In an alternative leak testing procedure, the sealed enclosure can be evacuated and allowed to reach pressure equilibrium with its vacuum pumps. The rate at which gas is being pumped to maintain this equilibrium is then measured to determine the rate of leakage from the test volume into the enclosure.

Pressurized Systems

In an alternative pumping technique for measuring leakage rates, the test volume can be pressurized and the compressor is then operated only sufficiently to keep the test system pressure constant. The leakage rate can then be calculated from the volumetric pumping speed (m^3/s) and the length of time the compressor must operate to regain a predetermined system pressure.

SENSITIVITY OF FLOW MEASUREMENT

The sensitivity of leakage rate testing by flow measurements is relatively low, compared to the sensitivity of many other leak testing techniques described in this volume. In most cases, the leakage sensitivity depends on that of the instrument used to measure the flow rate and is relatively independent of the test system volume. In a flow observation technique, leakage rates between 10^{-3} and 10^{-5} $Pa \cdot m^3 \cdot s^{-1}$ (10^{-2} and 10^{-4} std cm^3/s) can be detected, depending on the flow instrument used. If a sealed system is being evacuated, flow rates of the order of 0.1 $Pa \cdot m^3 \cdot s^{-1}$ (1 std cm^3/s) may be observed. (Note that 1 $Pa \cdot m^3 \cdot s^{-1}$ is equivalent to 10 std cm^3/s.)

The leakage sensitivity attainable with the pumping pressure analysis technique depends on the size (pumping speed) of the pumps. With evacuated test objects or test systems, leakage sensitivity depends critically on the outgassing within the system being measured.

ADVANTAGES AND LIMITATIONS OF FLOW MEASUREMENT

Flow measurement leak testing procedures are applicable to a large variety of test systems. The procedures are useful only for measurement of leakage. They are not appropriate for locating leaks. They are used to measure total leakage rates in small sealed parts. They can be used to measure total leakage rates in large sealed systems and in systems that can be pressurized or evacuated. The major advantages of leak testing by means of flow measurements are as follows.

1. No special tracer gas is necessary. The flow measurement leak testing procedure is applicable to whatever fluid is present within the system to be tested. The test system need not be placed in any special environment for leak testing. Instead, systems may be tested in their normal operating modes.
2. The cost of the equipment for flow measurement leak testing is relatively low.
3. The sensitivity of overall leakage measurement is independent of system volume.
4. The leakage rate can be measured without extensive calibration. However, the accuracy of leakage measurement is not as high, as compared with that for many other techniques.
5. When calibration is required, it can be readily attained with standard flow or volume measurement equipment.

There are two major disadvantages of flow measurement leak testing.

1. The test sensitivity is low when compared to other leak testing techniques.
2. Flow measurement procedures have not gained wide recognition outside of industrial process control applications.

Flow measurement uses various types of equipment with little similarity and different techniques are used to solve individual leak testing problems.

FLOW MEASUREMENT OF SEALED VOLUME

Figure 29 shows the arrangement of leak testing equipment using the most common technique of flow measurement by observation of the movement of fluid in a glass capillary tube. The system under test is enclosed and sealed within the test enclosure. The system being tested can be either evacuated or pressurized. It can either be sealed or connected to a source of pressure or of vacuum.

Care must be taken to ensure that the leakage being measured is not occurring in the connection to the source of pressure or vacuum. The capillary containing the indicating fluid is attached to the test enclosure. This type of testing can be performed with the capillary fluid indicator connected between the test enclosure and a standard testing volume on the other end of the capillary. In this way, the leak test can be compensated for temperature variations, if both test enclosure and the comparison volume are subject to the same temperature conditions. Alternatively, the capillary can be connected between the test enclosure and the atmosphere. For accurate leakage measurements and rapid response, the enclosure containing the system under test should have a net volume as small as practical.

One advantage in the construction of the sealed volume type of leak testing equipment shown in Figure 29 is that there are no critical, leaktight connections within the enclosure. This is because the system is operating at atmospheric pressure. Therefore, although it is possible that a leak could exist between the enclosure and the atmosphere, leakage does not occur through this leak because no pressure differential is applied across it. Any differences in pressure are compensated for by the pressure transmission through the liquid slug within the interconnecting capillary tube.

Glass Capillary (Pipette) Tubes

Glass capillary tubes containing a slug of indicating fluid provide a means for direct quantitative measurement of leakage rates if a record is made of the time required for the small liquid plug to move a given distance. Because the cross sectional area of the capillary bore is known, the volume swept out by the liquid plug during the measured time interval can be computed. A 1.5 mm (0.06 in.) diameter glass capillary tube is used to measure leakage rates in the range from 10^{-3} to 10^{-1} Pa·m^3·s^{-1} (10^{-2} to 10^0 std cm^3/s). A 0.5 mm (0.02 in.) glass capillary tube can be used to measure smaller leakage rates from 10^{-5} to 10^{-3} Pa·m^3·s^{-1} (10^{-4} to 10^{-2} std cm^3/s). These capillary tubes are marked with scales given in convenient units for computing leakage rates. A stopwatch is commonly used for timing the movements of the liquid plug within the capillary tube. Pipettes used for liquid measurements provide convenient calibrated capillary tubes.

The upper limit on leakage rates measurable with capillary tubes is reached when the liquid plug moves so fast that timing is difficult. The lower limit on leakage rate measurement is determined by the accuracy desired and is influenced by errors introduced by the resistive and inertial forces affecting the movement of the liquid plug within the capillary tube. Changes in atmospheric pressure (barometric readings) may move the liquid slug in capillary systems with one end open to the earth's atmosphere. As the speed of movement of the liquid plug decreases, these errors are increased. This causes the leakage measurements to become more inaccurate with slow movements of the liquid plug.

Errors due to starting inertia are decreased with liquids of lower density. Errors can be reduced, for example, by using a water plug about 1 mm (0.04 in.) long and timing the movement of the water plug only after it reaches a constant velocity. If a water plug is used, the error due to the resistive forces of surface tension can be minimized by coating the inside (bore) surface of the clean capillary tubing with an organosilicon compound. This coating acts to prevent the water from wetting the glass.

Mercury is almost impossible to use for the liquid slug in a glass capillary. Mercury has a very high surface tension and it is almost impossible to force it into a very small diameter capillary tube bore. However, there should be negligible gas transfer through a mercury plug.

An ideal fluid for the indicator plug in a glass capillary should have the following characteristics.

1. It should be a fluid in which the leaking gas is not soluble, so that no gas transfer by diffusion can occur through it.
2. The fluid should not wet the walls of the tube, so that the surface tension forces on either end of the plug are balanced.
3. The fluid should be opaque for easy visibility and measurement of its position.
4. The fluid should have a low surface tension so that it can be placed easily within the bore of the capillary tube.

OTHER FLOW MEASUREMENT INSTRUMENTS IN SEALED VOLUMES

The basic principles of sealed volume leak testing can be used in numerous ways. For large leaks, flow measuring devices such as a wet type gas meter or a rotameter may be used. These instruments produce accurate leakage rate measurements but are useful only on very large leaks. For measurements over a wide range of leakage rates, the instrument shown in Figure 30 can form a U tube capable of withstanding extremely high pressures. Tubes B and C have different diameters so that the proper tube can be selected for measuring various leakage rates.

When all the valves in Figure 30 are open and the test components are pressurized, the liquid columns all reach the same height. By closing the shutoff valve in the main line between columns A and B, leakage is indicated by upward movement of fluid in columns B or C. The meter in Figure 30 was designed primarily for determining leakage rates in hydraulic power systems. The principle of operations is to displace the leaking fluid with the indicating fluid. This can be done because there is a pressure loss in the leaking component. When the meter of Figure 30 is installed in the hydraulic power line to the component being tested, leakage can be measured by the displacement of the separation level between the two different liquids in column A as compared with column B or C.

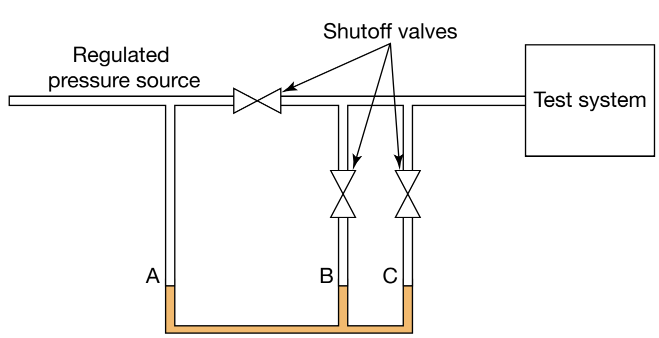


Figure 30. Connection of delta-vee U tube manometer for leakage measurements, with tubes (A, B, C) of different diameters.

In another type of flow meter, leakage flow in the line between meter and component under test is measured by the displacement of a bellows. The deflection of the pressure difference sensing bellows system varies the setting of a potentiometer. An output electrical signal from the potentiometer indicates leakage directly in volume units. This bellows system replaces the observation of movements of a liquid slug in a capillary tube. Each of the preceding types of flow meter will work with liquids as well as with gases, provided that the indicating liquid slug is immiscible in the fluid whose leakage is being measured. This versatility makes the sealed volume leak testing techniques extremely useful for leak testing under operational conditions.

FAST RESPONSE THERMAL MASS FLOW METER

In the twentieth century, thermal mass flow meters comprising a sensor, electronic circuitry, and a shunt measured gas flow rate from 0 to 60 $Pa{\cdot}m^3{\cdot}s^{-1}$ (0 to 600 std cm^3/s). The shunt caused the flow to divide such that the flow through the sensor was a precise percentage of the flow through the shunt. The circuit board amplified the sensor output linearly to a 0 to 5 V direct current signal proportional to the flow rate. A thermal sensor measured flow through a capillary tube. This flow was a fixed percentage of the total flow through the instrument. This sensor developed an essentially linear output signal proportional to flow. This signal was amplified by the meter circuitry and was routed to interface terminals and to decoding circuitry in the display. A metal capillary tube is heated uniformly by current from the transformer. The fast response of this instrument (typically a few seconds to a few minutes based on gas type) at very low rates of air flow allowed for fast, accurate leak testing by manual or automatic means. Table 14 lists multiplication factors for the air scale meter indications when this flow meter is used for gases other than air.

In the twenty-first century, thermal mass flow meters (Figure 31a) have a similar principle of operation, but a constant temperature platform uses a dual heating system to the metal capillary (Figure 31b). These dual heater windings serve as

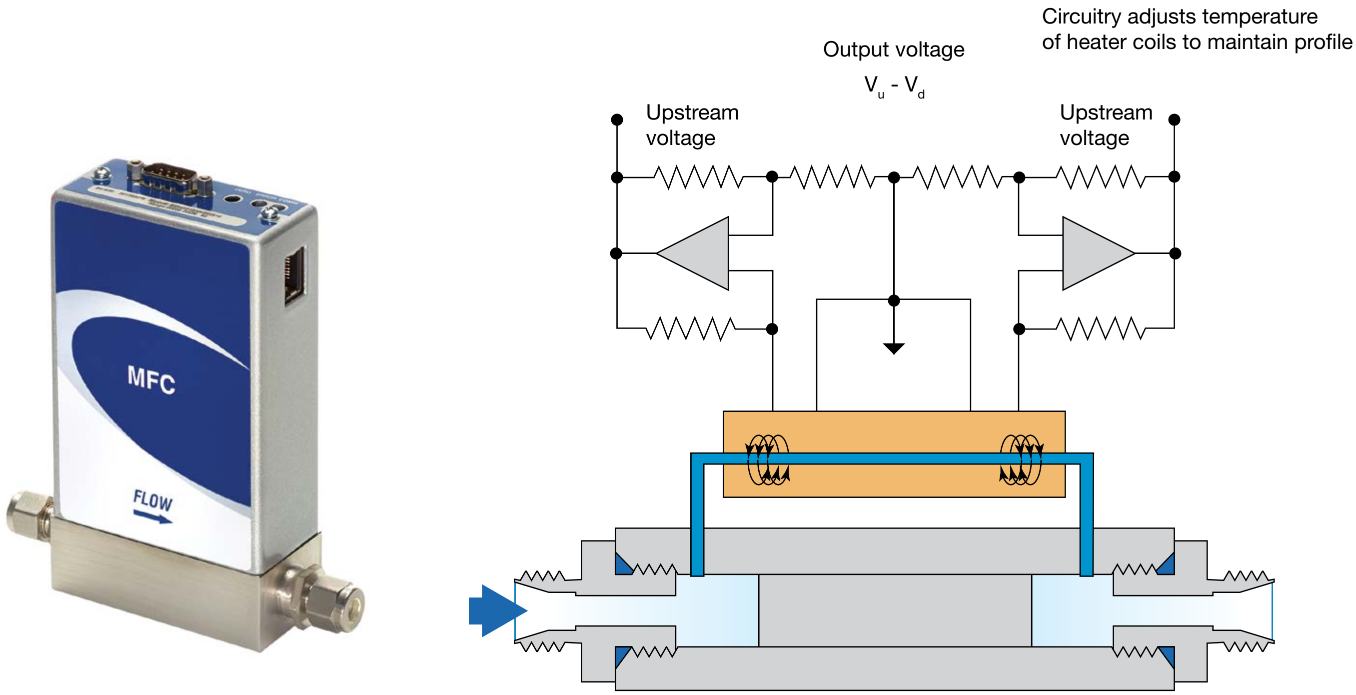
Table 14. Multiplication factors for different gases of mass flow meter air scale.[a]

Gas	Symbol	Conversion Factor[b]	Density[c] (g/L)	Relative Specific Gravity[d]	Gas	Symbol	Conversion Factor[b]	Density[c] (g/L)	Relative Specific Gravity[d]
Acetylene	C_2H_2	0.67	1.09	0.90	Krypton	Kr	1.39	3.49	2.90
Air		1.00[e]	1.20	1.00	Methane	CH_4	0.69[e]	0.68	0.56
Ammonia	NH_3	0.77	0.71	0.59	Neon	Ne	1.38	0.84	0.70
Argon	A	1.43[e]	1.66	1.38	Nitric oxide	NO	1.00	1.24	1.03
Arsine	AsH_3	0.76	3.25	2.70	Nitrogen	N_2	1.02[e]	1.17	0.97
Bromine	Br_2	0.88	5.98	4.96	Nitrous oxide	N_2O	0.75	1.85	1.54
Butane	C_4H_{10}	0.30	2.51	2.08	Oxygen	O_2	0.97[e]	1.33	1.10
Butene 1	C_4H_8	0.34	2.40	1.99	Pentaborane	B_5H_9	0.15	2.83	2.35
Carbon dioxide	CO_2	0.73[e]	1.84	1.53	n-Pentane	C_5H_{12}	0.22	3.18	2.64
Carbon monoxide	CO	1.00[e]	1.17	0.97	Phosphine	PH_3	0.79	1.53	1.27
Chlorine	Cl_2	0.85	2.98	2.47	Propane	C_3H_8	0.32[e]	1.89	1.57
Chlorine trifluoride	ClF_3	0.45	3.78	3.14	Refrigerant-11	CCl_3F	0.36	5.93	4.92
Cyclopropane	C_3H_6	0.52	1.75	1.45	Refrigerant-12	CCl_2F	0.36[e]	5.13	4.26
Diborane	B_2H_6	0.50	1.15	0.95	Refrigerant-13	$CClF_3$	0.42	4.59	3.81
Ethane	C_2H_6	0.56	1.26	1.05	Refrigerant-14	CF_4	0.48	3.65	3.04
Ethene (ethylene)	C_2H_4	0.69	1.17	0.97	Refrigerant-22	$CHClF_2$	0.43[e]	3.65	3.03
Ethylene oxide	C_2H_4O	0.60	1.79	1.49	Refrigerant-114	$CClF_2$	0.22[e]	6.99	5.80
Fluorine	F_2	0.93	1.58	1.31	Silane	SiH_4	0.68	1.33	1.10
Helium	He	1.43[e]	0.17	0.14	Sulfur dioxide	SO_2	0.70	2.72	2.26
Hydrogen	H_2	1.03[e]	0.08	0.07	Sulfur hexafluoride	SF_6	0.28	6.43	5.34
Hydrogen chloride	HCl	1.01	1.48	1.23	Tungsten hexafluoride	WF_6	0.23	8.22	6.82
Hydrogen fluoride	HF	1.00	1.53	1.27	Uranium hexafluoride	UF_6	0.23	14.65	12.16
Hydrogen sulfide	H_2S	0.85	1.43	1.19	Water vapor	H_2O	0.80	0.76	0.63
Isobutane	C_4H_{10}	0.31	2.48	2.06	Xenon	Xe	1.37	5.54	4.60

a. No corrections or compensations for temperature or pressure of gas required.
b. Multiply air scale by these conversion factors.
c. Density in grams per liter at 20 °C (70 °F) and 100 kPa (1 atm).
d. Specific gravity (air = 1.00).
e. Empirical data; other data is theoretical. Example: Flow meter NALL-1K, 0–1000 std cm^3/s in air would be 1000 × 1.43 = 1430 std cm^3/s at full scale in helium.

both heat and sensor elements, with the voltage to the heaters adjusted (by the onboard electronics) as the flow conditions change to keep the temperature profile constant. The output sensor is nonlinear, therefore onboard electronics are required to linearize the output. This results in extremely fast response of these new instruments (typically in the tens of milliseconds time frame) which again, results in fast, accurate leak testing by manual or automated means. These flow meter instruments with the applicable controllers give flexibility for both this leak test technique and the leak test technician.

The internal heating windings develop electromotive force outputs that establish and maintain the constant temperature for the device. When air or gas flows through the tubing, heat is transferred to the gas and back again, creating a uniform temperature distribution. For constant temperature input to the tube, the heater windings output voltage is a function of the mass flow rate and heat capacity of the gas. Changes in gas



(a) (b)

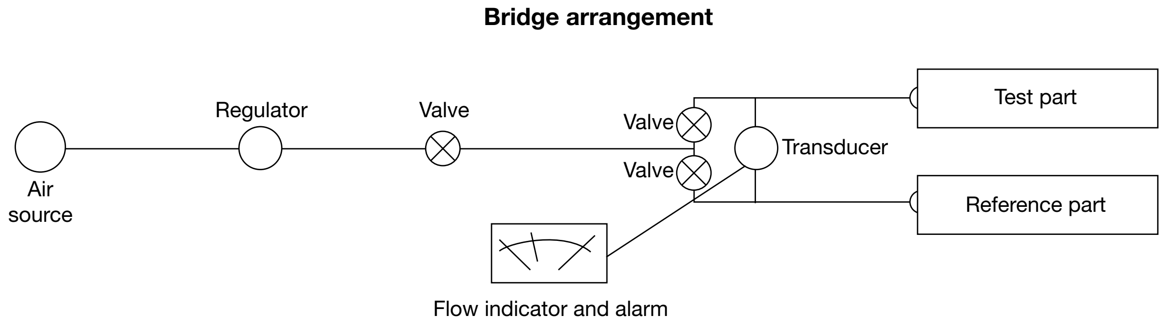
Figure 31. Thermal mass flow meters: (a) photograph; (b) principle of operation.

composition requires only a simple multiplier of the air calibration to account for the differences in heat capacity; alternatively, depending on the controller used, the leak test technician can change the gas composition via on board software. The flow meter can be used for a wide variety of gases during leakage rate testing. The full scale flow through the flow meter is about 1 $Pa \cdot m^3 \cdot s^{-1}$ (10 std cm^3/s). For higher flow rates some mass flow meters have bypass elements that allow the range to be extended to a much higher mass flow rate. The bypass element is a dimensionally similar channel which allows for maintaining laminar flow. The sensor in the mass flow meter will measure the total flow as the splitting ratio is constant.

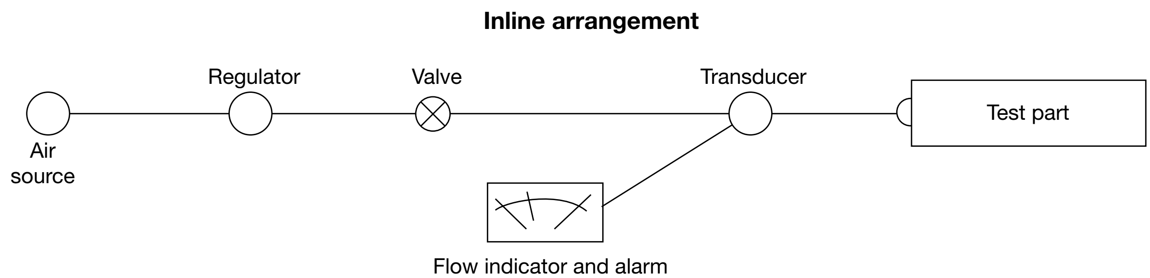
Figure 32 shows typical arrangements for leak testing of small items. Figure 32a shows a pneumatic bridge arrangement. The object to be tested and an identical, leaktight test object used as a reference volume are charged with air at pressures up to 135 kPa (20 $lb_f/in.^2$) gauge. The effects of adiabatic heating or cooling of the air during the pressurizing cycle should be avoided. The flow meter is then connected between the unknown and reference test objects to detect any evidence of leakage (which would allow the pressure to decrease in the object under test). Because the adiabatic effects are nearly identical in the reference and the test objects, the thermopile flow meter quickly detects the leakage rate without requiring a waiting period for attainment of full equilibrium in temperatures and pressures. Leakage testing may also be done by a direct inline leak testing procedure, as sketched in Figure 32b, but this test procedure requires a longer time cycle than the differential flow measurement technique.

ORIFICE FLOW DETECTOR WITH DIFFERENTIAL PRESSURE TRANSDUCER

Figure 33a shows a leakage test instrument system that uses an orifice to convert flow across the orifice element into a pressure differential sensed by the differential capacitance sensor (see also Figure 15). The orifice (which produces a pressure

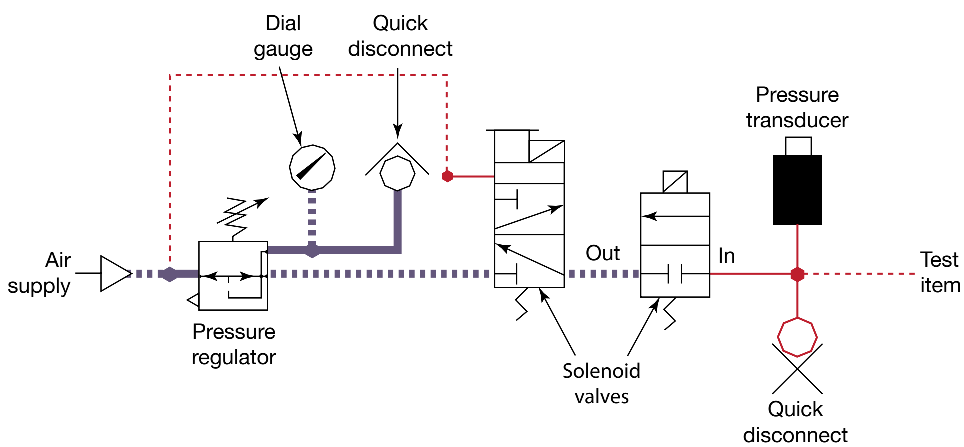


(a)



(b)

Figure 32. Arrangements for leak testing with thermopile air flow meter: (a) pneumatic bridge leakage testing arrangement with thermopile flow meter arranged to measure difference in pressure between test object and identical leaktight object (reference volume); (b) inline leakage testing arrangement in which test part is pressurized, line valve is closed, and leakage is indicated by pressure drop in flow meter sensing element.



(a) (b)

Figure 33. Air flow meter with orifice and differential pressure transducer: (a) photograph; (b) pneumatic circuit.

loss when air flows through it) is connected in series with the air supply line to the item under (Figure 33). This system is used with automatic flow and leakage testers providing fully automatic cycling and accept/reject test indicators and output signals. Leakage sensitivity and stabilization time are both programmable.

A compensation network provides a programmed electronic time base signal to match the dynamic characteristics of short time cycle flow measurements of instantaneous flow rate. Figure 33a shows a microprocessor based air flow calibrator incorporating a differential pressure sensor, a precision thermistor, an absolute barometric pressure sensor, and a precision machined venturi tube.

Electronic Flow Monitoring of Leakage Rate

Figure 34 shows a portable, digital electronic flow meter designed for fast, accurate indication of leakage rates of pressurized components such as valves, O-ring seals, pressure vessels, holding tanks, tank cars, and processing vessels. Its accuracy is from 0.4 to 0.8 of its reading with 0.2 percent full scale repeatability and a linear range is from 0.5 to 100 percent of full scale.

VACUUM PUMPING WITH FLOW MEASUREMENT

If the test system can be safely evacuated, leakage can be measured directly by means of flow meter with vacuum pumping arrangement sketched in Figure 35. The system under test is evacuated through an opened isolation valve connected to the vacuum pump inlet. The exhaust gases from the vacuum pump go through a surge tank to the flow meter. A bypassing valve around the pump provides an alternative path between the isolation valve and the surge tank. Before performing the leak test, the vacuum pumping system leak tightness is first determined by closing the isolation valve and measuring the rate of gas flow through the flow meter. If this flow is negligible, the isolation valve is then opened and the flow meter readings are taken only after an equilibrium (constant flow rate) condition has been achieved.

The vacuum pressure in the system under test is adjusted by means of the bypass valve, which controls the backflow of gas from the exhaust port of the vacuum pump to its inlet port. The lower limit of vacuum pressure for which the vacuum pumping leak analysis technique is useful is in the range of 3 kPa (25 torr). The lower limit of leak testing sensitivity is about 0.1 $Pa \cdot m^3 \cdot s^{-1}$ (1 std $cm^3 \cdot s^{-1}$)

Figure 34. Portable digital electronic flow meter for monitoring leakage rates in pressurized systems.

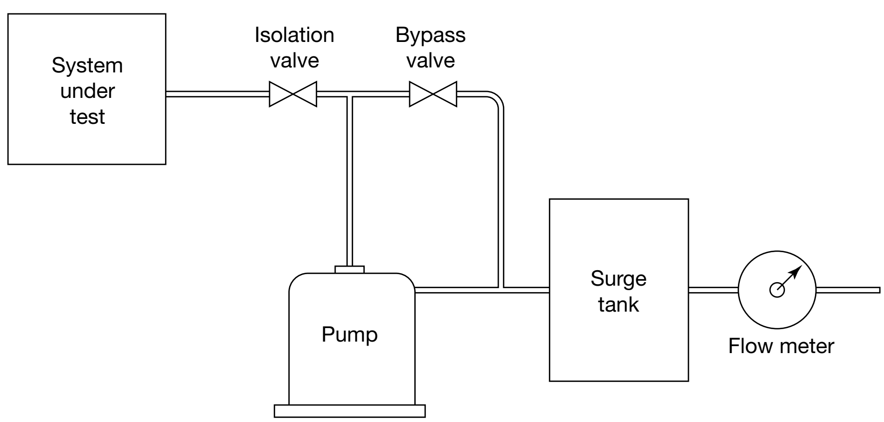


Figure 35. Arrangement for vacuum pumping technique of leakage measurement with flow meter.

and is mainly dependent on the availability of suitable flow meters for the vacuum pressure range used during the leak test.

FLOW METER LEAK TESTING OF SEALED VOLUME NUCLEAR CONTAINMENT SYSTEMS

Sealed volume leak testing techniques are also used on large volume systems such as nuclear containment systems. For this application, this procedure is commonly called a verification test. Its purpose is to verify the accuracy of the leakage test results and instrumentation used in that test. It also verifies the validity of the dewpoint and temperature sensor locations within the containment structure. Flow meters used in these large scale leakage rate tests include thermal mass flow sensors, rotameters, and integrating gas flow meters usually with ranges of 25 to 700 $Pa{\cdot}m^3{\cdot}s^{-1}$ (0.5 to 15 std $ft^3{\cdot}min^{-1}$). These flow meters are usually designed for the planned leak testing conditions, and they produce readouts compensated to standard pressure and temperature conditions. The accuracy of the flow meter must be commensurate with the accuracy of the leakage rate test instrumentation and also with the accuracy required in the containment leakage rate test results.

Procedures for Flow Meter Verification Test of Nuclear Containment Systems

The verification test is normally performed as the last phase of a containment test. It follows the test for the system measured leakage rate Q_{am} (usually given as a percentage of air mass lost in 24 h). The flow meter is installed in the system with a valve to isolate it from the system under test. The verification test may be performed by measuring either the out-leakage or the in-leakage that passes through the flow meter. For either technique, a meter valve is placed downstream from the direction of leakage flow through the flow meter, to minimize the pressure loss across the flow meter. After opening the isolation valve between the test system and the flow meter, this metering valve is adjusted to produce a leakage flow through the flow meter from (or into) the test system that is some required percentage (usually 75 to 125 percent) of the allowable leakage rate Q_a for the system under test.

The leakage rate test of the containment is then continued. After a period of 4 to 6 h with a minimum of ten sets of data, the combined leakage rate Q_c of the containment system and flow meter and the leakage rate Q_0 of the flow meter are determined using the flow meter readings. The difference between these two leakage rates is $Q_c - Q_0 = Q'_{am}$. This difference Q'_{am} in reading is then compared to the leakage rate Q_{am} measured previously on the containment test system alone, before the inflow or outflow of air from the containment through the flow meter. The two values must agree with 25 percent of the measured containment leakage rate Q_{am}. This is to say that $Q_{am} - Q_{am}$ must be equal to or smaller than 0.25 Q_{am}.

THERMAL METERS FOR ACCURATE MASS FLOW RATE

The containment verification test just described requires a mass flow meter that measures the mass of gas that passes through it. Figure 31a shows a mass flow sensor element which does not require temperature or pressure compensation and provides ±1 percent of full scale accuracy and linearity along with 0.01 percent full scale resolution. The sensor unit has a stainless steel flow tube with other alloys available based on operating environment. These thermal mass flow meters operate on the constant temperature platform. Signals can be used for measuring, recording, or controlling gas flow rates with valves and an automatic controller. Sensors for specific gases such as air, nitrogen, hydrogen, oxygen, and helium are available or as discussed previously. Depending on the controller used, the leak test technician can change the gas composition via on board software with ranges from 0 to 0.015 up to 0 to 10 $Pa{\cdot}m^3{\cdot}s^{-1}$ (0 to 10 up to 0 to 5 × 10^3 std cm^3/min). Repeatability of indications is claimed as ±0.2 percent of full scale. Output signals from the thermal mass flow sensors of Figure 36 can actuate indicating meters or provide 0 to 5 V direct current signals that can be transmitted up to 300 m (1000 ft) to recording instruments, digital indicators, or controllers.

Figure 36. Thermal mass flow meter with true mass flow sensor for measuring gas flow rates accurately.

FLOW METERS TO LOCATE LEAKS IN GAS FILLED ELECTRIC CABLES

Electric utility companies have used a U tube manometer equipped with appropriate valving as a flow meter for locating gas leaks in gas pressurized electric power cable sheaths. When the manometer is installed in a segment of the pressurized gas filled cable sheathing, oil will rise in the glass tube of the manometer, on the side closer to the leak. In this test, the manometer measures the pressure loss in the segment of cable across which it is connected, when gas flows toward the leak.

LEAK TESTING

of Vacuum Systems

CONTENTS

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