Outleakage? I thought NRC only cared about *inleakage*?

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ABSTRACT

The test techniques contained in ASTM Standard E741 are used by the nuclear power industry to measure inleakage into the Control Room Envelope (CRE) when the Control Room Envelope Emergency Ventilation System (CREEVS) is in operation during a radiological emergency. The calculational format in Standard E741 assumes that air provided to the CRE contains no background of tracer gas. For those nuclear power plants which do not include the Mechanical Equipment Room (MER) within the CRE boundary, it is likely that some tracer laden air will leak into the MER from components of the CREEVS that are under a positive differential pressure as well as across the CRE Boundary. Consequently, air leaking into CREEVS components exhibiting negative differential pressure relative to the MER will contain a non-zero concentration of tracer gas.

Tracer concentration in the MER may affect the inleakage calculation

Failure to account for a non-zero tracer gas concentration in the MER will result in an *underprediction* of inleakage into the CRE using the equations provided in Standard E741. Consequently, a correction for a background concentration must be made to the ASTM equations used in the calculation of inleakage.

This paper provides a derivation of the relevant correction equations and includes several tables which summarize actual correction values measured in operating US nuclear power plants.

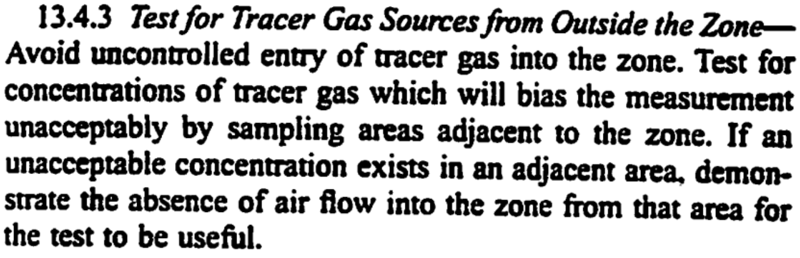
1.0 INTRODUCTION

The test techniques contained in ASTM Standard E741 [1] are used by the nuclear power industry to measure inleakage into the CRE when the CREEVS is operating during a radiological emergency. The NRC formally published testing recommendations suggesting use of this standard in 2003 [2, 3]. Tracer gas testing for inleakage became a regulatory requirement in 2007 [4]. These techniques have been exhaustively discussed in earlier presentations at prior Air Cleaning Conferences [5, 6, 7, 8, 9]. ASTM Standard E741 techniques are now employed for inleakage testing in all US nuclear power plants and have been utilized in selected plants in at least 6 other countries that generate electricity using nuclear reactors.

A number of nuclear power plants have the CREEVS emplaced in an MER that is located outside the CRE boundary. During an inleakage test, small amounts of air containing tracer gas can leak from the positively pressurized portions of the CREEVS into the MER. Also, a CRE which exhibits a positive differential pressure relative to the MER will allow leakage of tracer gas laden air into the MER through unsealed openings in the adjoining boundaries. Tracer gas entering the MER from components of the CREEVS or the CRE will mix with the surrounding air and create a background concentration. Sections of the CREEVS exhibiting a negative differential pressure will therefore allow tracer laden air into the CREEVS airstream. These leakage paths are schematically illustrated in Figure 1.

The calculational format in Standard E741 assumes that air leaking into the CRE through components of the CREEVS under negative differential pressure contains no background of tracer gas. In the event that a concentration of tracer gas exists in air leaking into CREEVS components due to a concentration of tracer in the MER, a correction must be made to the calculation of inleakage.

ASTM Standard E741specifically warns against the uncontrolled entry of tracer gas into the zone under test:



13.4.3 ***Test for Tracer Gas Sources from Outside the Zone*—Avoid uncontrolled entry of tracer gas into the zone. Test for concentrations of tracer gas which will bias the measurement unacceptably by sampling areas adjacent to the zone. If an unacceptable concentration exists in an adjacent area, demonstrate the absence of air flow into the zone from that area for the test to be useful.**

Since, in the nuclear power plant context, it is seldom possible to eliminate air containing tracer gas in the MER from entering the CRE through unsealed openings in the CREEVS, it is essential to correct the inleakage calculation for this uncontrolled entrance of tracer gas into the CRE. Figure 1 provides a schematic illustration of potential sources of tracer gas both as outleakage from positive differential locations and inleakage from negative differential pressure locations. Failure to include potential tracer gas inleakage into negative differential pressure portions of the CREEVS ductwork will result in an *underprediction* of the actual inleakage into the CRE.

The remainder of this paper provides equations that allow the calculated inleakage using the E741equations to be corrected for tracer gas entering the CREEVS due to a non-zero background in the MER. Tables 1, 2 and 3 are provided that present actual measured CRE tracer concentration data from selected US nuclear power plants. They also provide correction factor values to the initial inleakage values that were calculated assuming no background tracer concentration entering the CREEVS.

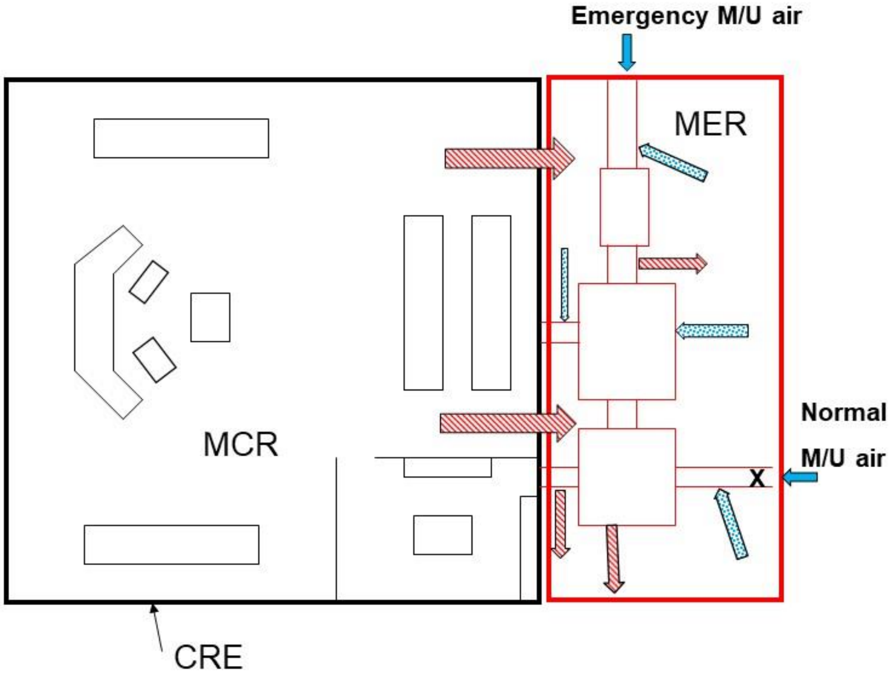


Figure 1. Schematic representation of a CRE that does not incorporate the MER. Red hatched arrows represent potential sites for leakage *into* the MER. Blue dotted arrows represent potential sites for leakage *into* components of the CREEVS.

2.0 INLEAKAGE MEASUREMENT WITH NO TRACER GAS BACKGROUND

To interpret data resulting from tracer gas methods assuming that no tracer background is exits, one employs a mass balance of the tracer gas released within a volume under test. Assuming that the tracer gas mixes thoroughly within the test volume, the mass balance equation is,

$$V\, dC(t)/dt = S(t) - q(t)C(t) \tag{1}$$

where V is the test volume, C(t) is the tracer gas concentration (dimensionless), dC(t)/dt is the time derivative of concentration, q(t) is the volumetric airflow rate out of the test volume, S(t) is the volumetric tracer gas injection rate, and t is time.

The solutions to equation (1) for the case of concentration decay or constant injection are summarized below. A complete discussion and derivation of these solutions may be found in reference [10].

2.1 CONCENTRATION DECAY METHOD

The simplest tracer gas technique is the tracer concentration decay method. After an initial tracer injection into the test volume, there is no source of tracer gas, hence S(t) = 0 in equation (1), and assuming A is constant, a solution to equation (1) is:

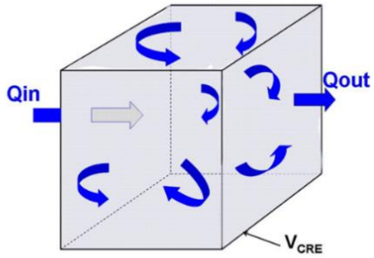
$$C = C_0 \exp(-A \cdot t) \tag{2}$$

The basic idea behind a concentration decay test is provided in Figure 2. The natural logarithm of the tracer concentration decreases linearly with time. The slope of this line is A, the air exchange rate. Calculation of the air inleakage rate requires independent knowledge of the CRE volume from which,

$$q_{Inleak} = A \cdot V \tag{3}$$

The results obtained with this technique are exact only for a well-mixed volume, (i.e., concentration at a given time is the same throughout the test volume). Otherwise, the results will be subject to errors, with the magnitude of these errors depending on the extent of the departure from homogeneity. Experimentally, the challenge is to ensure adequate mixing of the tracer gas.

1) Inject Tracer and Mix well



2) Measure Mean Concentration as a Function of Time

Time (hrs.)	Concentration (ppb)
0	C0
0.5	C1
1.0	C2
1.5	C3
2.0	C4

3) Plot ln (Concentration) vs. Time and calculate Slope by Regression

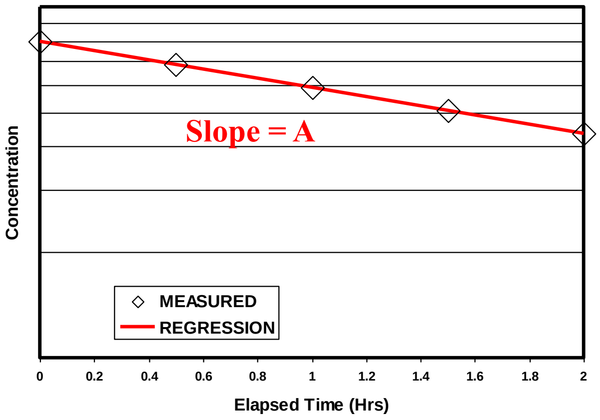


Figure 2. Concentration Decay Test

2.2 CONSTANT INJECTION METHOD

A companion tracer gas technique to the concentration decay method is referred to as the constant injection technique in which S(t) = constant. This technique is also known as the concentration buildup/steady state method. If A is also assumed to be constant, a solution to equation (1) is,

$$C(t) = (S/q) + (C_0 - S/q) \exp(-A \cdot t) \qquad (4)$$

The basic idea behind a constant injection test is provided in Figure 3 along with a plot of equation (4) .

As shown in Figure 3, the tracer concentration within the CRE initially increases with time but eventually reaches a constant value. After waiting a sufficient time, the exponential term dies out at which point concentration equilibrium occurs. Equation (4) then becomes the simple constant injection equation,

$$C = S/q \qquad (5)$$

Since both S and C are measured equation (5) can be written as

$$q_{Total} = S/C \qquad (6)$$

This value represents the Total air flow into the CRE. Subtracting the makeup flow rate, $m_{m/u}$ yields the inleakage q_{Inleak} . In symbols,

$$q_{Inleak} = q_{Total} - q_{m/u} \qquad (7)$$

The results obtained with this technique are exact only when the system is in equilibrium, (i.e., concentration is not changing as a function of time) and the gas is well mixed throughout the CRE. Otherwise, the results will be subject to errors, with the magnitude of these errors depending on the extent of the departure from equilibrium.

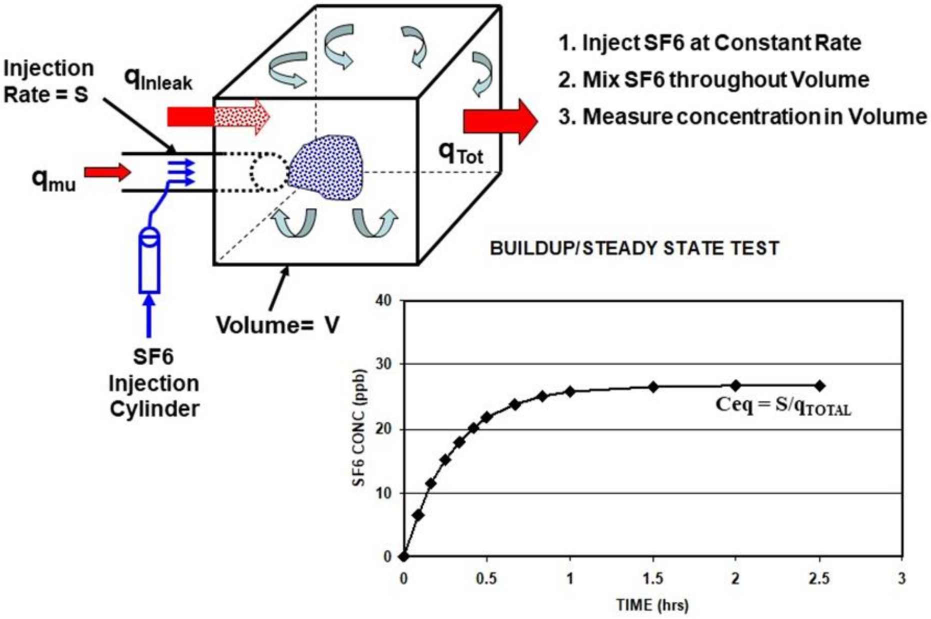


Figure 3. Concentration Buildup/Steady State Test

In use, the Concentration Decay method is suitable for measuring inleakage when the CREEVS is operating in the Isolation or Recirculation mode whereas the Constant Injection Method is better suited for measuring inleakage when the CREEVS is operating in the pressurization mode.

INLEAKAGE CORRECTION FOR PRESSURIZATION CREEVS

Referring to Figure 4, an equation can be derived to correct for the existence of a background concentration outside of any component of a CREEVS exhibiting negative differential pressure (duct run, air handler housing, fan housing, etc.) that is undergoing an inleakage test. Note that in this figure the symbol I represents inleakage of air *from* the MER *into* the CREEVS and the symbol q is the makeup air entering the CRE through the CREEVS components and ductwork. The various values of C represent mean tracer concentration values in their respective volumes.

Assuming that a uniform concentration of tracer gas of concentration C_{BG} surrounds the volume encompassing the CREEVS, and that concentration equilibrium has been attained, conservation of mass considerations lead to equation (8).

$$C_U \cdot q + C_{BG} \cdot I = C_D \cdot (I + q) \qquad (8)$$

Rearranging terms to obtain equation (9).

$$(C_U - C_D) \cdot q = (C_D - C_{BG}) \cdot I \qquad (9)$$

From which equation (10) follows.

$$I = \frac{(C_U - C_D) \cdot q}{(C_D - C_{BG})} \qquad (10)$$

Dividing both numerator and denominator by C_D, yields the following equation (11).

$$I = q \cdot \frac{\left(\frac{C_U}{C_D} - 1\right)}{\left(1 - \frac{C_{BG}}{C_D}\right)} \qquad (11)$$

C_U is the concentration of tracer gas entering the CREEVS via makeup or pressurization flow and C_D is also the resulting tracer gas concentration in the CRE at equilibrium assuming no other inleakage occurs into the CRE from adjacent spaces (i.e., CRE is positive to all surrounding spaces). Hence C_U equals C_{mu} and C_D is the mean concentration in the CRE namely C_{CRE}.

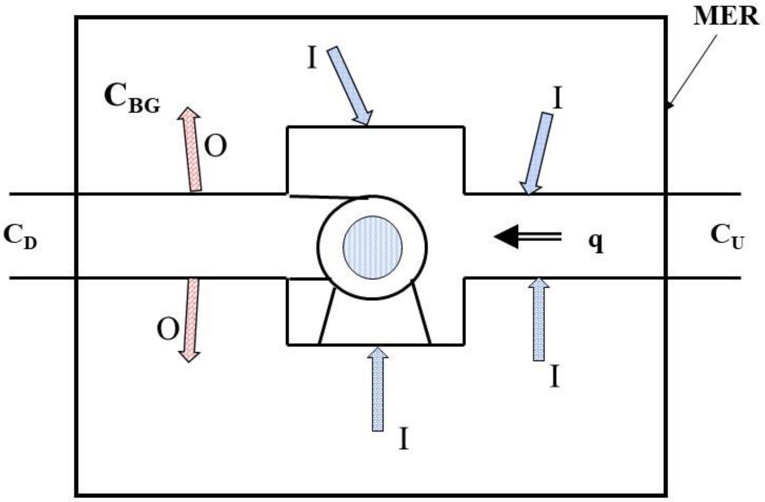


Figure 4. CREEVS undergoing inleakage with existing background concentration. Collectively the blue dotted arrows represent leakage into the duct(s) and AHU housing while the red dashed arrows represent outleakage from the duct and AHU housing.

Note that since $q_{mu} = S/C_{mu}$ equation (12) below can be written.

$$I = \frac{S \cdot \left(\frac{1}{C_{CRE}} - \frac{1}{C_{mu}}\right)}{\left(1 - \frac{C_{BG}}{C_{CRE}}\right)} \qquad (12)$$

where S = Tracer Injection Supply Rate

C_{CRE} = Mean CRE Tracer Concentration

C_{mu} = Mean Makeup flow (Upstream) Tracer Concentration

C_{BG} = Mean Background Tracer Concentration in MER

Note that the numerators of equation (11) or equation (12) represent two different forms of an equation which can be used to calculate inleakage in a constant injection test that has attained equilibrium assuming <u>*no*</u> background of tracer exists in the air that is entering the CRE via the CREEVS. In the remainder of this paper, this value will be denoted I_{INLEAK} .

The denominators of equations (11) and (12) represent a correction factor to allow for the fact the air leaking into the CREEVS ductwork or other ventilation system component(s) contains tracer gas. Hence the value of C_{CRE} is increased by the entrance of air into the CRE which contains additional tracer gas not provided by the injection system. This increase in C_{CRE} results in a calculated value of inleakage that is *lower* than the actual inleakage value.

This correction factor is the denominator of equation (12) and is denoted as CF as shown in equation (13) below.

$$CF = \left(1 - \frac{C_{BG}}{C_{CRE}}\right) \tag{13}$$

Note that equation (13) can be used to correct measured inleakage into the CRE if and only if the only leakage of additional tracer gas into the CRE is through components of the CREEVS. This implies that applying the CF correction will result in an *upper* bound (conservative value) on inleakage since inleaking air originating from places other than the MER will *not* contain tracer gas. Equations (11) and (12) can also be written as

$$I_{corrected} = \frac{I_{INLEAK}}{CF} \tag{14}$$

Note that the reciprocal of CF (denoted as M) represents the increase in the calculated inleakage due the existence of a tracer gas background concentration in the MER, i.e., M = 1/CF. M is a multiplicative factor for the CRE inleakage value that has been determined as if there were NO background concentration of tracer entering the CRE, i.e., if there is NO background concentration in the MER then M=1. Equation (14) becomes:

$$I_{corrected} = \frac{I_{INLEAK}}{CF} = I_{INLEAK} \cdot M \tag{15}$$

Equation (15) was used to calculate the corrected values for Pressurization Mode inleakage provided in Table 1.

Table 1

Inleakage Correction for Pressurization Mode CREEVS

(Concentration in ppb. Inleakage values in SCFM)

PLANT	CF	CALC. INLEAK	CORR. INLEAK	% INCREASE
A	0.603	1541	2558-FAIL	66
B	0.970	75	92-FAIL	3
C	0.781	90	90	28
D	0.966	527	548	4
E	0.774	63	81	29
F	0.861	208	241	16
G	0.606	49	97-FAIL	65
H	0.599	400	668	67
I	0.108	Invalid Test	Invalid Test	920!

a 2000 CFM allowable inleakage value
b 100 CFM allowable inleakage value exceeded due to requirement of +10 CFM for door opening/closing

INLEAKAGE CORRECTION FOR ISOLATION/RECIRCULATION CREEVS

It should be noted that a similar mathematical analysis also applies to the inleakage values calculated for a concentration decay test when the CREEVS is operating in a Recirculation or Isolation Mode. For this case the corrected inleakage value will represent an *upper* bound on the inleakage since the analysis assumes that no inleakage has occurred anywhere except for the CREEVS ductwork contained in the MER. Inleakage of air across any boundary that does not possess a tracer background would accordingly not require a correction to be made. Thus, by assuming that all inleaking air contains a tracer gas background, the resulting corrected inleakage value is larger than it would be if some of the inleaking air contained no tracer gas.

Recall that in a concentration decay test, the air inleakage rate is given by equation (3) which is written below as equation (16) with symbols previously defined.

$$A_{Measured} = \frac{q_{Total}}{V_{CRE}} \qquad (16)$$

The corrected inleakage value is obtained by augmenting the total air inflow in equation (16) with the Correction Factor, CF, as shown in equation (17) below.

$$A_{Corrected} = \frac{q_{Total}/_{CF}}{V_{CRE}} \qquad (17)$$

or equivalently,

$$A_{Corrected} = \frac{A_{measured}}{CF} = M \cdot A_{Measured} \qquad (18)$$

Equation (18) was used to calculate corrected inleakage values for the Recirculation Mode tests provided in Table 2 and Table 3. Table 2 is included to illustrate the calculation of individual CF values using decay concentration data points for a given plant. Note that in a concentration decay test, tracer gas values do not represent equilibrium values and the concentration values in both the CRE and the MER decrease with time. Table 3 provides a summary of the CF and M values calculated in Table 2.

Table 2

Inleakage Correction for Recirculation Mode CREEVS

(Concentration in ppb)

	Plant W			**Plant X**	
MEAN C_{CRE}	**MEAN C_{MER}**	**CF**	**MEAN C_{CRE}**	**MEAN C_{MER}**	**CF**
33.97	6.39	0.812	103.8	5.52	0.947
27.69	5.38	0.806	80.4	5.6	0.930
22.40	4.62	0.794	61.8	4.73	0.923
18.49	4.07	0.780	48.3	5.02	0.896
14.83	3.41	0.770	37.9	4.46	0.882
CF=	**0.792**		**CF=**	**0.916**	
MULTIPLIER=	**1.26**		**MULTIPLIER=**	**1.09**	

	Plant Y			**Plant Z**	
MEAN C_{CRE}	**MEAN C_{MER}**	**CF**	**MEAN C_{CRE}**	**MEAN C_{MER}**	**CF**
31.58	1.115	0.965	22.72	1.59	0.930
21.37	1.178	0.945	20.17	1.55	0.923
14.96	0.879	0.941	18.11	1.6	0.912
			16.13	1.62	0.900
			14.39	1.39	0.903
CF=	**0.950**		**CF=**	**0.914**	
MULTIPLIER=	**1.05**		**MULTIPLIER=**	**1.09**	

Table 3

Inleakage Correction Summary for Recirculation Mode CREEVS

(Inleakage values in SCFM)

PLANT	CF	M	CALC. INLEAK	CORR. INLEAK
W	0.792	1.26	1107	1395
X	0.916	1.09	424	462
Y	0.950	1.05	680	714
Z	0.914	1.09	279	304

DISCUSSION

The M factors for Pressurization Mode CREEVS in Table 1 range from 1.03 to 1.67. These multiplier factors imply that the inleakage calculated from the equilibrium concentration extant in the CRE assuming no background tracer concentration entering the CREEVS must be increased by between 3% and 67%. This increase may create a Tech Spec issue for those CREs whose corrected inleakage value exceeds the plant allowable (GDC 19) inleakage value. For three of the plants presented in Table 1, the measured inleakage exceeded the allowable inleakage value. For two of the failing plants remediation consisting of sealing ductwork, other air handling components, and/or walls separating the MER and CRE was required prior to retesting to achieve an acceptable inleakage value. The third plant was able to find additional calculational margin and thereby satisfy the GDC 19 operator dose criterion by recalculation of the plant habitability analysis.

Plant I exhibited a M value greater than 9! A value this large implies that the CRE and MER are directly communicating through significant openings in the CRE boundary. Furthermore, it implies that there is little to no dilution ventilation air provided to the MER. With the CREEVS operating, the CRE and MER are essentially indistinguishable from one another during tracer gas inleakage testing.

While it might be argued that such communication is rare, it should be noted that plant H also exhibited significant ventilation transfer from the CRE to the MER when the CREEVS was operating. During an initial inleakage test this issue was detected, and a remedial solution was implemented to allow testing to be continued. Copious quantities of fresh air (i.e., air not containing tracer) were provided to and exhausted from the MER using circulating fans located in an open doorway between the MER and the Turbine Deck in order to significantly dilute any tracer concentration within the MER. This allowed successful inleakage testing to be performed.

The data summary for Recirculation Mode inleakage testing provided in Table 2, provides mean concentration data for each plant over a 2 hour decay period as well as calculated CF values for each time step. The fact that CF values for each time step are approximately the same magnitude suggests that the assumption that inleakage occurs primarily though CREEVS ductwork in the MER is valid for these plants.

The M factors, as well as measured and corrected inleakage values for four plants are presented in Table 3. The M factors ranged from 1.05 to 1.26. These multiplier factors imply that the inleakage calculated from the concentration decay in the CRE must be increased by between 5% and 26%. For these plants, this increase did not create a Tech Spec issue.

CONCLUSIONS

It is apparent from the data provided in Tables 1 and 3 that for those MERs which are NOT incorporated into the CRE, a non-zero background tracer gas concentration surrounding the CREEVS requires a correction to the inleakage calculated using the formulas in ASTM Standard E741. For some of the plants tested the correction factor could be ignored since the uncertainty inherent in the overall inleakage calculation was significantly larger than the correction factor due to non-zero tracer concentration in the MER. For others, significant remediation and/or re-calculation was required to achieve acceptable CRE habitability.

We should note that for plants not included in this document however, a significant correction of calculated inleakage may be required. And, in a few of these plants, it is possible that ventilation communication between the CRE and the MRE is so large that for the purpose of tracer gas inleakage testing, the tracer gas concentration in the CRE and MRE are essentially the same. For these plants a means to dilute the tracer concentration in the MER is required.

Thus, it is strongly recommended that in all cases where the MER is not incorporated into the CRE, measurement of background tracer gas concentration in the MER should be undertaken during the course of a tracer gas inleakage test. The resulting correction factor

(M) should be applied to the inleakage value calculated using the equations provided in Standard E741.

Failure to apply this correction factor results in an ***underprediction*** of the actual inleakage value. Such an underprediction could result in the calculation of an inleakage value that satisfies the requirements of General Design Criterion 19 when, in reality, the true (i.e., corrected) inleakage value exceeds that allowable inleakage value. The allowable inleakage value is that value which results in the total dose to the operators during a design basis accident being less than 5 Rem for the duration of the accident. Exceeding this value is a violation of GDC 19 and Tech Spec habitability requirements for a given plant.

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