UNIT VENT AIRFLOW MEASUREMENTS USING A TRACER GAS TECHNIQUE

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ABSTRACT

An alternative method for assessing flowrates that does not depend on point measurements of air flow velocity is the constant tracer injection technique. In this method one injects a tracer gas at a constant rate into a duct and measures the resulting concentration downstream of the injection point. A simple equation derived from the conservation of mass allows calculation of the flowrate at the point of injection.

Flowrate data obtained using both a pitot tube and a flow measuring station were compared with tracer gas flowrate measurements in the unit vent duct at the Callaway Nuclear Station during late 1995 and early 1996. These data are presented and discussed with an eye toward obtaining precise flowrate data for release rate calculations. The advantages and disadvantages of the technique are also described.

In those test situations for which many flowrate combinations are required, or in large area ducts, a tracer flowrate determination requires fewer man-hours than does a conventional traverse-based technique and does not require knowledge of the duct area.

I. INTRODUCTION

Air balance and ventilation performance testing requires precise flowrate measurement. Conventionally, flowrates are calculated from duct area and air velocity data. Velocity data are usually obtained by performing a multi-point traverse at the duct using a pitot tube or hot wire anemometer. In order to minimize non quantifiable errors in the velocity measurement certain conditions must be satisfied:

(1) The flow streamlines are parallel to the axis of the duct.

(2) No significant flow change occurs upstream for 8 to 10 diameters and downstream for 2 to 4 diameters from the flow measurement point.

Often in the field, these conditions cannot be satisfied and significant non-quantifiable errors may exist in the measurement. For example, due to access conditions or ductwork design, velocity measurements may have to be performed near a duct transition, elbow or damper. In these cases, the flow profile is perturbed and the previously stated conditions for precise measurement cannot be achieved.

Other field situations exist which resist precise measurement by conventional techniques, e.g. the measurement of air flowrates in plant chiller equipment where duct runs are minimal and velocity traverse based measurements are severely compromised.

II. TECHNICAL BACKGROUND

For most ventilation type measurements, duct flow is completely turbulent resulting in differences in flow velocities measured across the diameter of a duct even in the absence of flow perturbing elements such as the above mentioned transitions, elbows or dampers. ANSI/ASHRAE Standard 111[1] requires that for any flow traverse measurement to be valid more than 75% of the traverse readings must be greater than 10% of the maximum velocity pressure. Yet sometimes a flow rate is required from a point where this condition is NOT satisfied. Any flow rate calculated from a traverse under these conditions is in error by an unknown amount. This standard also requires a minimum of 25 measurement points even in moderately sized ducts.[2] For rectangular ducts larger than 4.5 feet on any side a maximum measurement spacing of eight inches is recommended. This can require that a very large number of data points be obtained. Hence to perform a traverse measurement correctly can require a substantial investment of time to obtain the necessary individual data points in addition to requiring that the flow be well behaved.

For at least twenty years it has been known that an alternative method to measure duct flowrates exists. It entails the use of a tracer gas dilution method. This method is a *volumetric* as opposed to a point measurement. To undertake such a measurement, a tracer gas is continuously metered into a flowing duct at a known rate. After allowing for mixing, air samples are collected at a point downstream and the concentration of tracer gas is measured. The rate of flow is readily calculated from the ratio of the tracer injection flowrate to the diluted concentration--in symbols:

$$Q = S / C$$

where Q = volumetric flowrate

S = tracer injection flow rate

C = duct tracer concentration

Note that for this equation to be valid the tracer must be *well mixed* within the duct. Since mixing is enhanced by the existence of flow direction changes within a duct, unsatisfied conditions (1) and (2) above which serve to complicate a traverse-type flow measurement actually enhance a tracer dilution flow measurement.

The tracer dilution technique has been used in the mine engineering, industrial hygiene, and energy conservation communities, but has been largely ignored in the ventilation engineering community.[3,4,5] This is unfortunate since many difficult flow characterization problems can be easily accommodated using the technique.

The tracer gas of choice for tracer dilution flowrate testing is sulfur hexafluoride, SF_6. This gas is inert, non-toxic, non-reactive, and is easily measured by means of electron capture gas chromatography to concentrations approaching one part per trillion.(10^{-12}) although this sensitivity level is only required for the largest of flows. The gas is monitored on-site using specially designed monitors that have been optimized for the detection of SF_6 used as a tracer gas. These monitors are not affected by the presence of other gases in the plant background such as freons and halogenated solvents. In addition since SF_6 possesses a zero ozone depletion factor it will not harm the ozone layer.

Tracer gas is injected into a duct using a mass flow controller or calibrated orifice. If the duct is large or the sampling point is fairly close to the injection point without adequate flow disturbances to promote mixing, tracer gas may be injected using a distributed manifold inserted into the duct. Tracer gas samples are drawn from the duct using a recirculating pump to take samples for analysis using a gas chromatograph.

III. SYSTEM DESCRIPTION

Ventilation System Lineups

A combination of charcoal filtration units and fans discharge to the unit vent based upon the operational requirements of the plant. The components with their design flow rates for each applicable system are given in Table 1. Which fan or filtration unit is running depends on the ventilation system lineup required by the plant.

Table 1 Unit vent exhaust plenum

Fan/Filtration Unit	Design Flow	
Condenser Air Removal Filtration Unit (GE)	1000	cfm
Main Steam Enclosure Fan Exhaust (GF)	16500	cfm
Aux/Fuel Building Emergency Exhaust Filtration Unit-Train A(GG)	9000	cfm
Aux/Fuel Building Emergency Exhaust Filtration Unit-Train B(GG)	9000	cfm
Auxiliary Building Access Control Exhaust Filtration Unit(GK)	6000	cfm
Auxiliary/Fuel Building Normal Exhaust Filtration Unit(GL)	32000	cfm (Fast)
	13000	cfm (Slow)
Containment Mini-Purge Exhaust Filtration Unit(GT)	4000	cfm

There are five major ventilation system lineups that occur during normal plant operations. Each is given in Table 2 with the fan status as shown. These lineups are designated for testing purposes as Normal, Normal/Mini-Purge, FBIS (Fuel Building Ventilation Isolation Signal)/Mini-Purge, FBIS/CRVIS (Control Room Ventilation Isolation Signal)/Mini-Purge and FBIS/CRVIS. Each lineup is fully explained below.

Table 2 Ventilation lineups/fan status

(X) indicates running

VENTILATION LINEUP	GE	GK	GF	GL (SLOW)	GL (FAST)	GG	GT
NORMAL	X	X	X		X		
NORMAL/MINI PURGE	X	X	X		X		X
FBIS/MINI PURGE	X	X	X	X		X	X
FBIS/CRVIS/ MINI PURGE	X		X	X		X	X
FBIS/CRVIS	X		X	X		X	

Normal Ventilation Lineup-The normal ventilation lineup is a combination of charcoal filtration units GL(Fast), GE,GK and the GF exhaust fan. This ventilation lineup exhausts the Auxiliary Building, the Fuel Building, Access Control Area and the Condenser Air Removal System. The design air flow rates are listed in Table 1. The fans normally exhausting to the unit vent during this ventilation lineup are shown by the shaded portions in Figure 1.

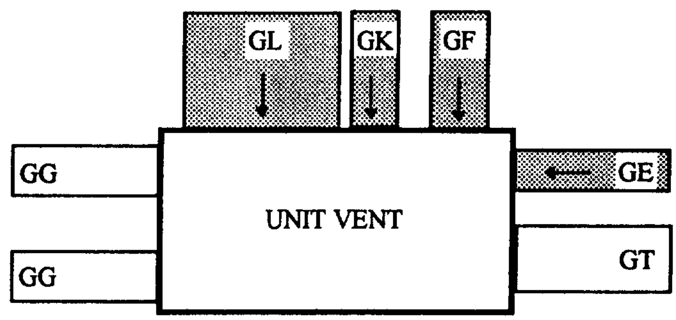

Figure 1 Normal ventilation lineup

Normal/Mini-Purge Ventilation Lineup-The Normal/Mini-Purge Ventilation Lineup is a combination of charcoal filtration units GL(Fast), GE,GK, GT and the GF exhaust fan. The Containment Mini-Purge Charcoal Filtration Unit, GT, controls the containment atmosphere during normal plant operations. The design air flow rates are listed in Table 1. The fans normally exhausting to the unit vent during this ventilation lineup are shown by the shaded portions in Figure 2.

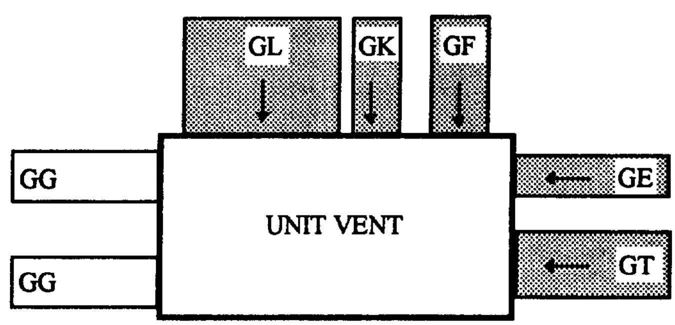

Figure 2 Normal/Mini-Purge ventilation lineup

FBIS/Mini-Purge Ventilation Lineup-The FBIS/Mini-Purge Ventilation Lineup is a combination of charcoal filtration units GL(Slow), GE,GK, GT, GG and the GF exhaust fan. This ventilation lineup supports special fuel handling operations for the Fuel Building. The design air flow rates are listed in Table 1. The fans normally exhausting to the unit vent during this ventilation lineup are shown by the shaded portions in Figure 3.

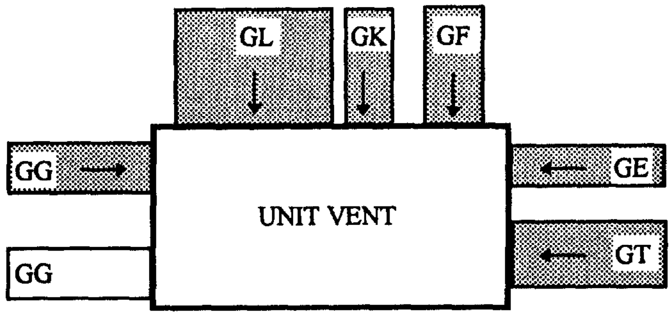

Figure 3 FBIS/Mini-Purge ventilation lineup

FBIS/CRVIS/Mini-Purge Ventilation Lineup-The FBIS/CRVIS/Mini-Purge Ventilation Lineup is a combination of charcoal filtration units GL(Slow), GE, GT, GG and the GF exhaust fan. The ventilation lineup supports special control room and fuel building ventilation requirements. The design air flow rates are listed in Table 1. The fans normally exhausting to the unit vent during this ventilation lineup are shown by the shaded portions in the Figure 4.

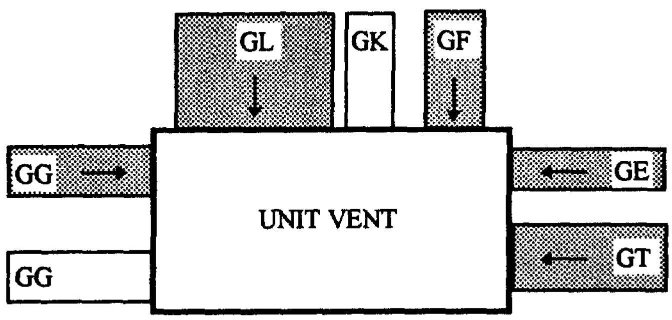

Figure 4 FBIS/CRVIS/Mini-Purge ventilation lineup

FBIS/CRVIS Ventilation Lineup-The FBIS/CRVIS Ventilation Lineup is a combination of charcoal filtration units GL(Slow), GE, GG and the GF exhaust fan. The ventilation lineup supports special control room and fuel building ventilation requirements. The design air flow rates are listed in Table 1. The fans normally exhausting to the unit vent during this ventilation lineup are shown by the shaded portions in Figure 5.

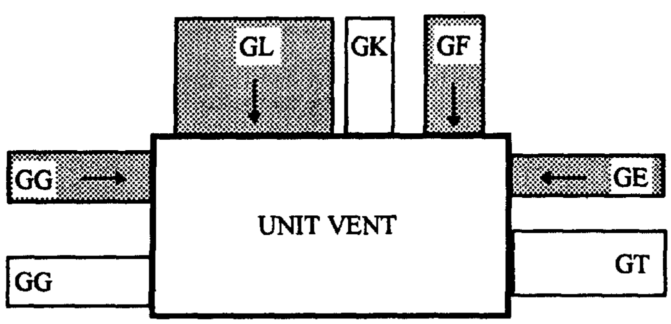

Figure 5 FBIS/CRVIS ventilation lineup

Unit Vent Configuration
The unit vent exhaust plenum exits the Auxiliary Building through the roof as shown by Figure 6 only to make two short coupled 90 degree turns before continuing along the Reactor Building containment structure.

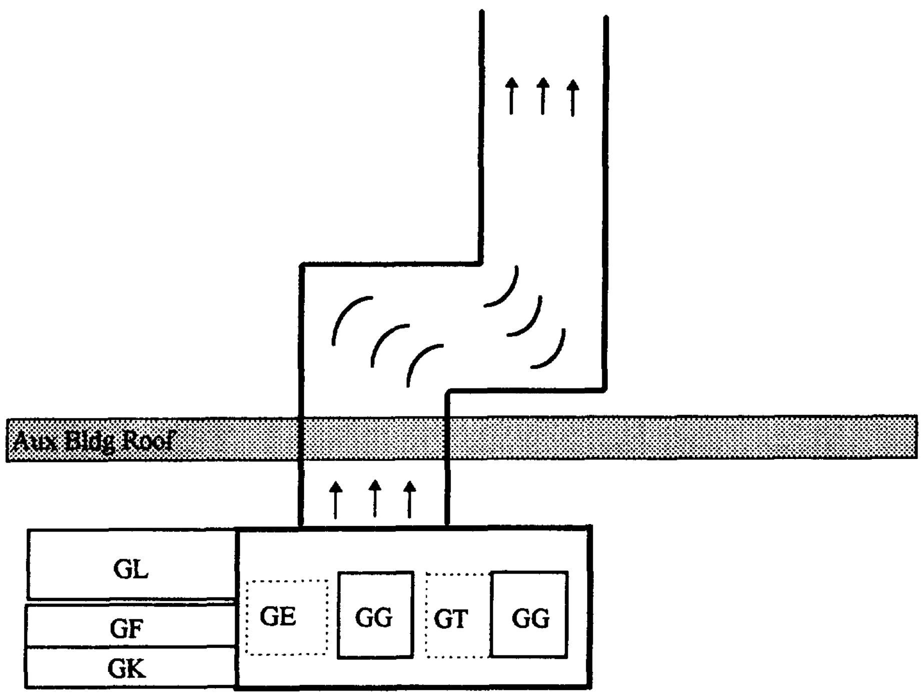

Figure 6 Unit vent exhaust plenum

Figure 7 below shows the physical location of the unit along the Reactor Building containment structure.

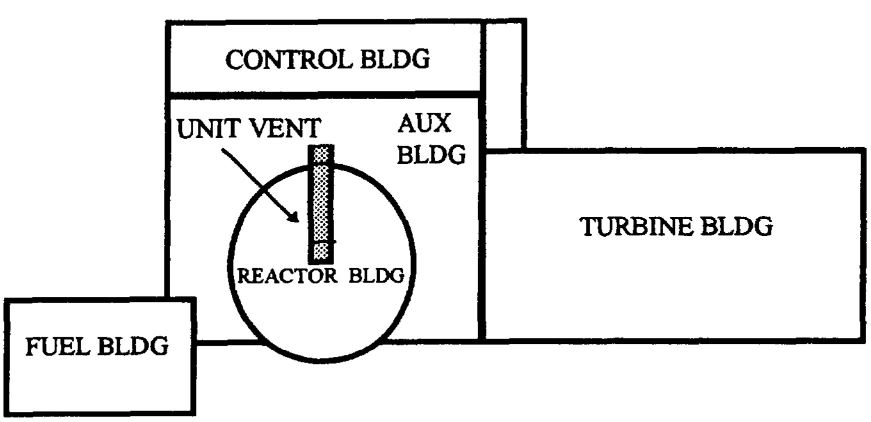

Figure 7 Unit vent location

Figure 8 below shows a side view of the unit vent ducting along the containment structure.

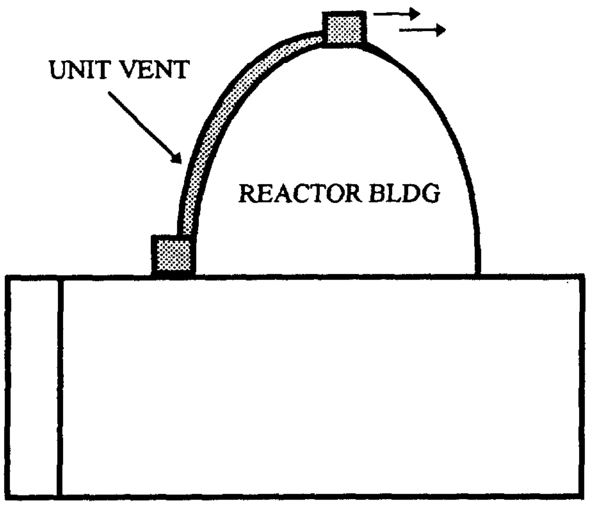

Figure 8 Unit vent physical layout

IV. HISTORICAL SYSTEM PERFORMANCE

The function of the flow measurement station is to provide a 0-5 VDC signal to the Wide Range Gas Monitor (WRGM) RM-80 microprocessor which in turn displays this flow value (cfm) on the RM-11 control panel. The 0-5 VDC output signal is used by the WRGM to maintain isokinetic flow control, isokinetic nozzle selection and perform effluent calculations. The RM-80 microprocessor data base file determines which set of sampling nozzles, *normal or accident*, to use based upon the flow signal developed by the flow measuring station. If the flow signal is above the isokinetic range (46,930 cfm), the *normal* nozzles will be on-line and conversely for the *accident* nozzles should the flowrate become non-isokinetic. An alarm will sound on the RM-11 panel should this condition exist. Nearly all normal operation flow lineups result in isokinetic flow conditions in the unit vent. Should the unit vent flow measuring equipment become inoperable, installation of conservative substituted flows will be initiated. Precise flow measurement to preclude premature switching of the sampling nozzles or the initiation of manual sampling due to inoperable sampling nozzles has proven to be labor intensive and a *work-around* for the unit operators.

October 1994 Testing

Corrective action measures were initiated as early as October 1994 to ensure the unit vent instrumentation components were properly calibrated. Each specific ventilation lineup imparts a different air flow signal for the instrumentation to acquire and condition. Not only did it take several days to affect a complete calibration but the instrumentation exhibited evidence of drift over a period of time.

A pitot tube traverse of the unit vent ducting was performed just upstream of the installed air flow measuring station for each ventilation lineup previously discussed in this paper. This required the erection of a thirty foot scaffolding adjacent to the unit vent ducting. In conjunction with the pitot tube traverse data, RM-11 readings were obtained for comparison. The results of this testing are documented in Table 3. Based upon the data obtained, a single correction factor was applied to the RM-11 readings using linear regression analysis to achieve an RM-11 flow more in line with the pitot tube traverse. This method proved to be precise on only certain areas of the curve.

Table 3 Unit vent measurements without Tracer-Oct 94

VENTILATION LINEUP	PITOT cfm	RM-11 cfm	Difference cfm
NORMAL	50194	63616	13422
NORMAL/MINI PURGE	50394	69014	18620
FBIS/MINI PURGE	44556	55545	10989
FBIS/CRVIS	36813	41639	4826

As can be seen from Table 3, a large difference existed between the RM-11 reading and the pitot tube traverse results for most lineups. Since the unit vent instrumentation was calibrated just prior to the test, the difference between the RM-11 and the pitot tube traverse results was due to the inability to precisely measure the effective duct area or achieve optimum pitot tube orientation in the duct. Figure 9 shows the basic internal construction of the ducting in the area of the flow measuring station. One inch diameter cross-members extend diagonally across the duct every two feet. Additionally, a two inch internal angle iron web is added for strength every two feet as well. The cross-members and the internal web serve to decrease the effective flow area of the duct by approximately 16% as well as set up turbulence throughout the flowstream. These turbulence coupled with an unknown flow area imposes non quantifiable errors for calculating the air flow rate in the duct.

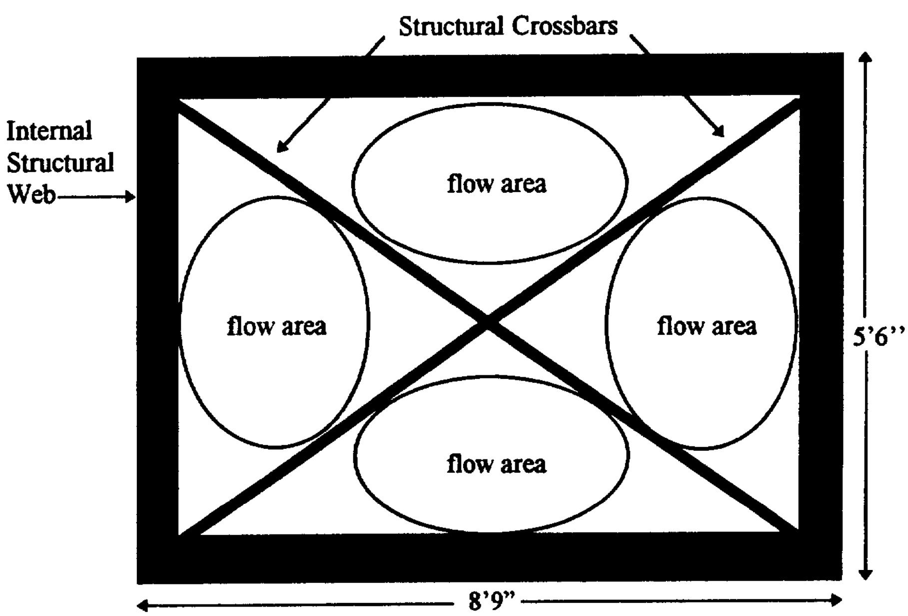

Figure 9 Internal duct construction

V. TRACER GAS TECHNIQUE

Tracer Gas Test Setup

Figure 10 shows the equipment setup to perform the tracer gas test. A 150 ft^3 cylinder of 0.1 % SF_6 injection gas was connected to a flow control valve. The mass flow controller served to finely control the flow of SF_6 injection gas to the injection tube manifold. The injection point for the gas was selected upstream of a fan inlet approximately 50 feet from the unit vent plenum and a total of 90 feet from the sampling point. The injection gas was introduced at three different points across the traverse of the duct with insignificant changes in the results. This established the fact that the gas was sufficiently mixed prior to pulling a sample. The downstream sample was obtained by inserting a sample tube at specific locations in the flowstream and using a pump to retrieve the sample. A list of specific equipment and test precautions is provided in the appendix attached to this paper.

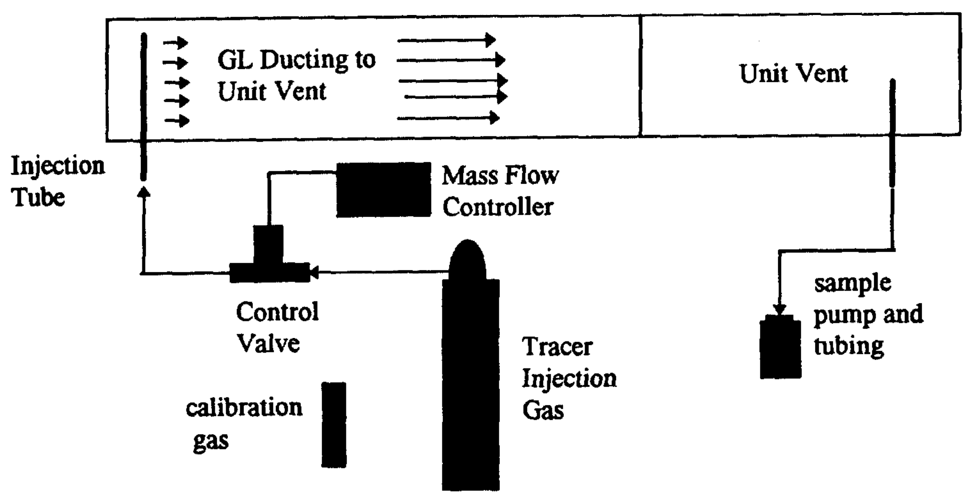

Figure 10 Tracer gas injection setup

Preliminary tracer gas testing-October 1995

Tracer gas technology was tested as to the applicability to Callaway Nuclear for potential incorporation not only in unit vent flow measurement but in the routine checks of all systems and components capacities. The technology had been used for other applications within the nuclear industry to check the migration of noble gases. [6] Basic test verification was conducted to demonstrate the desired results could be achieved on the unit vent.

By October 1995, procedures were in place and equipment had been obtained to perform a trial test of the Tracer Gas Technique in the Normal Ventilation Lineup. A total of 15 samples were taken in the unit vent as shown on Figure 11. There are seventeen access plugs available for testing. Plug #4, #9 and #14 were selected since they were evenly spaced across the duct area and were representative of the total flow within the unit vent. Five samples were taken in each plug location and the samples were labeled accordingly. The results of the test are given in Table 4.

Table 4 Preliminary single test-October 1995

VENTILATION LINEUP	PITOT cfm	TRACER cfm	Difference cfm (pitot - tracer)	RM-11 cfm	Difference cfm (RM 11-tracer)
NORMAL	51037	50812	225	54960	4148

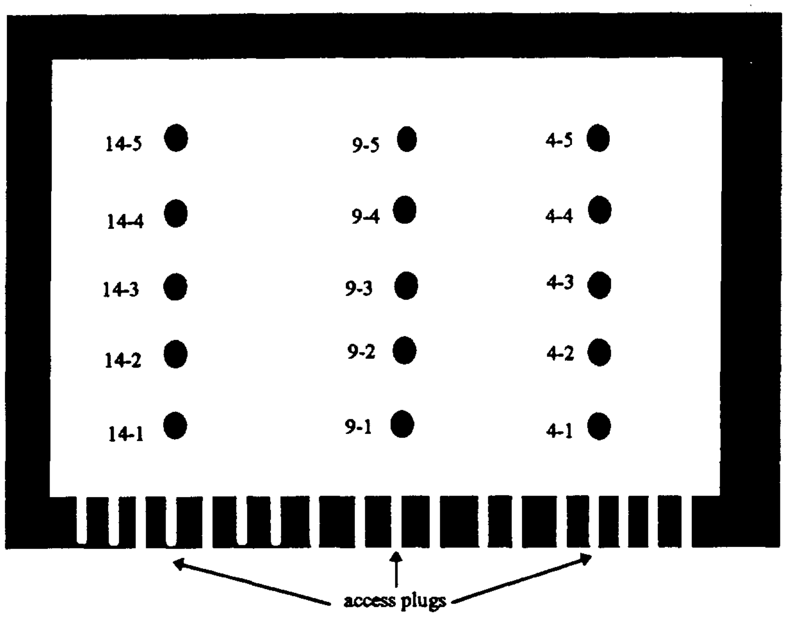

Figure 11 Unit vent sample locations-top view

Tracer gas test-January 1996

January 1996 marked to first unit vent test to be performed at Callaway Nuclear with the Tracer Gas Technique. Ventilation systems were placed in standard lineups that would occur during normal plant operation. A pitot tube traverse was performed on the unit vent ducting just upstream of the flow measuring station at 170 points. The ducting area was estimated based upon the outside diameter of the duct minus the area of the internal web and the cross-members. There would still be non quantifiable errors due to the estimation of area as well as effects from turbulence set up by the design. Nevertheless, attempts were made to meticulously measure the velocity pressures in the duct without encountering the effects of any cross-member. Table 5 below shows the results of this test for the standard ventilation lineups.

Based on the data shown in Table 5, it was apparent that the RM-11 instrumentation was out of calibration. Additionally, the observed difference between the pitot traverse and the tracer gas measurement under these same conditions also indicated a greater difference than projected. The test was rescheduled and the instrumentation was to be calibrated just prior to the next test.

Table 5 Tracer gas test-January 1996

VENTILATION LINEUP	PITOT cfm	TRACER cfm	Difference cfm (pitot-tracer)	RM-11 cfm	Difference cfm (RM-11-tracer)
NORMAL	55881	52027	3854	78200	26173
NORMAL/MINI PURGE	55254	58674	3420	79600	20926
FBIS/MINI PURGE	51480	52614	1134	71800	19186
FBIS/CRVIS/MINI PURGE	48752	43151	5598	66700	23549
FBIS/CRVIS	45186	47247	2061	63000	15753

Tracer gas test- February 1996

The unit vent instrumentation was calibrated and verified to be operating correctly. The same ventilation lineups used in January 1996 were repeated. Table 6 shows fairly good alignment between the pitot traverse and the tracer measurement for most ventilation lineups. Where differences were greater, this would be attributed to the error in determining the effective flow area. Some disparity existed between the RM-11 and the tracer gas test but to a lesser degree after calibration. This can be attributed to several factors in addition to the calibration of instrumentation. The use of a recorder with much better resolution than that used in any previous test improved the precision of this testing. Another impact was the experience level of the individuals performing the testing and refining the test methodology.

Table 6 Tracer gas test-February 1996

VENTILATION LINEUP	PITOT cfm	TRACER cfm	Difference cfm (pitot-tracer)	RM-11 cfm	Difference (RM 11-tracer)
NORMAL	56984	49187	7797	52400	3213
NORMAL/MINI PURGE	56588	53245	3343	56000	2755
FBIS/MINI PURGE	53547	44409	9138	49600	5191
FBIS/CRVIS/MINI PURGE	46167	44187	1980	45400	1213
FBIS/CRVIS	45978	42748	3230	42600	148

Test preparation

Several preliminary items were required prior to the actual performance of the test such as determining the injection rate for the SF_6 gas. This is calculated based upon the estimated flow rate of the system based upon the design flow for the ventilation lineup described given in Table 1 and 2 above. Injection rate is a function of the volumetric flowrate of the system and concentration of tracer gas as discussed in Section II, Technical Background , of this paper. The selection of the concentration value is based upon testing experience to render acceptable results when using a mixture of 0.1% or 0.01% SF_6 in nitrogen or air as the tracer gas. Other parameters such as airstream temperature and barometric pressure are required for conversion assistance.

The equipment was configured as described in Figure 10. Sample retrieval was obtained using heavy duty syringes and needles. Each syringe was clearly marked prior to the test so as not to delay sampling. The syringe with needle attached was exercised prior to sampling to ensure no clogging of the tip occurred.

Tracer gas injection and sampling

Radio communications were established between the injection gas operator and the sampling station at the unit vent. The injection gas was introduced into the airstream and the sampling station was notified. Injection rate was monitored every 30 seconds. A delay of 1-2 minutes was required prior to taking the first sample to ensure the injection gas mixing had time to stabilize. A sample was taken every 30 seconds until all samples for a given access hole were taken. The sampling tube was moved from access hole #4 to #9 and finally to #14 until all samples were obtained. The samples were transported to the counting station taking care not to depress the syringe prematurely.

Sample analysis

Before any sample was analyzed, the atmospheric level of SF_6 (if any) in the vicinity of the gas chromatograph was determined. In addition, two calibration gas standards were read to provide the standard response level for calculating the gas concentration in each sample. Each sample was successively injected into the gas chromatograph after the proper stripchart response was achieved.

Data reduction

The response of each sample is determined by measuring the peak height of each sample. From this value and the standard response level of the calibration gas samples, the concentration of the downstream sample can be determined. From this concentration level and a known tracer gas injection rate, the flowrate of the airstream can be precisely determined.

VI. CONCLUSIONS

By performing flow tests using the tracer dilution method, *volumetric* flowrate data can be easily obtained in the worst duct configurations. Errors introduced by probe orientation, manometer orientation, state of the thermoanemometer batteries, marginal duct velocities, physical configuration, operator fatigue, vents, grilles, and the condition of the flow are eliminated. Another benefit is that expensive flow probes do not have to be inserted into potentially contaminated ducts. The only equipment that actually goes into the airstream is cheap, disposable tubing. Other benefits include minimizing the number of penetrations that must be made in a duct thereby reducing the amount of inleakage or outleakage induced by these holes as well as creating less structural weakening. Flow measurements by the tracer dilution method are more rapid than those by conventional techniques thereby decreasing the time required in high radiation areas in keeping with ALARA considerations of the Health Physics staff.

Since the flow data are not dependent on operator skill and the other physical problems associated with the flow measurement process, more reliable, precise and defensible test data can be generated. These flow rate data can be directly compared to one another to assess the effect of various operational configurations. In-place flow measurement instruments can be directly and wholly calibrated with real volumetric flows using real time data. This provides Health Physics personnel with reliable flowrates to calculate precise radioactive release data. The technique can also provide operations personnel with precise air flow monitoring information, and systems engineering personnel with flow balancing data that are more reliable than those obtained by conventional techniques.

VII. REFERENCES

(1) ASHRAE STANDARD 111, "Practices for measurement, testing, adjusting, and balancing of building heating, ventilation, air-conditioning, and refrigeration systems", American Society of Heating, Refrigerating, and Air Conditioning Engineers, 1988

(2) Industrial Ventilation-20th Edition, American Conference of Government Industrial Hygienists, 1990

(3) Technical Note AIVC 34, "Air flow patterns within buildings-measurement techniques", Air Infiltration and Ventilation Centre, University of Warwick, England, 1991

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(5) Lagus, P.L., Flanagan, B.F., Peterson, M.E., Clowney, S.L., "Tracer dilution method indicates flowrate through compressor", Oil & Gas Journal, February, 1991

(6) Lagus, P.L., Kluge, V., Woods, P., Pearson, J. , "Tracer gas testing within the Palo Verde Nuclear Generating Station unit 3 auxiliary building".

Appendix A. Equipment list and test precautions

Equipment list

- Electron capture gas chromatograph with SF_6 oven installed
- Mass flow meter
- Mass flow meter, extension transducer
- 30 ft^3 cylinder SF_6, 1 ppb calibration gas with regulator
- 30 ft^3 cylinder SF_6, 10 ppb calibration gas with regulator
- 150 ft^3 cylinder .1% SF_6 injection gas with regulator
- 150 ft^3 cylinder .01% SF_6 injection gas with regulator
- Sample pump with tubing and septa
- Tracer gas injection manifold and tubing
- Tracer gas sample retrieval tube and tubing
- Needles-(23 X 1")
- Syringes-(12-20 cc)
- Spare septum
- External recorder

Test precautions

- An electron capture gas chromatograph was used to measure the samples obtained. This same instrument was used to perform bypass leakage test on charcoal filter beds however, the oven column was replaced with one compatible with SF_6 gas. Approximately 24 hours is required for the unit to properly warm-up.
- Cross contamination of the SF_6 gas within hoses and regulators is a constant prevention requirement.
- Background samples of the surrounding atmosphere where the samples are being analyzed is required for pre and post test validation.
- Calibration gas samples are analyzed prior to sample counting.
- Septum on the Calibration Gas tank and sample pump should be periodically changed out.
- New syringes should be used for each sample series/location to preclude any cross contamination.
- A high resolution printer with an integrator is best for a more precise reading.
- Care should be taken to use needles on the syringes that do not clog when the septum is penetrated.
- This test is currently limited to areas where the exhaust from the airstream does not communicate with the compartment where injection is taking place.
- If air flow is $< 5,000$ cfm, the .01% injection gas should be used.
- Samples should be pulled from the downstream at least every 30 seconds during the injection phase.
- Purging of calibration gas through the regulator prior to taking a calibration sample is essential.
- Samples should not be injected into the gas chromatograph more frequently than 3 minutes apart.
- If replacement of the sample oven is performed on site, ensure the oven snaps fully in place to prevent contamination of the system.
- The holes in the injection tube should point into the direction of flow.
- Only polyethelene or nylon tubing is recommended for use with SF_6.
- All SF_6 containing cylinders and tubing should be stored in a separate cabinet, to prevent cross contamination.

DISCUSSION

RICKETTS: I am wondering if you addressed the compatibility of your choice for a test gas with the proper operation of iodine adsorption filters?

ADAMS: I am not sure I am qualified to answer that. Seeing that the trace gas was inert and non-toxic and that the same tracer gas has been used in other industries, we felt comfortable in doing likewise. Especially because it was not ozone depleting. In fact, I made some calls to some of the charcoal vendors prior to doing the test, and it was their determination that it did not affect the carbon or the HEPA filter tests. The other thing we did to make sure it would have less effect on the filters, was to inject it downstream of the charcoal filtration units. The real answer to your question, I think, is that we injected downstream of the adsorber units and upstream of a fan to get proper mixing.