Wet-Aerosol Leakage through Simulated Containment Leak Paths

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ABSTRACT

Some types of postulated accidents in a nuclear reactor can result in the formation of radioactive wet aerosols in containment and their subsequent release into the environment. Wet-aerosol leakage was investigated using simulated leak paths for isolation damper valves and airlock door seals. Leakage was calculated from measured uranine concentrations deposited on high-quality filters positioned downstream of the simulated leak paths. Test results indicated that a small fraction of wet aerosols leaked through the simulated isolation damper valves, whereas a large fraction leaked through the simulated airlock door seals. Data on wet-aerosol leakage through containment leak paths are needed to develop and validate models in safety analysis codes.

1. INTRODUCTION

During some postulated accidents involving a break in the primary heat transport system (PHTS) of a reactor, a high-energy jet of hot water can discharge from the break into containment. As the jet undergoes a rapid de-pressurization inside the containment, it finally atomises into a mist of steam (water-droplet aerosols and water vapour) that spreads to the large free volume due to air circulation and turbulence inside the containment building. The relatively cool atmosphere inside the building condenses the vapour into more water-droplet aerosols.

These types of accidents can result in the release of significant amounts of radioactivity from the reactor core into the containment building. The water-droplet aerosols could be the carriers of dissolved fission products or radionuclides released from the reactor core (or fuel) [1], and may remain suspended in the containment air for an extended period of time. The released activity can consist of a combination of fission products, activation products and actinides, and these can be released in the form of gases, vapours, water-solvated species or aerosols. Aerosols may contain either dissolved activity or embedded insoluble particles.

In the worst-case scenario of a prolonged discharge from the break, pressure inside the containment building can increase and force the aerosols carrying fission products to leak through various leak paths of the building. If the water droplets remain suspended for an extended period of time, a significant quantity of fission products can potentially leak out of containment. Estimating the release rate of these droplets from containment will allow to make more realistic predictions of public radiation dose. On the other hand, if the size of aerosols is large, more aerosols will tend to deposit inside the containment due to agglomeration and settling, and some may even get trapped inside the containment leak paths.

The current safety-analysis methodology for assessing public radiation dose assumes that gases, but not aerosols, leak from an isolated containment. Preliminary experiments performed at

AECL with simulated containment leak paths indicated aerosols leakage through some components of airlock door seals and isolation damper valves. Therefore tests with more representative leak paths are needed in support of the preliminary findings. Other possible containment leakage routes include concrete penetration gaps, concrete joints, cracks and pores. A realistic estimate of aerosol leakage is essential for the analysis of station post-accident habitability by reducing the conservatism in the currently used assumption of no aerosol leakage from some types of containment buildings.

Most published work reported results on aerosol deposition rather leakage. Leakage of aerosols is the amount remaining after deposition on the wall of a leak path. Tests were performed [2, 3] for the deposition of water droplet aerosols of 27- to 40-micron size on the surface of tubular and rectangular ducts to study the phenomena associated with aerosol transport; the water droplets were suspended in air flowing at 25 to 90 m/s and the hydraulic diameter of the ducts ranged from 1.7 to 4.7 cm. The investigators suggested that the turbulence in the air stream as well as the droplet concentration strongly affected the deposition on the wall. Deposition of dioctyl-phthalate (DOP) aerosols of 2 to 25 micron size was studied in 1.68-cm diameter vertical and horizontal tubes connected through bends at flow velocities ranging from 0.5 to 5 m/s [4]. Deposition on the horizontal tubes dominates at low velocities and deposition at bends dominates at high velocities. Study [5, 6] of olive-oil aerosol deposition on the surfaces of glass and copper tubes show that deposition increased with increasing aerosol size (high inertia) and turbulence in the air stream. The aerosols had a size range of 2 to 21 micron with flow velocity ranging from 12 to 62 m/s.

Ongoing deposition of aerosols in leak paths results in decreased leakage and the eventual plugging of some leak paths. Studies [7] showed some evidence of plugging of containment leak paths by deposited aerosols, and most reviewed work dealt with dry aerosols or solid particles. Wet aerosols are expected to block porous concrete such that it becomes impervious to further aerosol and gas flows. Some large-scale leakage experiments showed that concrete pores were quickly plugged when steam was introduced into containment, and the cessation of leakage was attributed to the plugging of leak paths by steam condensate [8].

The published work reveals no information on the transport of wet aerosols through potential leak paths in containment (although information is available for dry aerosol leakage from some types of containment buildings). As containment pressure builds up after a postulated accident, the flow through the constricted portion of certain leak paths can attain choked conditions, i.e., flow velocity reaching 340 m/s. It has been postulated that at very high velocity, the turbulent deposition would strongly influence aerosol deposition on the wall [2], and thus leakage through these paths. The leak rate for various paths used for the current study of some reactors is equal to the Test Acceptance Leakage Rate at Commissioning (0.5% of containment volume per day at the specified design pressure). This paper describes the experimental study of wet aerosol leakage through simulated isolation damper valves and airlock door seals at conditions relevant to post-accident containment. The data maybe used to develop and validate models for safety analysis codes for aerosol leakage through containment leak paths.

2. CONTAINMENT LEAK PATHS

Containment buildings are designed to achieve a high degree of leak tightness. The inner surfaces of the exterior walls are coated with an epoxy liner to minimize leakage through the concrete. Despite this, the barrier provided by the outer walls and liners are breached at various locations by airlocks, by sealed penetrations carrying process, control piping and electrical wiring, and by ventilation and spent-fuel discharge systems. These structural discontinuities constitute a set of potential leak paths that could allow the post-accident fission products to escape from the containment building. Leak paths past airlock door seals and isolation damper valves have relatively short path lengths and low flow resistance compared to leak paths in containment concrete. Consequently, a differential pressure of 124 kPa(g) that could occur in the early stages of a loss-of-coolant accident (LOCA) can result in leakage at choked-flow condition. The flow velocity through any leak path at choked condition can attain the speed of sound.

Leak paths past airlock door seals and isolation damper valves are characterised by abrupt changes in cross-sectional area, high flow velocities and relatively short path lengths. The abrupt changes and high velocities within the leak paths suggest that the entrance and inertial effects will be of definite importance for the deposition and leakage of aerosols on these paths. The short leak paths also represent the least available surface area for aerosol deposition, and thus allowing more aerosols to leak out.

2.1 Isolation Damper Valves

The ventilation ducts in a containment building contain redundant pairs of isolation damper valves that isolate the containment in the event of activity release from the reactor. Each damper consists of a carbon-steel butterfly valve that sits on a carbon-steel flange (Figure 1). A new damper valve seals reasonably well, but its continued usage results in the gradual development of leakage between the valve and the flange. Preliminary calculations suggest that these isolation damper valves pose the greatest concern for potential aerosol leakage. The concern arises from two factors; namely, 1) no data for wet aerosol penetration through the leak paths and 2) the lack of validated models to estimate the retention of micron- and submicron-sized aerosol particles.

The representative damper valve repair information was used to derive the maximum effective opening sizes for different leak rates. The resulting reference diameters for the leak paths range from 0.029 to 0.15 cm (depending on the type of damper valve) and a leak path length of 6 cm. Although the actual leak paths have more complex geometry, simulating leak paths as cylindrical holes will be conservative for aerosol leakage.

2.2 Airlock Door Seals

Some containment building contains two airlocks that penetrate the containment boundary. Each airlock consists of a cylindrical shell with doors at either end. A pair of inflatable tubes seals the air gap between the doorframe and the door (Figure 2). Pressurization tests at the Gentilly-2 (G2) Nuclear Generating Station indicate that leakage past the door seals is the primary contributor to the overall leakage. The present work assumes that all the airlock leakage occurs past the inflatable seals. The cross-sectional areas of openings past door seals are based on effective opening areas calculated for G2 airlock door seals from the pressurization tests.

An action plan for the repair or replacement of airlock door seals was developed based on the results of inter-seal pressurization tests. The opening sizes, and the corresponding adjusted leak diameter identified in the plan, represent the maximum leak size that can develop before an airlock seal is repaired or replaced. A cylindrical tube was assumed while deriving the size of the leak path. Actual leak paths generally have more complex geometries; however, modelling leaks past airlock seals as right cylindrical holes will be conservative for aerosol leakage. Containment leakage past airlock-door seals is assumed to occur through circular holes of 0.6-cm long with diameters of 0.016 to 0.029 cm.

3. SIMULATION OF CONTAINMENT LEAK PATHS

Test section design for leakage simulation involved experimental leak paths that were representative of actual isolation damper valve and airlock door seal leak paths. Aerosol leakage past these leak paths is assumed to occur under choked-flow conditions at the constricted portions of these paths. A choked condition results in a constant mass-flow rate through an opening when the upstream conditions are maintained constant and the downstream absolute pressure drops below 0.53 of the upstream pressure [9].

Choked-flow conditions can be achieved by either pressurizing the upstream side of the leak paths or by maintaining a sufficiently low pressure downstream, so that the (downstream-to-upstream) pressure ratio is lower than 0.53 (possible pressure ratio following an accident is 0.45, atmosphere at 101 kPa and containment at 225 kPa). The pressure ratio 0.53 was selected because it was expected to adequately simulate aerosol leakage from containment, but without the experimental difficulties associated with a design in which the upstream chamber would be at an elevated pressure.

3.1 Isolation Damper Valves

The leak path for one isolation damper valve was simulated using a commercially available copper tube of the 0.158 cm diameter and 6 cm length. This diameter is about 5% larger than the maximum diameter within the reference range, but would allow for conservative estimate for aerosol leakage through the damper valves.

3.2 Airlock Door Seals

The geometry of the simulated leak path for one airlock door seal was a cylindrical tube of 0.6-cm long and 0.029-cm diameter. As there is not enough length to connect the tube to the aerosol chamber and to a flow meter, two special test sections were designed and fabricated to facilitate testing for aerosol leakage. These test sections were mounted on the appropriate sampling ports of the aerosol chamber. The 0.029-cm hole was simulated using a 0.011" (~0.028 cm) drill (the nearest size available) and the length of the hole was 0.6 cm.

3.3 Aerosol Test Chamber

The aerosol test-chamber (Figure 3) consisted of a cubic reservoir with sampling ports (for characterization and filtration) and an aerosol injection port. The reservoir was made of rigid plastic sheets (Makrolon®) held together with Dexion® steel angles and sealed with silicon adhesive. Aerosol was injected from a cyclone fogger into the reservoir through the off-centred injection port. One of the perpendicular sides of the chamber also contained a 16-cm diameter aerosol-characterization port.

The same side also contained a pair of filtration ports. The ports, shown in Figure 4, were 10 cm apart. A deflector was installed above each port to prevent collection of surface runoff from the vertical surface in to the port entrance. A thermocouple was inserted from the top and the thermocouple tip was located close to the filtration ports; a vent (on the top) with a filter maintained atmospheric pressure inside the chamber; and a pressure gauge downstream of the rotameters was used to measure the low pressure required for the choked flow condition.

3.4 Production of Aerosols

The study of aerosol retention in leak paths requires the production of suitable wet aerosols. A solution of uranine dye (sodium fluorescein, Reidel-de Haen, product no. 28803) and distilled water was used for aerosol production in the present experiment. The uranine-salt stock solution was prepared by dissolving 1 g of uranine in 50 g of distilled water, and then adding 2 mL of the solution to 1 L of distilled water. A Cyclone Fogger (Curtis Dyna-Fog®, Model 3000) was used because of its capability to operate with a wide range of liquid feedstock and to generate wet aerosols with droplet diameters ranging from 5 to 30 μm.

4. EXPERIMENTAL SYSTEM AND PROCEDURE

4.1 Flow Characteristics of Leak Paths

The first step in aerosol leakage study is to establish the flow characteristics of a leak path. As the flow velocity (of air) through a constricted part increases (with increasing chamber pressure), the flow becomes choked as the chamber pressure reaches about twice the outside pressure. The critical or choked mass-flow rate, m_c, for any gas flowing through a narrow passage is given as [10]:

$$m_c = A_l \, p_u \left[\frac{2}{RT_u} \frac{\gamma}{1+\gamma} \left(\frac{2}{1+\gamma} \right)^{2/(\gamma-1)} \right]^{1/2} \tag{1}$$

where A_l is the area of constriction (m^2), p_u is the upstream pressure (Pa), R is the gas constant ($m\text{-}N/kg\text{-}K$), T_u is the upstream gas temperature (K), and γ is the specific heat ratio.

4.2 Test Procedure

The simulated leak paths were connected to the aerosol chamber with filter assemblies as shown in Figure 4. The U2 line was more representative of containment leakage as it connected the leak path directly to the aerosol chamber; the U1 line represented any entrance effect on leak paths during aerosol flow. The vacuum pump was turned on and the rotameters were adjusted to read the same airflow rate through the U1 and U2 lines. The vacuum pump was turned off, and aerosols were injected into the chamber with the cyclone fogger. Once the aerosol flow was stabilized (after about one minute), the vacuum pump was turned on and aerosol-laden air was drawn for three minutes through the U1 and U2 lines.

The vacuum pump was turned off, and both U1 and U2 lines were disassembled taking care not to dislodge any droplets deposited on surfaces. The filters from both lines were removed and placed in separate containers with distilled water (50 mL for damper valve tests and 20 mL for airlock door tests). The interior deposits in U1 connector and U2 leak path were washed using distilled water in separate containers. The contents of four bottles were then analysed using a spectrophotometer (Varian Fluorescence Spectrophotometer, Cary Eclipse) to measure uranine concentration in each bottle.

Fractional aerosol penetration (or leakage) and deposition for both isolation damper valves and airlock door seals were calculated from the measured uranine concentration on the components of simulated leak paths. With reference to Figure 4 and with the assumption of balanced flows through U1 and U2 lines, the fractional penetration and deposition in leak paths were calculated as:

$$\eta_p^{II} = \frac{(U2\ filter)}{(U1\ connector) + (U1\ filter)} \tag{2}$$

and

$$\eta_d^{II} = \frac{(U2\ leak\ path)}{(U1\ connector) + (U1\ filter)} \tag{3}$$

where, $(U1\ connector)$ = amount of uranine deposited in the connector in the U1 line (μg/L), $(U1\ filter)$ = amount of uranine collected on the filter in the U1 filter assembly (μg/L), $(U2\ leak\ path)$ = amount of uranine deposited in the U2 leak path (μg/L), $(U2\ filter)$ = amount of uranine collected on the filter in the U2 filter assembly (μg/L), and the *II* superscript of η_p^{II} and η_d^{II} denotes fractions calculated from data for both leak paths.

The fractional penetration and deposition of aerosols were also calculated from uranine concentrations collected solely in the U2 line:

$$\eta_p^{I} = \frac{(U2\ filter)}{(U2\ leak\ path) + (U2\ filter)} \tag{4}$$

and

$$\eta_d^{I} = \frac{(U2\ leak\ path)}{(U2\ leak\ path) + (U2\ filter)} \tag{5}$$

where the *I* superscript of η_p^I and η_d^I is used to differentiate these calculations from the "dual-path" calculations defined by Equations 2 and 3. The "single-path" calculations defined by Equations 4 and 5 were expected to be less sensitive to the relative flow rates through the U1 and U2 leak paths. For either of the approaches used for estimating aerosol penetration and aerosol deposition, the mass conservation requires that

$$\eta_p^{II} + \eta_d^{II} = \eta_p^{I} + \eta_d^{I} = 1 \tag{6}$$

4.3 Aerosol Size Distribution

A phase-Doppler anemometer (PDA) was used for measuring the mean diameter of wet aerosols generated by the cyclone fogger. The aerosol diameter is an important parameter as leakage depends on the square of the diameter [9]. The PDA is a non-intrusive optical device, and it is used for obtaining information on aerosols, both diameter and velocity simultaneously [11]. In a PDA, two laser beams are focused into an intersecting measurement volume (a flared cylinder in shape). Droplets or aerosols passing through the measuring volume scatter the incoming laser light by refraction. The scattered light forms an interference pattern, and two photomultiplier tubes record the phase and intensity of the scattered light. An interferogram is constructed in each of these tubes from the phase and intensity relationship between the signals. A Fourier transform of the interferogram provides the size and velocity of the passing droplet. Three sets of PDA measurements were performed to measure aerosol diameter generated by the fogger, and the measured (arithmetic) mean diameter of aerosols was 9.7 µm.

5. RESULTS AND DISCUSSIONS

5.1 Flow Characteristics of Leak Paths

Table 1 lists the comparison of test results with calculated choked flow rates (Equation 1) for simulated leak paths for the isolation damper valves and airlock door seals. The measured airflow rate, on average, was 7% higher than the calculated flow rate. The small discrepancy could be due to the uncertainty in the leak path diameter (e.g., a 2.5% uncertainty in diameter could produce a 5% uncertainty in measured flow rate).

5.2 Leakage through Simulated Leak Paths

Fractional aerosol penetration and deposition on leak paths were calculated based on the measured uranine concentration in the U2 leak path, U2 filter assembly, U1 connector and U1 filter assembly. The fractional penetration and deposition were calculated using Equations 2-5; the results are listed in Table 2 for isolation damper valves. These results suggest that for the simulated damper valve leak path, fractional deposition on surface is higher than that leaked out or penetrated through the leak path. Based on the "single-line" (U2-line) test results, the average fractional penetration, η_p^I, is 0.38±0.06(1σ), and the average deposition, η_d^I, is 0.62±0.06(1σ).

Using the similar methodology, the fractional penetration and deposition of uranine-traced aerosol through the simulated airlock door seals were calculated to be 0.80±0.02(1σ) and 0.20±0.02(1σ), respectively; Table 3 lists these results.

5.3 Leak Path Plugging

From the depressurisation tests performed with a simulated isolation damper valve leak path, it was observed that the post-accident elevated pressure in a containment building would level off in about 15 minutes. Hence, tests were performed to monitor plugging of the U1 and U2 lines as aerosols flowed for the same duration of time through the simulated leak paths and the filter assemblies.

Flow through the U2 line which had the simulated leak path attached to the aerosol chamber did not change much even after 15 minutes of aerosol flow through it. However, flow through the U1 assembly decreased by about 12% after 15 minutes of aerosol flow. The results (Table 4) suggest that the aerosol penetration through the U2 assembly (i.e., simulated leak path) was insignificant compared to that through the U1 assembly. Photographic examination of the filter assemblies revealed that the U1 filter had more uranine deposits compared to the U2 filter.

The connector (between the aerosol chamber and the U1 filter assembly) in the U1 leak path was a larger size tube and that allowed more uranine to deposit on a larger area of the filter. This deposition might have blocked some flow through the U1 leak path after 15 minutes of aerosol flow. In comparison, the uranine collection on the U2 filter was on a smaller area. Therefore, plugging of the leak path should not be expected during 15 minutes of aerosol flow.

For the airlock door seals, flow through the U2 line which has the simulated leak path attached to the aerosol chamber did not change after 15 minutes of aerosol flow through it; however flow through the U1 assembly decreased slightly (~4%). A visual examination of the filter assemblies revealed that U1 filter had slightly more uranine deposits compared to U2 filter, but the deposits were not enough to cause significant plugging of the lines. As in the case of isolation damper valve, plugging of the leak path should not be expected during 15 minutes of aerosol flow.

6. FINAL REMARKS

Leakage of wet aerosols through containment isolation damper valves and airlock door seals was simulated using cylindrical tubes, and data for fractional leakage of wet aerosols through these leak paths were obtained. An industrial-type cyclone fogger was used for generating wet aerosols, and the filtration technique was used for calculating fractional penetration and deposition of the leak paths under choked flow condition.

The choked flow characteristics of the leak paths were established using air as the working medium. The measured flow rates through the leak paths compared well with the calculated choked flow rates. The fractional deposition and penetration of aerosols were calculated from the measured uranine concentrations on the surface of these leak paths, and on the filters placed in both leak paths.

The simulated leak path for the isolation damper valve was a 0.15-cm diameter and 6-cm long cylindrical tube. The average fractional penetration or leakage of wet aerosols was 0.38 (or 38%), and the rest (0.62 or 62%) deposited on the leak path surface. Hence for the isolation damper valve leak path, more aerosols would tend to deposit in the leak path compared to those leaking through it.

The simulated leak path for the airlock door seal was a 0.03-cm diameter and 0.6-cm long cylindrical tube. The average fractional penetration of wet aerosols through the leak path was 0.80 (or 80%), and the rest (0.20 or 20%) deposited on the leak path surface. Therefore, for the airlock door seal leak path, more aerosols would flow through the leak path than deposit on its surface. The aerosol flow rates through both leak paths were measured for 15 minutes and there was no evidence of plugging by deposited aerosols of either leak path.

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Table 1. Critical flow through simulated leak paths

Leak Paths	Flow Lines	Critical Flow Rate (L/min)	
		Measured	Calculated
Isolation Damper Valve	U1	25.0	23.2
	U2	24.2	
Airlock Door Seal	U1	0.87	0.82
	U2	0.87	

Table 2. Fractional aerosol leakage and deposition for simulated isolation damper valve

Test number	η_p^{II}	η_d^{II}	η_p^{I}	η_d^{I}
1	0.37	0.45	0.46	0.54
2	0.38	0.59	0.39	0.61
3	0.18	0.44	0.29	0.71
4	0.37	0.47	0.44	0.56
5	0.38	0.69	0.36	0.64
6	0.35	0.66	0.34	0.66
Average	0.34	0.55	0.38	0.62

Table 3. Fractional aerosol leakage and deposition for simulated airlock door seal

Test number	η_p^{II}	η_d^{II}	η_p^{I}	η_d^{I}
1	1.13	0.33	0.77	0.23
2	0.69	0.17	0.80	0.20
3	0.85	0.18	0.82	0.18
Average	0.89	0.23	0.80	0.20

Table 4. Leak path flow rate after 15 minutes

Leak Path	Time (min)	Flow Rate (L/min)	
		U1 Line	U2 Line
Isolation Damper Valve	0	24.2	24.4
	5	21.3	25.2
	10	21.0	25.2
	15	20.8	25.2
Airlock Door Seal	0	0.84	0.84
	5	0.82	0.84
	10	0.82	0.84
	15	0.81	0.84

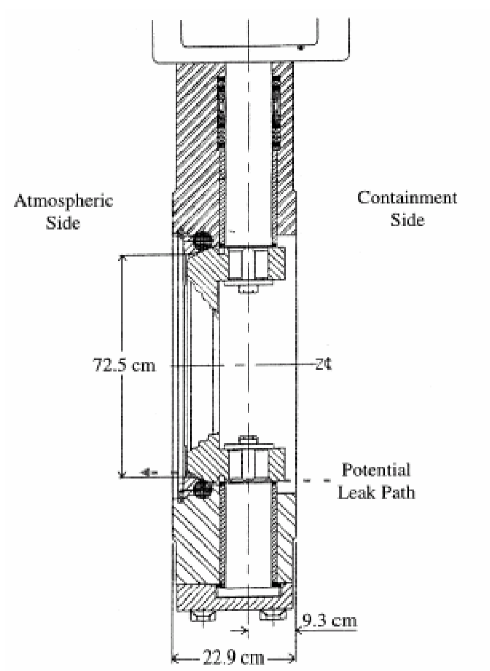

Figure 1. Schematic of a closed isolation damper valve

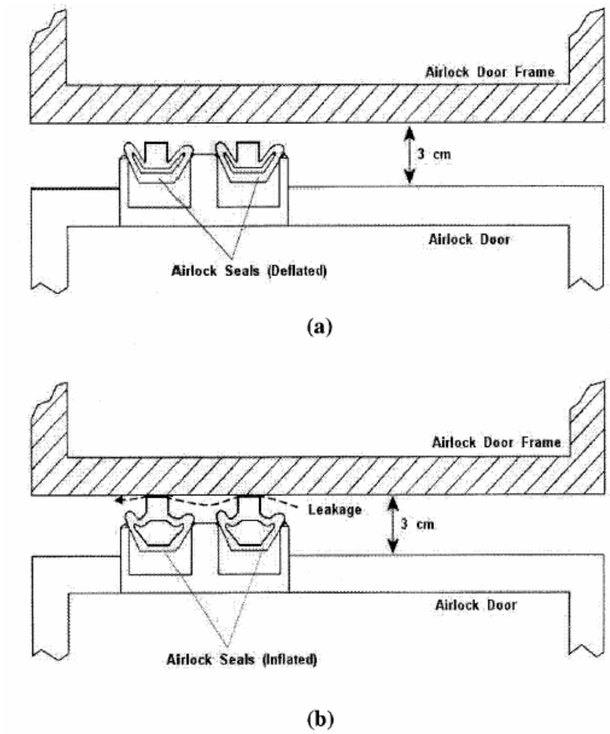

Figure 2. Schematic of airlock door seals; (a) seals deflated, (b) potential leakage between frame and inflated seals

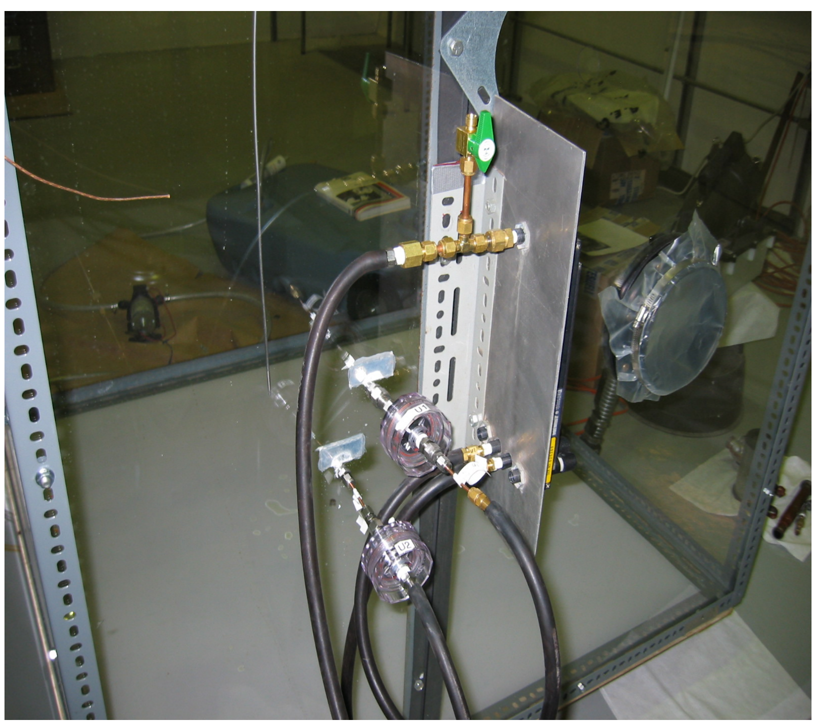

Figure 3. Filtration ports connected to rotameters

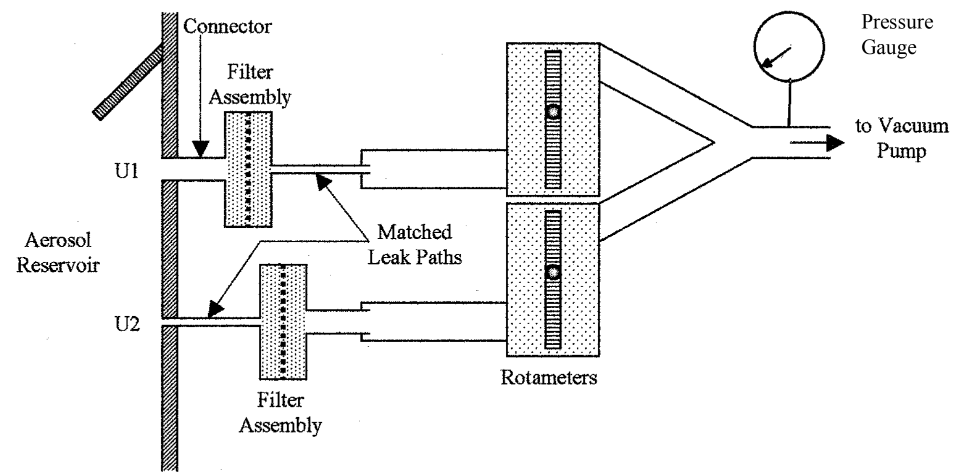

Figure 4. Schematic of filtration and sampling lines