Recommended practices for measuring the performance and characteristics of closed-loop gaseous helium cryopumps

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This article establishes a set of uniform procedures for quantitatively characterizing closed-loop gaseous helium cryopumps. Topics include a listing of technical definitions and hardware illustrations of cryopumps; safety considerations in the use of cryopumps; methods and procedures for determining the speed, ultimate pressure, capacity, cool-down time, impulsive gas load tolerance, regeneration time, thermal radiation tolerance, and maximum throughput tolerance of cryopumps; and, a method of measuring the vibration characteristics of cryopumps. © *1999 American Vacuum Society.* [S0734-2101(99)06405-2]

I. FOREWORD

This document establishes a set of uniform procedures for quantitatively characterizing closed-loop, gaseous helium cryopumps. It does not treat the characterization of cryopump refrigerators or liquid helium cryopumps. The former subject is primarily relevant to the design of cryopumps, and beyond the scope of this practice. The latter is of very limited use, and believed not to merit inclusion in this recommended practice.

These recommended practices are based on sources and information believed to be reliable. However, the American Vacuum Society and the authors disclaim any warranty or liability based on or relating to the contents of this material. Nothing in this practice should be construed as an endorsement of a manufacturer or supplier of equipment. Special attention should be paid to Sec. III, SAFETY, before proceeding with any of the recommended practices.

I.1 Gauging and Instrumentation

Calibration of all critical instrumentation such as vacuum gauges, gas flow meters, and temperature measuring instruments, shall be traceable to the National Institute of Standards and Technology (NIST), or some other recognized national standards laboratory. However, it is permitted to assume that vacuum gauging (e.g., Bayard–Alpert gauges) will be linear over several orders in magnitude beyond the immediate range of calibration. Instrumentation used to measure cryopump array temperatures in all applicable tests shall have accuracies of ±0.5 K.

I.2 Accepted vacuum practices

These recommended practices require high standards of quality and workmanship when preparing and operating the vacuum test equipment. It is assumed that the user has prior knowledge in acceptable vacuum practices, and in the use of good experimental technique. The user unaware of these technologies is referred to existing American Vacuum Society Recommended Practices published in the literature, basic

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vacuum technology courses offered by the Society, books on cryopumping,[1,2] and some basic vacuum technology textbooks.[3–10]

I.3 Error analysis of experimental results

All reported test results and data shall be presented using error bars comprising one standard deviation. Methods of error analysis shall be in accordance with accepted experimental technique.[11]

I.4 Assembly and test procedure conditions

Certain assembly, test procedures, and experimental conditions are common to many of these recommended practices. For the purpose of brevity, these as referred to later, are *Conditions*:

Condition A: The entire test apparatus is to be constructed and assembled following accepted high vacuum (elastomer seals) or ultrahigh vacuum (UHV) (metal seals, if specified) standards of cleanliness and leak tightness. All equipment shall be operated in accordance with procedures and recommendations of the manufacturer. Gases used in all tests shall be $\geqslant$99.95% pure. [Note, a 1% trace impurity of a type-II gas in a type-III gas may result in a 10% error when measuring the speed of a cryopump for the type-III gas. See Sec. IV, Glossary of Terms, for the definitions of type-II and type-III gases.]

Condition B: The cryopump will be in a fully regenerated condition, isolated from all other forms of auxiliary pumping, and, unless otherwise noted, be under vacuum prior to the start of this test. The manufacturer's recommended regeneration procedure shall be used.

Condition C: Temperatures of the first and second stage pump arrays, T_1 and T_2, respectively, shall be constant and at equilibrated operating temperatures for a period of $\geqslant$0.5 h prior to the start of the test.

Condition D: The experimental vacuum apparatus is to be baked to a temperature not exceeding 523 K. The upper limit of the bakeout temperature shall be constrained by the extent of the parasitic heating of the cryopump and helium expander. It is desirable to bake the test dome at a temperature of $\geqslant$423 K. However, at no time during regeneration and bakeout shall any component of the cryopump, including the helium expander, be allowed to exceed the manufacturer's maximum temperature limit. Exceeding this temperature limit may result in damage to the cryopump. The duration of the bakeout shall not exceed 12 h.

An auxiliary pumping system will be required during bakeout of the test dome. It is recommended that some form of oil-free pumping be used. An elastomer-sealed or all-metal valve shall be used to isolate the auxiliary pump from the test dome and to isolate the regeneration apparatus from the cryopump. The same valve and flanged system port may be used for both purposes. The type and number of valves selected for use in these applications shall be reported.

Condition E: Except as affected by the cryopump or by prescribed conditions of the test and test apparatus, all test hardware and the room ambient temperature shall be at 293 $\pm$3 K, during tests.

Condition F: Array *locations* for the purpose of defining temperatures T_1 and T_2 are to be established and shall be experimentally determined by measurements. These temperature locations are the *warmest extremities* of the cryopump first and second stage arrays (T_1 and T_2, respectively), with a pump throughput, Q, of type-II gas which is $\geqslant$30% of the maximum pump throughput capacity using procedures as defined in Sec. V.8.

I.5 SYMBOLS USED IN THIS PRACTICE

Symbol*	Definition, Units
a	acceleration, m/s^2
average	the arithmetic mean of data
c	damping coefficient, kg/s
C	conductance, ℓ/s
D	diameter of dome or manifold, mm
D_A	diameter of aperture, mm
f	frequency in cycles/s, Hz
F (t)	forcing function in time, kg-m/s^2
h	time, h
k	spring constant, Nt/m,
K	temperature, K
ℓ	liters
m	meters
m	mass, kg
m_p	mass of pump, kg,
m_t	total mass of system, kg
M	molecular weight of gas, g/mol
ω	angular frequency, rad/s
P	pressure, Torr (1 Torr = 133.3 Pa)
ΔP	pressure difference, Torr
P_b	base pressure of pump, Torr
P_n	pressure of gauge n or in region n, Torr
Q	throughput, Torr ℓ/s
RT	room temperature, 293$\pm$3 K
s	time, s
S_p	measured pump speed, ℓ/s,
$S_{\max}$	maximum pumping speed, ℓ/s
t	time, seconds or hours,
T	temperature, K
T_1	temperature of the warmest extremity of the first stage array, K
T_2	temperature of the warmest extremity of the second stage array, K
B	magnetic field, Tesla,
V	volume, ℓ
$(P_i V_i)$	impulsive gas load, Torr ℓ at RT,
x, y, z	Cartesian coordinate system

*Please note the distinction between that which is and is not italicized.

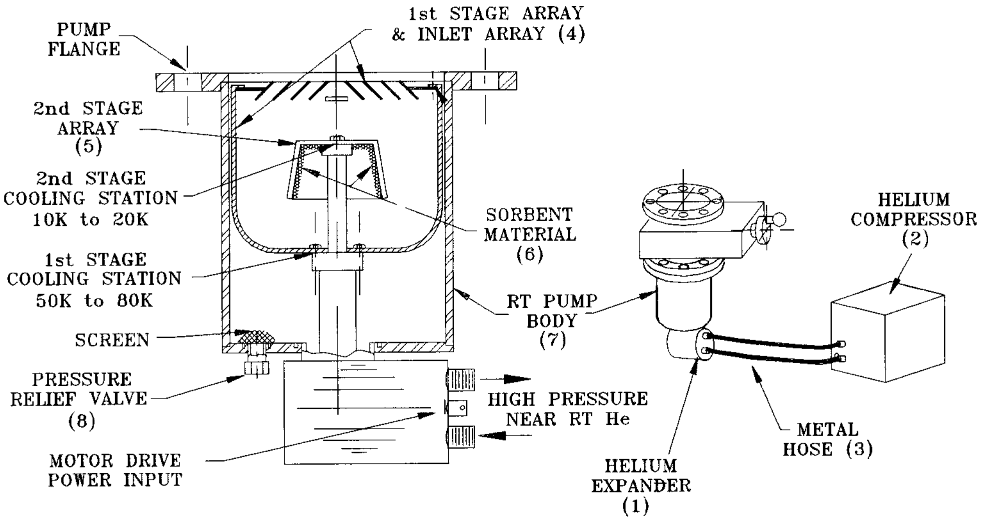

FIG. 1. Cross section of a typical two-stage, closed-loop gaseous helium cryopump with Gifford–McMahon refrigerator.

II. PUMP CONFIGURATION

A cryopump using a closed-loop, gaseous helium refrigerator (e.g., see Fig. 1), consists of the refrigerator, cryopanels or arrays, and a pump body. The refrigerator comprises a two-stage expander (1) connected to a helium compressor (2) with flexible metal hoses (3).[12] The cryopanels comprise fabricated sheet-metal first-stage array and inlet array (4), and second stage array (5) which are attached at the cooling stations of the two-stage helium expander. Sieve (i.e., sorbent) material (6) is usually bonded to portions of the second stage array. In certain applications, the expander and arrays may be sealed to and protrude into a vacuum system envelope where pumping takes place on the cold arrays. This is referred to as a *nude pump* application. In other applications the pump body (7) forms a vacuum envelope which is secured to a flange appending the vacuum system.

Cryopumped gases are retained within the pump as long as the pumping arrays are maintained at cryogenic temperatures. On warming of the cryopump, these gases are released. A pressure relief valve (8) is located on the pump body. This valve serves as a safety device to prevent over-pressurization of the system on warm-up of the cryopump.

Some form of temperature sensor is usually used to measure the temperature of the second stage cooling station. This usually takes the form of a hydrogen vapor bulb or a silicon diode sensor. In many applications silicon diodes are attached proximate to and used for measuring temperatures of both the first and second stage cooling stations of cryopumps. The properties and limitations of silicon diodes are reported elsewhere.[13]

Comments on cryopump operating considerations are given in Appendix A.

III. SAFETY

Warning: *Under no circumstance in any series of measurements, and in any of these practices shall combinations of gases be pumped, which on desorption or vaporization comprise mixtures of potentially chemically explosive gases. Under no circumstance shall either air or oxygen be included as one of the test gases.*

III.1.1 Scope

This section discusses some of the safety issues and considerations which are unique in the use of closed-loop cryopumps.

III.1.2 Comments

The means by which cryopumps pump and retain gases are unique compared to all other forms of pumps. When the pumping processes are understood, they can be reliably and safely applied to most pumping applications. Cryopumps are *capture pumps*, and function by condensing and adsorbing gases. These gases are retained on surfaces within the pump until such time as the source of refrigeration is turned off. The user should be aware that the potential exists for physical explosions, chemical explosions, and the release of toxic or hazardous gases during planned regenerations or accidental pump warm-up. *The user is strongly urged to obtain, refer to, and follow instructions and procedures found in the manufacturer's instruction manual.*

III.2 Over-pressure explosion

Without the use of pressure relief provisions, the physical explosion of a pump could occur during a scheduled regeneration or accidental warm up of the pump after pumping large quantities of gas. For example, the argon capacity of a typical 200 mm diam cryopump is $\sim 7.6\times 10^5$ Torr ℓ (1.01×10^5 Pa m^3). During a power failure, this quantity of gas, if contained in the 10-liter volume of a *valved-off* pump, would generate a pressure of 100 atm, or $\sim$1500 psi. To prevent this from occurring, commercial cryopumps are fitted with either a pressure relief valve mechanism or rupture disk. *The* *user should be aware that if the pump pressure relief provisions are blocked or tampered with, serious injury to personnel or damage to equipment could result.*

III.3 Chemical explosion

A chemical explosion could occur during a normal or accidental pump warm-up or immediate loss of vacuum if explosive gas mixtures or strong oxidants have been pumped. Also, some gases such as ozone can undergo a spontaneous detonation. *The cryopump user is cautioned to carefully consider the nature and quantities of the process gases being pumped to insure, if at all possible, that explosive mixtures of gases do not occur.* As a further safety consideration, an inert gas purge should be used during warm-up.

III.4 Use of pump isolation value

It is strongly recommended that a vacuum valve be used so that it is possible to isolate a cryopump from the system to which it is attached. This isolation valve should be closed during pump regeneration or warm-up. Interlock provisions should exist so that the isolation valve will automatically close and *latch* in the event that the system pressure exceeds ~1.0 Torr (133.3 Pa), or in the event that power is interrupted to the refrigerator for some reason. *Potential sources of ignition (e.g., vacuum gauges) should be isolated from the cryopump with this isolation valve.*

III.5 Toxic/hazardous gas exposure and asphyxiation (anoxia)

The release of toxic or hazardous gases could occur during a normal or accidental warm-up of a cryopump used in a process which uses or generates toxic gases. If a cryopump is used for such a process, an action plan should be made and implemented for the protection of personnel from the released gases. Careful consideration should be given to provisions for handling released gases stemming from pump warm-up, or during a *worst-case accident.* These provisions must take into account possible release of toxic or hazardous gases through normal exhaust systems, safety relief valves, or rupture disks. Also, fairly large quantities of otherwise inert gases could accumulate in confined spaces and displace enough oxygen to cause asphyxiation (anoxia).

IV. GLOSSARY OF TERMS

(1) Base (ultimate) pressure, indicated: The minimum cryopump pressure which can be achieved after a given time and after it has been preconditioned by a prescribed procedure.

(2) Capacity, single-gas pump: When pumping one gas species, *single-gas pump capacity* for that species is the amount of RT gas, in Torr ℓ, which can be pumped prior to the pumping speed for that gas decreasing to a prescribed value at a prescribed pressure.

(3) Capacity, multigas pump: When simultaneously or sequentially pumping type-II and type-III gases, the *multigas capacity* of the pump is the amount of RT type-II gas, in Torr ℓ, which can be pumped prior to the speed of the pump for the type-III gas decreasing to a prescribed value at a prescribed pressure.

(4) Throughput, maximum: The maximum continuous RT gas flow rate, in Torr ℓ/s, which a cryopump can pump while the second stage array is at a temperature of 20 K.

(5) Capture (sticking) coefficient: The probability that a gas atom or molecule when impinging on a surface will permanently remain on that surface.

(6) Compressor: The apparatus that provides high pressure helium gas to the expander.

(7) Cool-down time: The elapsed time for the RT first and second stage arrays of a cryopump to achieve prescribed operating temperatures subsequent to turning on the refrigerator.

(8) Cryopump arrays (cryopanels): Metal panels secured to the first and second stage cooling stations of the expander, and onto which gases are cryopumped.

(9) Cryocondensation: The pumping of gas due to a phase change of the gas into a solid (i.e., *ice* or *frost* of the gas).

(10) Cryosorption: The pumping of gas on a sorbent or surface where the amount of gas which can be pumped is dependent on the surface density of the gas, and the equilibrium gas pressure over the sorbent or surface.

(11) Cryotrapping: The concurrent or sequential cryopumping of two or more gases so as to trap the less readily pumped gases in the cryodeposits of the more readily cryopumped gases.

(12) Expander: That part of the cryopump refrigerator configured to produce regions which are cooled to cryogenic temperatures by the expansion of helium gas.

(13) First stage array: The higher temperature (i.e., ~80 K) array of a two-stage cryopump. This array is cooled by attaching it to the first (expansion) stage cooling station of the expander. This array is used to shield the second stage array from thermal radiation. The inlet array of the first stage array assembly also serves as a pumping surface for type-I gases.

(14) Gas, type I: A gas which is cryocondensed at the operating temperatures of the first stage array (e.g., gaseous H_2O).

(15) Gas, type II: A gas which is cryocondensed at the operating temperatures of the second stage array (e.g., N_2, O_2, Ar, etc.).

(16) Gas, type III: A gas which can only be cryopumped by cryosorption, and usually through the use of a sorbent material operating at temperatures of $\leqslant 20$ K (e.g., H_2, He, and Ne).

(17) Impulsive gas load tolerance: The quantity of RT gas, in Torr ℓ, which can be admitted to a cryopump in a defined time interval, without causing the second stage array temperature to exceed 20 K. This circumstance might occur when opening a vacuum valve isolating

an operating cryopump from a vacuum vessel at a higher pressure. This is also called the *cross-over tolerance*.

(18) Pressure recovery time: The time for a cryopump to recover to a defined pressure after operating at high throughput conditions.

(19) Pumping speed: A volumetric displacement rate or volumetric flow rate. The latter definition is the value of the quotient Q/P anywhere in the vacuum system.

(20) Refrigerator capacity: The thermal load (watts) which can be sustained at the first and second stage cooling stations of a cryopump refrigerator while maintaining those cooling stations at prescribed temperatures.

(21) Regeneration time: The elapsed time from when an operating cryopump with temperatures $T_2 \leq 20$ K and $T_1 \leq 130$ K: (i) is turned off; (ii) temperatures T_2 and T_1 are increased so that prescribed gases are desorbed from the arrays; (iii) desorbed gases are thereafter evacuated from the pump; and, (iv) the pump is then turned on and temperatures $T_2 \leq 20$ K and $T_1 \leq 130$ K are achieved.

(22) Second stage array: The lower temperature (i.e., ≤ 20 K) array of a two-stage cryopump. It is attached to the second stage cooling station of the expander. This array is used to cryosorb type-III gases and cryocondense type-II gases.

(23) Sorbent: A porous material with a very high effective surface area to unit mass ratio (e.g., 200–900 m^2/g), and which effectively cryosorbs type-III gases at temperatures of ≤ 20 K.

(24) Thermal radiation tolerance: The property of a cryopump to simultaneously maintain first and second stage array temperatures of ≤ 130 K and ≤ 20 K, respectively, and at specified locations, when a *blackened* object of defined geometry, location, and temperature is placed proximate to the entrance of a cryopump. The temperature of the *blackened* object is the indirect measure of the cryopumps *thermal radiation tolerance.*

(25) Vibration characteristics: The vibration characteristics of a cryopump are the root-mean-square (rms) amplitudes of the acceleration (vibration) vector components of an operating pump plotted in both the time and frequency domain.

V. RECOMMENDED PRACTICES

V.1 Base or ultimate pressure, indicated

V.1.1 Scope

This practice defines the meaning of the term *cryopump base pressure*, and the procedure by which it shall be determined.

V.1.2 Definition

This test is intended to establish the minimum achievable base pressure of a cryopump which has been preconditioned following prescribed evacuation and bakeout procedures, and which is thereafter operated at a minimum temperature for a prescribed duration. While this is not necessarily indicative of the lowest pressure which can be achieved with the cryopump, it does represent a realistic minimum pressure which can be obtained following good vacuum practice, and with reasonable levels of pre-evacuation and bakeout.

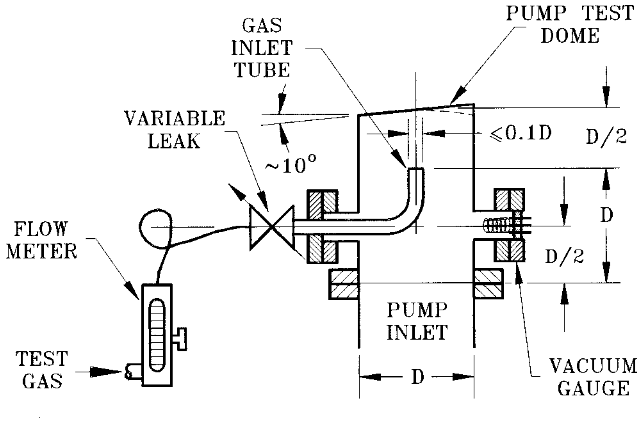

FIG. 2. Single-dome flow-meter pump speed measuring apparatus.

V.1.3 Test equipment

A test dome is used which is comparable to that shown in Fig. 2. All instrumentation ports not required for this test shall be *blanked-off* using UHV metal sealing gaskets. A total pressure and (optional) partial pressure gauge shall be mounted to the test dome. Vacuum gauge flanges must also be attached to the dome with UHV metal sealing gaskets. A metal seal which is compatible with o-ring grooves may be used on the pump inlet flange.[14] If a metal seal is used in this instance it must be reported. Either a metal burst diaphragm or an elastomer sealed pressure relief valve shall be attached to the pump during these tests. If a metal burst diaphragm is used in this test, it must be reported. Heater tapes or a heater blanket will be required for bakeout of the test dome and associated apparatus.

V.1.4 Test procedure

Conditions A, B, C, and D, of Sec. I.4, apply to this procedure. Measurements are to commence ≤ 24 h after the bakeout, and be taken with Condition E. Pressure gauges mounted to the test dome shall be degassed no less than four (4) h prior to the base pressure reading. The type of total pressure gauge used shall be noted (e.g., Bayard–Alpert, Cold Cathode, etc.). The gauge shall be calibrated for nitrogen gas.

V.1.5 Rating

The *cryopump indicated base* pressure, P_b, is defined as the indicated total gauge pressure achieved by the pump ≤ 24

h after the cryopump cool-down is initiated. The total pressure gauge shall be calibrated for nitrogen, and results **not** compensate for other gas species.

V.1.6 Comments

Gas species in the cryopump test dome subsequent to the 24 h pump cool-down period will comprise primarily H_2 with traces of CO and CO_2. A slight trace of H_2O may also be present, the magnitude depending on the amount of elastomers used in the apparatus. Should the *indicated base pressure* be primarily due to the presence of H_2, the indicated pressure will be $\lesssim\times 3$ lower than the actual pressure. The error in the absolute base pressure reading will decrease as the proportion of H_2 decreases relative to the abundance of other gas species present at the time of the reading. This is sufficiently rigorous for this practice.

The option exists for the user to use some form of calibrated partial pressure analyzer in an attempt to compensate for the relative abundance of gas species, and therefore be able to report absolute base pressure at the time of the reading. If such compensation is made, the species relative amu peak current amplitudes must be tabulated and reported, in addition to the total indicated pressure. The results may then be calculated and reported, with appropriate error bars.

V.2 Capacity

V.2.1 Scope

This practice defines the meaning of *pump capacity* and the procedure by which it shall be determined.

V.2.2 Definitions

V.2.2.1 Single-Gas Pump Capacity: The quantity of a specified RT gas, in Torr ℓ, which can be pumped at any pressure, while thereafter, at a specified pressure P_t, the pump speed S_p, is 50% of the speed at P_t, and as measured subsequent to a regeneration (i.e., see Sec. V.6).

V.2.2.2 Multi-Gas Pump Capacity: The quantity of RT type-II gas, in Torr ℓ, which can be pumped at any pressure while the pump, at a specified type-III gas pressure P_t thereafter maintains 50% of the pumping speed for the specified type-III gas, as measured at pressure P_t, subsequent to a pump regeneration (i.e., see Sec. V.6).

V.2.3 Test equipment

A test dome, configured as illustrated in any of Figs. 2–5, shall be used to test all pump sizes. The dome, gauges and valving must be bakeable within the limits described in Sec. I.4. Partial and total pressure gauges are required. A means must also exist for measuring and recording the total quantity of each gas which has been admitted to a pump during a given test procedure.

V.2.4 Test procedure

Conditions A, B, C, D, and E, of Sec. I.4, apply to this procedure. When conducting each sequence of speed measurements, a statistically significant number of speed measurements (e.g., $\geqslant 10$ data) shall be taken at each test pressure. When making speed measurements using type-III gases, a partial pressure gauge shall be used to check the purity of the test gas being introduced into the test dome. The sum of the absolute partial pressures of all type-II gases shall be $\leqslant 0.5\%$ of the total absolute pressure in the speed dome when making pump speed measurements with type-III gases.

V.2.4.1 Single-Gas Pump Capacity Procedure: (1) Speed measurements shall be conducted for a specific test gas and for a period of $\geqslant 1.0$ h at a test pressure, P_t, in a freshly regenerated and baked pump. Calculate the average results of speed data taken. However, do not use data taken during the first 0.25 h of this initial speed measurement. The average calculated speed is defined as $S_{\max}$. (2) The test gas shall thereafter be admitted at any desired Q as long as this Q is $\leqslant 30\%$ of the maximum rated Q of the pump. (3) Test gas flow shall be turned off, and the pump pressure allowed to decrease to a value $<P_t$. (Note: If the pressure does not decrease to $\leqslant P_t$ within 0.25 h, it shall be assumed that the pumps gross capacity has been exceeded.) (4) Pump speed shall again be measured at test gas pressure P_t, and for a test duration $\geqslant 0.25$ h. (5) Repeat steps (2)–(4) until the pump speed, S_p, at the test pressure P_t, is 50% of $S_{\max}$ observed in Step 1.

Speed data and the cumulative quantity of test gas pumped (i.e., $\int Q(P)dt$ for the test duration) shall be logged for each successive measurement. When reporting the value of the *single-gas pump capacity*, the gas species, $S_{\max}$, P_t, the final value of S_p, and $\int Q(P)dt$ shall be reported.

V.2.4.2 Multi-Gas Pump Capacity Procedure: (1) Measure the pump speed for a specified type-III gas, at fixed test pressure P_t, and for a test interval $\geqslant 1.0$ h. Calculate the average results of speed data taken. However, do not use data taken during the first 0.25 h of this initial speed measurement. This average calculated speed is defined as $S_{\max}$. (2) Thereafter, introduce a type-II gas at any pressure such that the measured Q is $\leqslant 30\%$ of the maximum rated Q of the pump. (3) Stop admission of the type-II gas at periodic in-

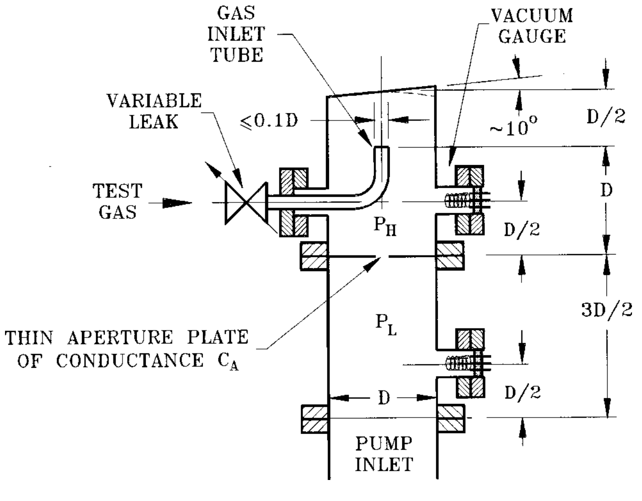

FIG. 3. Two-gauge Fischer–Mommsen speed measuring dome.

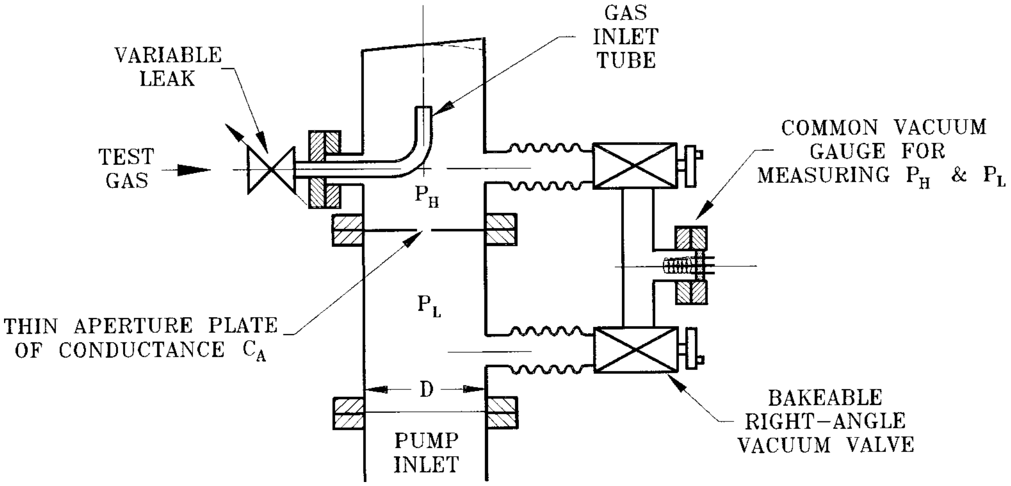

FIG. 4. Modified Fischer–Mommsen speed measuring dome.

tervals. (4) Introduce the type-III gas again at pressure P_t, and measure and record the pump speed S_p, for this gas over a period ≥0.25 h. (5) Repeat steps (2)–(4) until such time as the pump speed, S_p, for the type-III gas, at test pressure P_t, is 50% of the average speed $S_{\max}$, observed in Step (1) of this section.

V.2.5.1 Rating, single-gas pump capacity: Plot the pump speed for test gas as a function of the amount of gas which has been pumped. Interpolate the data to establish the quantity of gas pumped at which time the pump speed S_p at P_t is 50% of the average speed, $S_{\max}$, observed in Step (1) of Sec. V.2.4.1. The amount of gas pumped at pressure P_t and at which time the speed is 50% of $S_{\max}$ for that gas is defined as the single-gas pump capacity of the pump for that gas.

V.2.5.2 Rating, multi-gas pump capacity: Plot the pump speed for type-III gas as a function of the amount of type-II gas which has been pumped. Interpolate the data to establish the quantity of type-II gas pumped at which time the pump speed S_p at P_t, for type-III gas, is 50% $S_{\max}$, as observed in Step (1) of Sec. V.2.4.2. The quantity of type-II gas pumped, at which time the speed at pressure P_t for the type-III gas is 50% of $S_{\max}$, is defined at the multigas pump capacity for the type-II gas.

V.2.6 Comments

Capacities of cryopumps for both condensible and adsorbable gases are quite large. Therefore, in order to accelerate tests, the pressures at which capacity measurements are conducted may be excessive compared to some practical applications of these pumps.

V.3 Cool-down time

V.3.1 Scope

This practice defines the *cool-down time* of a cryopump, and the procedure by which it shall be measured. It applies to a cryopump for which the cryopump, expander assembly and compressor are identified.

V.3.2 Definition

Cool-down time is defined as the elapsed time between when: (1) the cryopump second and first stage array temperatures, T_2 and T_1, respectively, are ≥RT; (2) the refrigerator is turned on; and, (3) temperatures T_2 and T_1 of ≤20 and ≤130 K, respectively, are achieved.

V.3.3 Test equipment

The test is conducted using a blank-off flange at the entrance of the cryopump. The blank-off flange shall be constructed of electropolished stainless steel. The first and second stage arrays and the sorbent material bonded to the second stage array shall be configured as in the case of a standard model of the pump under test, or if modified, accordingly specified and recorded.

V.3.4 Test Procedure

Conditions A, B, E, and F, of Sec. I.4, apply to this procedure. During tests the operating voltages and frequency of the compressor and expander shall be reported, and be within the specified limits of the equipment instruction manual. If

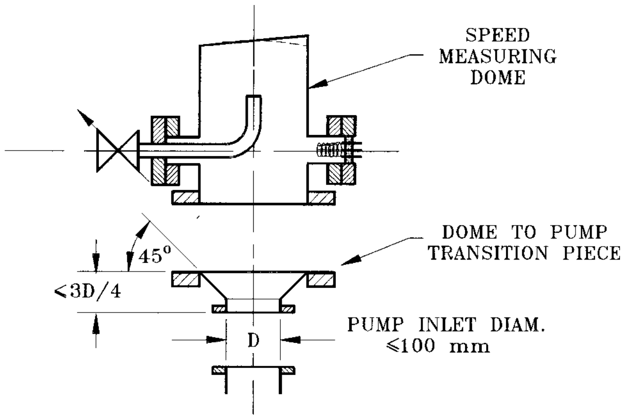

FIG. 5. Pump-to-dome transition piece to adapt measuring domes to pumps having diameters ≤100 mm.

the reciprocating frequency of the expander is increased for purposes of accelerating cool-down, both the normal expander operating frequency and the cool-down expander frequency shall be noted.

Also, the static compressor and expander helium pressure shall be similarly specified and reported. Cool-down time shall be measured in accordance with the Sec. V.3.2 Definition.

V.3.5 Rating

The rating is the time required to achieve the limiting temperature prescribed in Sec. V.3.2 to within an accuracy of one minute, while the partial pressures of type-II and type-III gases are $\leqslant 10^{-4}$ Torr ($\leqslant 1.33\times 10^{-2}$ Pa) and $\leqslant 10^{-5}$ Torr ($\leqslant 1.33\times 10^{-3}$ Pa), respectively.

V.3.6 Comments

It is the intent of the test procedure to minimize thermal loading due to radiation, gas conduction, and gas condensation. Therefore, cool-down time will primarily be a function of the mass of the pump components being cooled and the rate at which refrigeration is being produced. Cool-down times will be longer if the starting temperatures of pump components are >RT, the cryopump is exposed to a radiant heat load, or if there is sufficient residual gas in the cryopump to cause conductive heat transfer from the housing to the arrays. Cool-down time will not be measurably increased if the partial pressures of type-II and type-III gases are $\leqslant 10^{-4}$ Torr ($\leqslant 1.33\times 10^{-2}$ Pa) and $\leqslant 10^{-5}$ Torr ($\leqslant 1.33\times 10^{-3}$ Pa), respectively.

V.4 Impulsive gas load (''crossover'') tolerance

V.4.1 Scope

This practice defines the meaning of the *impulsive gas load tolerance* of a cryopump, and establishes the procedure whereby it shall be quantitatively measured.

V.4.2 Definition

The *impulsive gas load tolerance* is the maximum quantity of RT nitrogen or argon gas, $(P_i V_i)$ in Torr ℓ, which can be admitted into a cryopump in a time interval of $\leqslant 3.0$ s, while T_2 remains at a temperature of $\leqslant 20$ K.

V.4.3 Test equipment

The impulsive crossover rating of the cryopump is established using a test dome such as illustrated in Fig. 2. The impulsive gas load is injected from a source external to the dome, and of volume V_i, into the test dome via the gas feed port normally used during the cryopump speed measurements. The conductance of the gas injection system must be large enough to insure the injection of 98% of the total impulsive gas load within $\leqslant 1.0$ s.

Alternatively, the dome itself may be used as the impulsive gas volume, V_i. In this case, a vacuum isolation valve must be used to isolate the cryopump from the test dome. The impulsive gas load is injected into the pump by opening the valve isolating the (injection) dome from the pump.

The value of the product $(P_i V_i)$ shall be established by either measuring P_i in the injection volume or in the dome. In the former case, V_i would be the measured volume of the injection volume. In the latter case, V_i would be the measured volume of the dome. Temperature T_2 shall be measured as a function of time when introducing the test gas. It is recommended that some form of automatic data logging provision or fast response time (i.e., $\leqslant 100$ ms) strip chart recorder be used for this purpose.

V.4.4 Test procedure

Conditions A, B, C, E, and F, of Sec. I.4, apply to this procedure. It is the intent of this test that the initial quantity of gas introduced into the pump be less than that which will result in a temperature $T_2 > 20$ K, and that the product $(P_i V_i)$ be increased in successively larger quantities to afford experimental control.

(1) The injection volume, V_i shall be filled with nitrogen or argon gas to a predetermined pressure, P_i. (2) Measure P_i $\geqslant 5$ min after the injection volume is pressurized. (3) Record temperature, T_2. (4) Open the injection volume isolation valve, allowing the test gas to enter the pump. (5) Measure T_2 as a function of time, and record the maximum temperature, $T_{2\max}$, for the associated product $(P_i V_i)$. (6) Repeat steps (1)–(5) with successively greater values of the product $(P_i V_i)$, and until the value 15 K$\lesssim T_{2\max} \lesssim$25 K. (7) Plot $T_{2\max}$ as a function of the product $(P_i V_i)$.

V.4.5 Rating

The impulsive gas load tolerance rating of the pump is the interpolated value of the product $(P_i V_i)$ which results in a second stage array temperature $T_{2\max}$ of 20 K.

V.4.6 Comments

The capture and storage of large quantities of type-II gases on the second stage array of the cryopump will increase the thermal inertia of this cryopanel. Therefore, the number of impulsive gas loads which may be successively introduced during any test sequence shall be limited to ten (10), after which, the pump must be regenerated.

V.5 Regeneration time

V.5.1 Scope

This practice describes conditions and regeneration procedures for cryopumps used in production applications such as on semiconductor processing equipment. See Sec. III, SAFETY, prior to proceeding.

V.5.2 Definition

Cryopump *regeneration time* is the elapsed time from when an operating cryopump with temperatures $T_2 \leqslant 20$ K and $T_1 \leqslant 130$ K: (i) is turned off; (ii) temperatures T_2 and T_1 are increased so that prescribed gases are desorbed from the arrays; (iii) desorbed gases are thereafter evacuated from the pump; and, (iv) the pump is turned on and temperatures $T_2 \leqslant 20$ K and $T_1 \leqslant 130$ K are achieved. Sufficient gas shall be pumped prior to start of regeneration such that the prescribed gas species and capacity (i.e., either *single-gas* or *multigas capacity*) of the cryopump has been achieved.

V.5.3 Test equipment

The cryopump may be mounted directly to a test dome as illustrated in Fig. 2. A vacuum valve may be used to isolate the pump from the dome. The dome system used shall be specified. The pump shall be operated vertically, with the first stage inlet array facing up. Regeneration accessories may be installed on the pump as specified by the manufacturer. Accessories and controls may include, but are not limited to, the following: (i) regeneration controller; (ii) purge gas controller; (iii) purge gas heater; (iv) pump body heater; (v) first stage and/or second stage array heaters; (vi) provisions for array heating by reversing the cycle of the refrigerator; (vii) helium cryogen gas heater; (viii) rough pumping system; and, (ix) associated valves, pump traps, and temperature monitoring equipment.

V.5.4 Test procedure

(1) Either *single-gas pump capacity* for a type-III gas (i.e., see Sec. V.2.2.1) or *multi-gas pump capacity* for type-II and type-III gases (i.e., see Sec. V.2.2.2) shall first be achieved in the pump. (2) Conditions A, E, and F, of Sec. I.4, apply to this procedure. Condition C, of Sec. I.4, applies after the cessation of gas flow. (3) The power to the refrigerator will then be turned off. This constitutes the start of regeneration. (4) The cryopump will be regenerated in accordance with the manufacturer's recommended procedure. (5) Temperatures T_2 and T_1 will be recorded for the duration of the regeneration cycle. (6) The refrigerator will be turned on and the time at which temperature T_2 decreases to $\leqslant 20$ K and temperature T_1 decreases to $\leqslant 130$ K shall be recorded. (7) The *single-gas* or *multigas pump capacity* for the type gases used in Step (1) shall again be achieved in the pump.

V.5.5 Rating

The rating is defined as the elapsed time from the start of Step (3) of Sec. V.5.4 to the completion of Step (6) of that same section, and for which either the *single-gas* or *multi-gas pump capacity* of Step (7) corresponds to that capacity measured in Step (1) to within 10%. The elapsed time shall be rounded to the nearest minute. The type-II and/or type-III gases used in the procedure shall be reported. The *single-gas* or *multigas capacities* of the pump, as defined in Sec. V.2.2, and measured in Steps (1) and (7), shall be reported. All accessories, controls and test equipment used in this test must be defined and reported on when reporting the rating.

V.5.6 Comments

Many factors affect regeneration time. These include the type of gas which has been pumped, and the use of alternate sources of heat input to accelerate the warm-up process. The thermal inertia of cryocondensed type-II gases tends to increase the coast time (defined elsewhere), whereas the presence of type-III gases will have the opposite effect.

Further, most of the type-II gases will be liberated from the second stage array on warming this array to 100 K. However, if this is the extent of warming of this array during regeneration, the sorbent material may be partially plugged by type-II gases, and have reduced capacity for the pumping of type-III gases on subsequent cool-down.

V.6 Pumping speed

V.6.1 Scope

The term *pumping speed* is defined, and test procedures and equipment are described for measuring the pump speed of cryopumps for various gases and under high and low throughput conditions.

V.6.2 Definition

Pump speed is defined as a volumetric displacement rate or volumetric flow rate, and is the value of the quotient Q/P anywhere in that system. The units of pumping speed are liters per second, or ℓ/s.

V.6.3 Test equipment

Two methods may be used for the measurement of pumping speed: (1) the *single-dome* method used in conjunction with a gas flow meter (e.g., see Fig. 2); or, (2) the known conductance, or *two-gauge* method (e.g., see Fig. 3).[15] The advantages and limitations of these and other methods of making speed measurements are given elsewhere.[16] A modified two-gauge dome, as shown in Fig. 5, has certain advantages regarding establishing relative gauge calibration constants, though the dome is more complex to build.

The diameter, *D*, of the dome shall in all cases be the same as the pump inlet unless the pump inlet diameter is $\leqslant 100$ mm. In this instance, a transition adapter, such as shown in Fig. 5, may be used.

Single-dome Method, Additional Requirements: The single-dome, flow meter method may be used when the pump pressure, P_P, is such that the mean free path of the test gas is always greater than *D*. A calibrated gas flow meter is required to measure the value of the throughput, *Q*, which is introduced to the test dome.

Two-Gauge Method, Additional Requirements: The two-gauge method may be used for speed measurements in all applications wherein the *high* dome pressure, P_H, is such that the mean free path of the test gas in the upper dome is greater than that of the diameter of the dome.

Apparatus requirements include: (i) the dome must be bakeable; (ii) gas species verification through the use of a bakeable partial pressure gauge; and (iii) some means for normalizing gauge indicated pressures P_L and P_H with respect to each other. The modified dome of Fig. 5 has the advantage of yielding absolute speed measurement results.

However, the gauge must be calibrated to allow for the accurate placement of the speed data on the pressure-speed coordinate system plane.

A thin metal foil or aperture plate shall be used to separate the upper and lower domes. The conductance, C_A, of the centrally located aperture, shall be such that the ratio of $P_H:P_L$ is $\geqslant 4$ for the test gas. The conductance of this aperture, C_A, in ℓ/s, and the difference in pressure on each side of the aperture, are used to calculate the throughput into the pump.

Warning: *Under no circumstance shall potentially flammable mixtures of gases be pumped either simultaneously or sequentially in any of these practices.*

V.6.4 Test procedure

Read Sec. III, Safety, prior to starting tests. Conditions A, B, C, D, and E, of Sec. I.4, are applicable to this procedure. Speed data for type-III gases which are recorded and used for reporting purposes will be applicable only after the equivalent of $\geqslant 5\%$ of the single-gas capacity for that gas (see Sec. V.2.2.1) has been previously pumped.

Effort shall be made to maintain the pressure as near constant as possible during a measurement series at a given pressure. A minimum of ten (10) speed measurements shall be taken at each pump pressure setting. Pressure may vary by $\pm 10\%$ at a given setting. Measure the speed of the cryopump at a minimum of three pump pressure settings within any one pressure decade.

Measure and record the base pressure of the pump prior to the start of speed measurements. However, this base pressure value of the pump shall **not** be factored into the speed measurement calculation. Measure the speed for pressures varying over several orders in magnitude, but such that the temperature of the second stage cooling station remains $\leqslant 15$ K.

Single-Dome Method: Within the limitations of the flow meter, take speed measurements over as wide a pressure interval as possible. Pump speed, S_p, is herein defined as

$$S_p = Q/P_p, \tag{1}$$

where P_p is the corrected (for gas species) gauge pressure at the pump inlet, and Q is the indicated throughput of the gas flow meter.

Two-Gauge Method: Within the limitations of the apparatus, take speed measurements over as wide a pressure interval as possible. Pump speed, S_p, is herein defined as

$$S_p = C_A(P_H - P_L)/P_L, \tag{2}$$

where P_H and P_L are the *high* and *low* corrected pressures in the speed dome, respectively, and C_A is the conductance of the dome aperture for the test gas. Note: P_L is herein defined as P_p.

V.6.5 Rating

The speed of the cryopump at a given pressure is the average of the results of either Eq. (1) or (2) for data taken under the specified conditions.

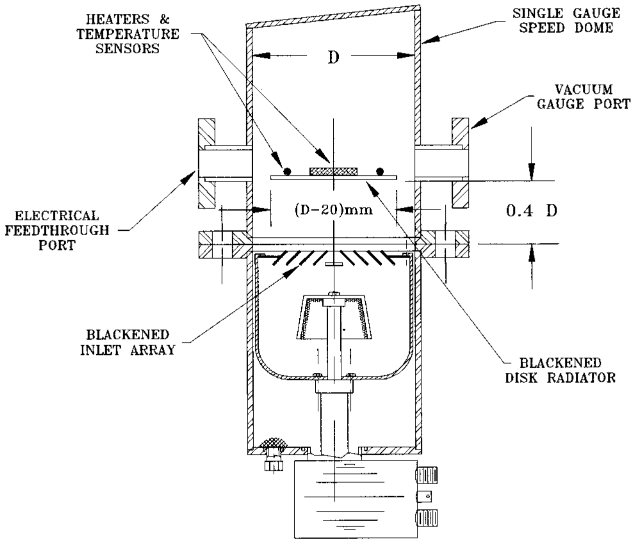

FIG. 6. Single-gauge speed dome, with blackened disk radiator, used to measure the thermal radiation tolerance of a cryopump.

V.6.6 Comments

If the highest and the lowest measured values of the pumping speed differ by more than two standard deviations from the average speed observed at any one pressure setting, the data must be excluded and a new average speed calculated with the remaining data. Unless *capacity* measurements are being made (i.e., see Sec. V.2), speed measurements shall be taken when the amount of test gas pumped is $\leqslant 30\%$ of the capacity of the pump.

If gauges used in these tests are calibrated for nitrogen, and another gas is used in these tests, the gauge sensitivities should be corrected for by using gauge calibration constants published by the gauge manufacturer.

V.7 Thermal radiation tolerance

V.7.1 Scope

This practice defines the term *thermal radiation tolerance*, and the procedure by which it shall be measured.

V.7.2 Definition

The *thermal radiation tolerance* of a cryopump is the maximum temperature of a blackened object, viewed at the inlet of the cryopump, while temperatures $T_1 \leqslant 130$ K and $T_2 \leqslant 20$ K are maintained.

V.7.3 Test equipment

A dome equivalent to the *single-dome* speed apparatus (i.e., Fig. 2) shall be used for these measurements. It shall be modified as shown in Fig. 6 to accommodate a heated disk. The heated disk, which serves as a blackened radiator, shall comprise a material of high thermal conductivity, preferably copper or aluminum. Referring to Fig. 6, the disk diameter shall be (D-20) mm, where D is the diameter of the test dome. The disk shall be of sufficient thickness so that variations in disk surface temperatures will be $\leqslant 5$ K. The surface

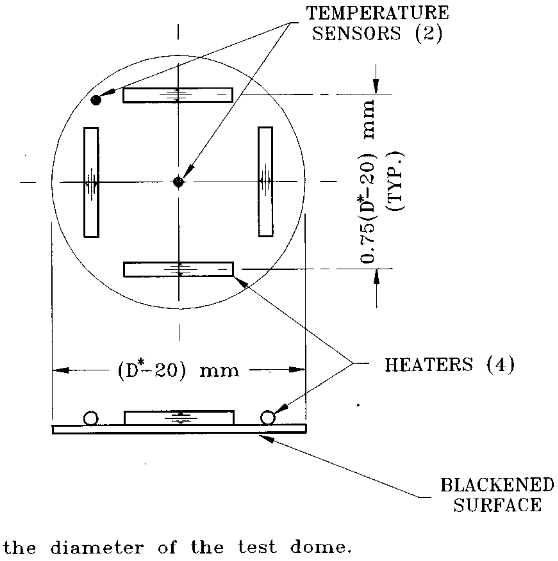

FIG. 7. Blackened disk radiator used in measuring the thermal radiation tolerance of a cryopump.

of the disk facing the cryopump shall be treated so that it has a total hemispherical emissivity of >0.90. Mount heaters and temperature sensors on the side of the disk opposite the cryopump (i.e., see Fig. 7). The average temperature measured with these sensors is defined as the *disk temperature*. Mount the disk within the test dome, so that it is spaced a distance $\leqslant 0.4D$ from the pump inlet flange, and its surface is parallel with this flange face.

V.7.4 Test procedure

Conditions A, B, C, E, and F, of Sec. I.4, apply to this procedure. The cryopump inlet array must be made to have a total hemispherical emissivity of >0.90. This can be accomplished by: (i) treating the inlet array in a fashion similar to that of the blackened disk; or (ii) by introducing and pumping gaseous H_2O on the inlet array in sufficient amounts to create a layer of H_2O frost with a thickness of $\geqslant 0.1$ mm. The pressure in the test dome shall be $\leqslant 10^{-5}$ Torr (1.33×10^{-3} Pa) during tests.

Slowly increase the temperature of the blackened disk until either (i) temperature T_2 equilibrates at 20 K; or (ii) temperature T_1 equilibrates at 130 K, which ever occurs first. That array reaching the prescribed temperature limit is the *limiting* array. Record temperatures of both the limiting and nonlimiting arrays.

Vary the temperature of the blackened disk, while maintaining temperature T_2 within the range of 20 ± 5 K. Record a minimum of six equilibrated temperatures of the heated disk, and temperatures T_1 and T_2, under Condition C, of Sec. I.4. Of the six temperature measurements, at least two T_2 temperature measurements must be recorded at >20 K, and at least two T_2 temperature measurements at <20 K.

With a minimum of six data points, least squares curve fit a linear relation between the log of the blackened disk temperature and the log of the limiting array temperature.

V.7.5 Rating

Thermal radiation tolerance is the maximum blackened disk temperature that can be sustained while simultaneously keeping temperature T_1 at $\leqslant 130$ K and temperature T_2 at $\leqslant 20$ K.

V.7.6 Comments

Thermal radiation from a high temperature source places an additional load on the cryopump. A relevant measure of the cryopump's ability to adsorb thermal energy is the system temperature it can *view* while maintaining temperatures sufficient for cryopumping. This *viewable* temperature can be used to assess the appropriateness of using a particular cryopump in a higher than ambient temperature environment.

V.8 Maximum throughput

V.8.1 Scope

This practice defines the term *maximum throughput,* and the procedure by which it shall be measured.

V.8.2 Definition

The *maximum throughput* is the maximum constant RT gas flow rate, in Torr ℓ/s, which a cryopump can pump with temperature T_2 at 20 K.

V.8.3 Test equipment

The single-dome test apparatus, gauging and flow meter, illustrated in Fig. 2, shall be used for this test. Argon will be used as the test gas.

V.8.4 Test procedure

Conditions A, B, C, E, and F, of Sec. I.4, apply to this procedure. During the test, the first stage array shall be operated at a temperature $\geqslant 65$ K. (This will prevent the pumping of argon on the first stage array during this test.) Initiate the flow of gas, and incrementally increase the flow rate until temperature T_2 has stabilized to 20 ± 3 K. Record flow rate, and temperature. Change the flow, but only sufficiently to stabilize temperature T_2 in the range of 17–23 K. In such a manner, record a minimum of six stabilized temperatures and flow rates. Both array temperatures must equilibrate for $\geqslant 0.25$ h prior to each reading. Of the six data points, at least two T_2 temperature measurements must be taken above 20 K, and at least two T_2 temperature measurements taken below 20 K.

With a minimum of six data points, least squares curve fit a linear relation between throughput and the maximum second stage array temperature.

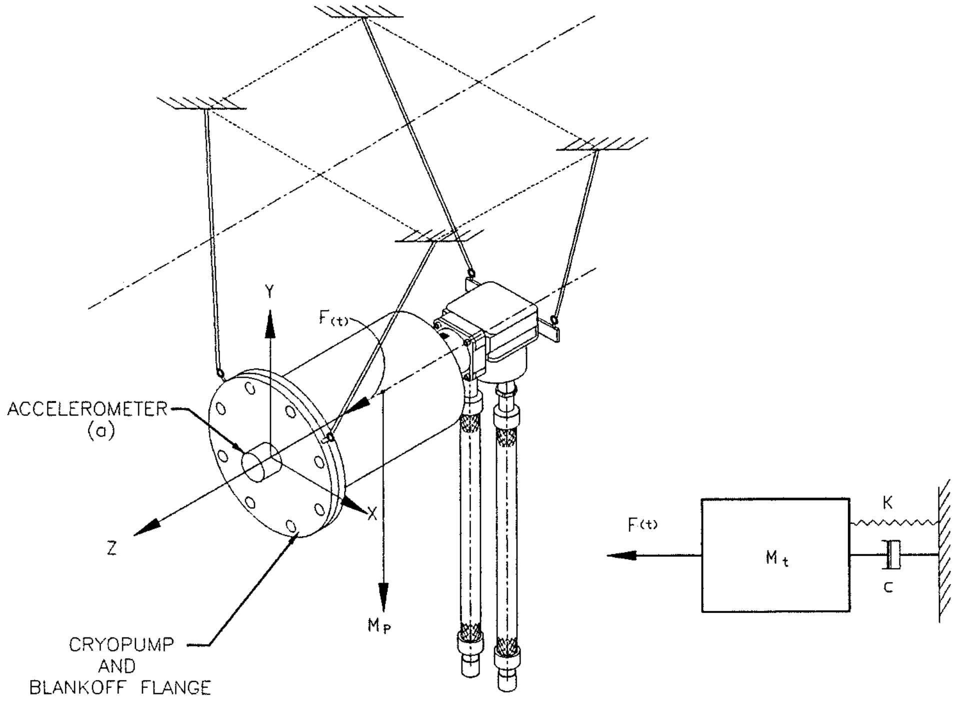

FIG. 8. Cryopump vibration measurement support system.

V.8.5 Rating

The maximum throughput is the rate of RT argon flow, in Torr ℓ/s, at which temperature T_2 stabilizes at 20 K for the prescribed time.

V.8.6 Comments

Argon was arbitrarily selected for the earlier tests. However, other type-II and even type-III gases could have been chosen for use in this test.

V.9 Vibration

V.9.1 Scope

This practice defines the procedure by which the vibration amplitudes of a cryopump can be characterized along three coordinate axes. The vibration characterization cannot be made independently of the support system. Therefore, this practice also recommends the configuration of the support system which shall be used.

V.9.2 Definition

The cryopump vibration characteristics, as defined in this practice, are the rms acceleration amplitudes plotted in both the time and the frequency domain. The acceleration shall be referenced to acceleration due to the force of gravity (G's) and shall be plotted in the frequency domain covering a range of $\leqslant 10\%$ of the lowest operating frequency of the cryopump expander to a frequency $\geqslant 500$ Hz.

Time and frequency domain acceleration measurements shall be taken in three coordinate directions as defined later. The time and frequency domain measurements, taken in all three coordinate directions, will yield a total of six acceleration plots.

V.9.3 Test equipment

The free suspension system illustrated in Fig. 8 shall be used for measuring cryopump vibration. As shown in this figure, the helium metal hoses connecting the compressor to the expander shall be plumbed vertically downward to the floor, and in such manner so as to minimize the restriction and damping of the cryopump's horizontal movement.

The suspension arrangement shown in Fig. 8 is characterized by measuring parameters including the cryopump mass, m_t (this includes the cryopump mass, m_p, the cryopump blank-off flange, cryopump roughing valve and accelerometer and associated mounting block), system natural frequency, f_n (in the z and x direction), system spring constant, k, and the system viscous damping coefficient, c. The cryopump blank-off flange shall be of the same thickness as the pump flange, and be constructed of stainless steel. Pump suspension brackets attached to the pump, if used, shall be constructed of an aluminum alloy.

The four system suspension wires shall comprise multistrand, wire-rope cables 3.0–3.5 mm in diam, and of appropriate strength to safely support the apparatus. The suspension cables shall each have a length $\geqslant 0.7$ m, and be free to pivot on each end. The cable pairs, where they attach to each end of the pump, shall be spaced apart a minimum of 100 mm. The cables shall be suspended so that the angle between each cable and any imaginary line parallel to the y axis of Fig. 8 shall be $\leqslant 5°$. The suspension system viscous damping coefficient, c, shall be low enough in magnitude to insure that the displacement amplitude of the system is observed to decay to no less than 10% of its initial value after five (5) consecutive cycles of motion.

Vibration plots generated using this procedure must be accompanied by tabulated values for m_t, f_n (in the z, x, and y directions), k, and c. Data in the y axis direction of Fig. 8 is obtained by rotating the cryopump 90° about the z axis, and using 90° gas line elbows at the cryopump/flex hose connector. Knowledge of these system parameters together with the plots of acceleration rms amplitude totally characterize the amplitude of the cryopump periodic forcing function, $F(t)$.[17]

Methods for measuring or calculating the values of f_n, k, and c are as follows:

The system natural frequency, $f_n \approx (1/2\pi)(g/L)^{1/2}$,

where $g = 9.8$ m/s^2 and L=the length of the wire rope measured to axis of the pump, m.

The value f_n may be more accurately measured by *bumping* the pump along the axis of interest, and measuring the system natural resonant frequency with an accelerometer.

The system *spring* constant, k = the force required to push the pump a small, measured distance off of equilibrium, nt/m.

The system damping constant, $c = c_c \zeta$,

where $c_c = 2(km_t)^{1/2}$ and $\zeta = (1/2\pi)\ln(a_i/a_{i+1})$, where a_i and a_{i+1} are, respectively, successive decaying peak amplitudes of the system as it oscillates at its natural resonant frequency.

The recommended vibration measurement equipment comprises: (1) Fast Fourier transform (FFT) spectrum analyzer capable of measuring acceleration in both the frequency and time domain. The frequency span shall be 0–500 Hz with a band width $\leqslant$1.25 Hz. The measurement scale should be linear with flat-top filtering and rms averaging. Averaging should be carried out with a sample population of about 100 readings. (2) Accelerometer capable of accurately covering a range of $<$1 Hz up to $\geqslant$500 Hz. (3) Accelerometer mounting block which shall be rigidly mounted to the cryopump blank-off flange, as shown in Fig. 8. Mounting studs on this block shall permit measurements to be taken in the x, y, z directions. (4) Accelerometer charge amplifier which matches the accelerometer impedance characteristics and provides the proper signal interfacing for the FFT analyzer.

V.9.4 Test procedure

The cryopump shall be mounted in accordance with Fig. 8. System suspension parameters such as m_t, f_n, k, and c shall be measured and recorded. Conditions A, B, and C of Sec. I.4, apply to this procedure. The cryopump vacuum roughing hose shall be disconnected prior to the start of the vibration analysis. Time and frequency domain rms acceleration measurements shall be taken in the x, y, and z-coordinate directions (total of six acceleration plots). The frequency scan shall cover a range of from $\leqslant$10% of the lowest operating frequency of the cryopump expander to a frequency $\geqslant$500 Hz. As previously discussed, the measurement scale should be linear with flat-top filtering and rms averaging taken on a population of about 100 readings.

V.9.5 Rating

The cryopump vibration rating shall consist of the six rms acceleration plots referenced to 1 G rms. Time and a frequency domain plots shall be recorded for each of the three coordinate directions (x, y, z). The highest amplitude on each plot shall be ~75% of the maximum vertical scale height. Both the vertical acceleration scale (G's rms) and the frequency and time horizontal scales must be clearly marked. A total characterization of the cryopump/suspension system must accompany each vibration plot and shall consist of tabulated values for m_t, f_n (x, y, z directions), k (x, y, z directions), and c (x, y, z directions).

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APPENDIX A: OPERATING CONSIDERATIONS

Operation: A cryopump must be rough pumped prior to operation. Roughing is required to reduce heat transfer to the arrays stemming from gas conduction at high pressures, and to prevent undesirable selective pumping of gases on the second stage sorbent material. Typically, pumps are rough pumped to pressures of 10^{-3}–10^{-2} Torr (0.133–1.33 Pa) prior to starting the refrigerator. However, if high backgrounds of He or H_2 exist in the cryopump it may be necessary to rough-pump the pump to $\sim 10^{-4}$ Torr (0.0133 Pa) prior to starting the refrigerator. For this reason, dry N_2 gas is often released into the pump for the purpose of diluting and aiding in the viscous flow *sweeping out* of gases such as H_2 and He during the regeneration process.

The rough pumping operation also serves to remove contaminants such as water vapor from the second stage sorbent or sieve material. A rate-of-pressure-rise measurement within the cryopump is usually made immediately after regeneration and rough pumping to determine if the rough pumping operation was of sufficient duration.

It is strongly recommended that a valve be used to isolate the cryopump from the system. If an isolation valve is not used during cool-down of the cryopump, it is possible that contaminants resident in the system will be pumped by the second-stage sorbent material. Certain contaminants will result in the *plugging* of this material rendering it useless in the pumping of certain gases. This isolation valve should also be used for reasons related to safety (see Sec. III, SAFETY).

When operating in the very high vacuum region [i.e., $\leqslant 10^{-6}$ Torr (1.33×10^{-4} Pa)], the temperature of the second stage array is usually $\leqslant 14$ K, whereas the temperature of the first stage array will typically be 55–80 K. If the pump is used in a sputtering application (i.e., at higher pressures) the second stage array may operate at temperatures as high as 20 K. A brief increase in second-stage temperature may also occur when opening the pump isolation valve to a chamber which is at a higher pressure than the pump.

Controlling the variations in the temperature of the second-stage array in the range of 12–20 K is important when pumping type-III gases. For example, assume that 150 Torr ℓ (20.0 Pa m^3) of H_2 was pumped per gram of sorbent material (e.g., activated coconut charcoal) on the second stage array, operating at a temperature of 12 K. On closing the pump isolation valve, the resultant H_2 equilibrium pressure in the cryopump would be $\sim 10^{-13}$ Torr (1.33×10^{-11} Pa). If the temperature of the array was thereafter increased to 20 K, the resultant H_2 equilibrium pressure would increase to $>10^{-6}$ Torr ($>1.33 \times 10^{-4}$ Pa). That is, small variations in the temperature of the second stage array of a cryopump can cause large variations in the partial pressure of H_2. Similar considerations apply to He and Ne when pumped on the activated charcoal. The measure of variation in pressure with variation in temperature depends on the type and amount of gas which has been pumped, and the type and amount of sorbent material which is used.

Cryopumps are capture pumps. They retain pumped gases as long as their capacity is not exceeded and the arrays are maintained at appropriate temperatures. Cryopump gas *capacity* is dependent on gas species. When approaching the capacity limit for a specific gas, the cryopump should be *regenerated*.

Regeneration usually consists of warming the cryopump sufficiently to desorb specific gases, and pumping on it with an oil-free or *trapped* auxiliary pump. Use of this auxiliary pump serves to remove gases and vapors that would otherwise plug the sorbent material, or make it impossible to restart the cryopump because of gas thermal conduction losses. A variety of regeneration procedures and equipment are offered by cryopump vendors; some are totally automated. The pump vendor regeneration should be followed in order to achieve optimum pump performance, and assure a safe regeneration process.

Refrigerator system: The refrigerator, as shown in Fig. 1, comprises a helium expander connected to the compressor with helium supply and return lines. The purpose of the compressor is to supply RT, high-purity, high pressure helium to the expander. Portions of the expander operate at very low temperatures. Because of this, if impurities such as the air gases or hydrocarbons exist in the helium stream, they will condense within the expander. If this occurs, the refrigeration capacity of the refrigerator may be severely diminished. For this reason, replaceable filters, called *adsorbers*, are used in the compressor to filter out hydrocarbon contaminants from the helium stream. These filters should be replaced at the time interval recommended by the manufacturer. Air gases (e.g., A, N_2, O_2, etc.) are not effectively filtered out of the He stream by these adsorbers. For this reason, it is important to use high-purity He in the refrigerator, and to make sure that no gas contamination is inadvertently introduced into the He inventory of the refrigerator.

A diminished refrigeration capacity may manifest itself as cyclical changes in the temperature of the second stage cooling station, with a periodicity of perhaps a few hours. Also, a continuous and gradual increase in the temperature of the second stage may occur as contaminants accumulate in time in the expander. Note, also, that the accumulation of contaminants in the expander may be reversible. That is, on warming up the cryopump, say for the purpose of regeneration, these accumulated contaminants may leave the expander and reenter the helium stream. Initial refrigeration performance thereafter may be totally acceptable (i.e., low second stage temperatures may again be achieved). However, if the gas contaminants remain in the He inventory, the refrigeration deterioration process will be repeated as gas contaminants again accumulate in the expander.

Gas interactions: Cryopump performance, when simultaneously or sequentially cryopumping different gas species, can be difficult to characterize. Physical pumping processes are varied, and can be somewhat complex. For this reason vendor performance ratings relating to the sequential or simultaneous pumping of more than one gas species are a rarity.

Gases are classified based on physical processes by which they are pumped in significant amounts by the cryopump. Since the cryopumping of gas is both temperature and surface area dependent, the types of gases are distinguished based on the three regions of the cryopump arrays onto which they are predominantly pumped. For example, *Type-I* gases (e.g., H_2O, CO_2, etc.) are those gases which are cryocondensed on the first stage pumping array. *Type-II* gases (e.g., N_2, O_2, CO, Ar, etc.) are cryocondensed on the second stage array. *Type-III* gases, including He, H_2, and Ne, are cryosorption pumped on the sorbent material bonded to the second stage array.

The accumulation of gas *frost* on pumping arrays can result in either an increase or decrease in pump speed. For example, *frost* may buildup on the first stage chevron (inlet) array to the extent of impeding the flow of type-II and type-III gases into the pump. Type-II gases accumulating on the second-stage array may increase the effective surface area of this array, and thus the pumping speed of this array for type-II gases. Conversely, the buildup of type-II gases on the second stage array may impede the passage of type-III gas to the sorbent material to the extent of reducing pump speed for the type-III gases. Last, the pumping of type-II gases on the second stage sorbent material may *plug* the sorbent material and render it ineffective in the pumping of type-III gases. Therefore, the effectiveness with which the sorbent material is shielded from type-II gases is important in the characterization of a cryopump. One of these recommended practices is directed at quantitatively assessing the effectiveness of this adsorbent *shielding* from type-II gases.

There are both cause and effect relationships between gases and surface temperatures of a cryopump. For example, pumping a small amount of H_2O on the first stage inlet array will result in an increase in the spectral emissivity of this panel to ~0.9. A higher spectral emissivity implies that the cold surfaces will more readily absorb thermal radiation. Should sources of thermal radiation be significant, this could result in an increase in the temperature of the first stage array, and result in an increase in the temperature of the second stage array. This could cause a decrease in the effectiveness of the second stage array in the pumping of type-III gases.

Coast time: Coast time is the elapsed time between when the refrigerator is turned off, with the pump equilibrated at some minimum temperature, and when the second stage array reaches a temperature of 20 K. The duration of coast time will vary significantly depending on the amount of gas pumped on the second stage array. Accumulated type-II gases will not be liberated in significant amounts at temperatures $\leqslant 20$ K. Therefore, the specific heat of the added mass of type-II gases on the second stage array will result in increased coast times.

However, as previously noted, slight increases in the temperature of the second stage sorbent material can cause significant amounts of type-III gases to be liberated. If the pressure of type-III gas is sufficiently high to cause thermal conduction losses to the arrays, there will be an acceleration in the rate at which the second stage temperature increases. Because of this effect, accumulated type-III gases will generally decrease coast times.

Magnetic fields: High magnetic fields can cause most cryopump expander drive motors to stall, and adversely affect expander operation. Magnetic fields can also adversely effect some compressor control components. Expander drive motors that have permanent magnets can be operated in high dc magnetic fields if the external field reinforces rather than opposes that of the permanent magnet magnetic field. Magnetic fields of the order of 0.1 T may permanently demagnetize the rotor of a permanent magnet motor.

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