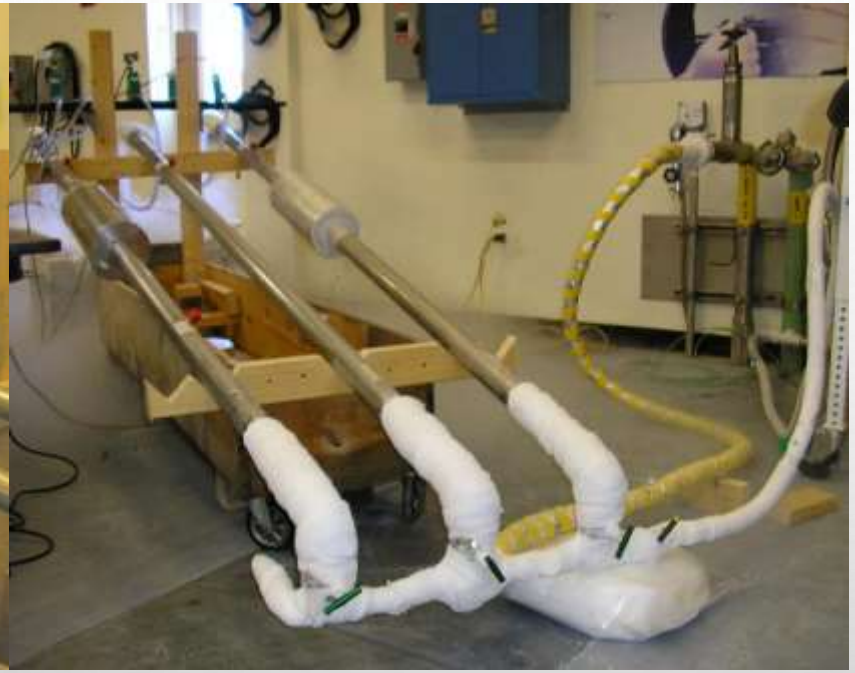
Example test results for cryogenic-vacuum pipelines: VIP (Pipe 2) and FJP (Pipe 3)





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

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

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

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

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

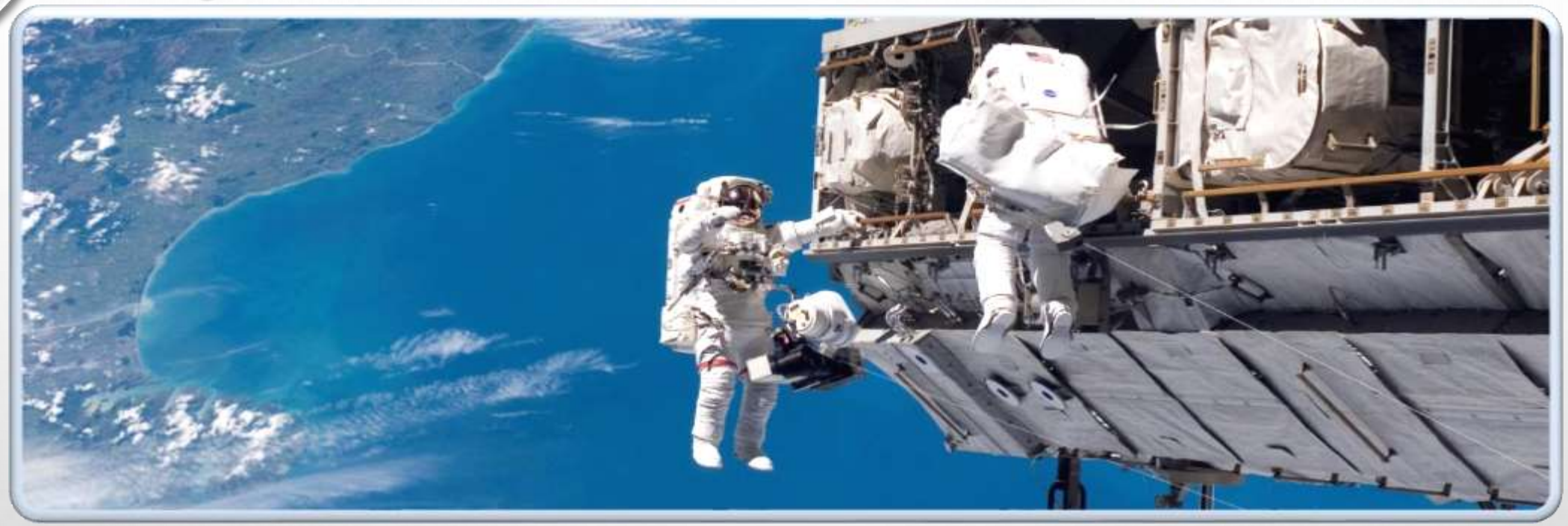
Symbol	Description	Unit	% Error
V	Volumetric flow rate (boiloff) at STP	m^3/s	0.500
ρ	Density of GN_2 (boiloff) [0.0012502 g/cm^3]	kg/m^3	n/a
h_{fg}	Heat of vaporization	J/g	2.37
d_o & d_i	Outer and inner diameters of insulation specimen	m	1.53 & 1.23
x	Thickness of insulation specimen	m	n/a
L_e	Length, effective heat transfer	m	0.730
A_e	Area, effective heat transfer area	m^2	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).

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



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REFERENCE PUBLICATIONS

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