Neutral Pressure CREEVS Inleakage Measurements

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ABSTRACT

In 2007, a series of inleakage measurements was undertaken on the Control Room Envelope (CRE) of a two-unit PWR nuclear power plant in Japan. The test series described in this paper represents the first such testing undertaken at any PWR plant in Japan. This particular plant incorporates redundant emergency operating trains. In response to a potential emergency condition, the Control Room Envelope Emergency Ventilation System (CREEVS) isolates the CRE and enters a recirculation operating mode.

As a part of the inleakage testing program, repeat tests were undertaken on successive days. Inleakage testing utilized tracer gas techniques as described in US NRC Regulatory Guide 1.197. All testing was performed using written procedures based on ASTM Standard E-741.

In addition to obtaining inleakage data, an additional objective of this program was to investigate the reproducibility of tracer gas inleakage tests under nominally identical plant operating conditions.

For the A Train CREEVS, three tests were undertaken with five sets of samples taken 30 minutes apart from thirty-one different locations. An initial test obtained only three sets of samples taken from thirty-one different locations at 30 minute intervals. Tracer gas mixing was not good, yet the four tests yielded air inleakage rates exhibiting a standard deviation of the mean air inleakage rate of less than 3%.

To the knowledge of the authors, this is the first time that the repeatability of tracer gas inleakage measurements for nuclear power plant CREs has been systematically investigated. It appears that, at least for neutral pressure CREEVS, repeatability, and hence consistency, of the E-741 tracer gas test within the nuclear power plant control room environment is excellent.

1.0 Introduction

Since 1973 nuclear energy has been a national strategic priority in Japan because the nation is heavily dependent on imported fuel, with such imports accounting for 61% of energy production. In 2008, after the opening of 8 new nuclear plants in Japan, the country became the third largest nuclear power user in the world with 53 nuclear reactors. With all reactors operating, approximately 49,500 megawatts of power can be supplied. This represents 34.5% of Japan's electricity demand.

Both pressurized water and boiling water reactors are utilized within the Japanese nuclear power industry. In response to a potential emergency condition, all Japanese plants isolate the CRE and the Control Room Envelope Emergency Ventilation System (CREEVS) enters a neutral pressure (recirculation) operating mode.

Within Japan, nuclear power plants are regulated by the Nuclear and Industrial Safety Agency (NISA) which is a part of the Ministry of Economy, Trade, and Industry (METI). NISA, in particular, pays close attention to technological developments within the US nuclear power industry and to changes in the regulatory framework of the US NRC. With the origination of Generic Letter 2003-01and the subsequent publication of TSTF 448, considerable interest was expressed in Japan toward instituting an inleakage testing program similar to that being developed in the US.

In order to understand the technical and logistical issues involved in tracer gas testing in an operating nuclear power plant, Mitsubishi Heavy Industries (MHI) was tasked to develop a program for inleakage measurement in those plants which MHI provides support services on an ongoing basis.

In 2007, a series of inleakage measurements was undertaken on the Control Room Envelope (CRE) of a two-unit PWR nuclear power plant in Japan. The test series described in this paper represents the first such testing undertaken at any PWR plant in Japan. This particular plant incorporates redundant emergency operating trains.

In addition to obtaining inleakage data, an additional objective of this program was to investigate the reproducibility of tracer gas inleakage tests under nominally identical plant operating conditions. Accordingly, repeat tests were undertaken on successive days. Inleakage testing utilized tracer gas techniques as described in US NRC Regulatory Guide 1.197. All testing was performed using written procedures based on ASTM Standard E-741.

Differential pressure measurements between the MCR and all surrounding areas were also obtained during each inleakage test. These data demonstrate that the plant operating conditions during the four tests were essentially identical.

2.0 Measuring Building Air Flows Using Tracer Gases

There are three principal tracer gas techniques for quantifying airflow rates within a structure; namely, the tracer concentration decay method, the constant injection method, and the constant concentration method. All three of these techniques are incorporated in the most recent revision of ASTM Standard E741-00 "Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution" [1].

Basic conservation of mass considerations provide the following equations for the measurement of inleakage in a neutral pressure CRE [2,3]:

After an initial tracer injection into CRE, the concentration of tracer gas, C, decays according to the following equation (1)

$$C = C_0 \exp(-A \cdot t) \qquad (1)$$

where C_0 is the concentration at time t=0. The air exchange rate, A, is given by A= L/V. The units of A are air changes per hour (h^{-1} or ACH). The value of A represents the volume-normalized flow rate of "dilution air" entering the volume during the test interval. In equation (1) L is the inleakage rate, and V is the volume of the test structure.

This method requires only the measurement of relative tracer gas concentrations, as opposed to absolute concentrations, and the analysis required to determine A is straightforward. In use, equation (1) is often recast to the following form:

$$\ln C = \ln C_0 - A \cdot t \qquad (2)$$

In practice one obtains a series of concentration versus time points and then performs regression analysis on the logarithm of concentration versus time to find the best straight line fit to the form of the equation given by equation (2). The slope of this straight line is A, the air exchange rate.

As depicted in Figure 1, the natural logarithm of the tracer concentration decreases linearly with time. The slope of this line is A, the air exchange rate. To calculate the air inleakage rate, one must have independent knowledge of the test room volume from which,

$$L = A \cdot V \qquad (3)$$

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 measurement uncertainty, with the magnitude of this uncertainty depending on the extent of the departure from homogeneity.

In this paper, the total uncertainty of each air inleakage rate was calculated using the prescription provided in ANSI/ASME Standard PTC 19.1-1985 (Reaffirmed 1990) "Measurement Uncertainty" and represents 95% confidence limits. This analysis is based upon equations (2) and (3) for concentration decay tests. Uncertainties for all derived and measured quantities are incorporated into the analysis.

In simplest terms, a 95 % confidence limit means that if a measurement were to be repeated 100 times, 95 times the resulting value would lie between the Lower and Upper Confidence Limit. Statistically all values between the Lower Confidence Limit (LCL) and Upper Confidence Limits (UCL) are valid data. If, however, the Confidence Limits are relatively large there is no guarantee that any given measured value will lie close to the mean value.

Mathematically the inleakage rate data in this paper are quantified as a value, L, plus or minus a 95% Confidence Limit (Urss). In symbols one obtains an Inleakage value that lies between these extremes.

$$L - U_{rss} \le L \le L + U_{rss} \tag{4}$$

3.0 Inleakage Measurements

On successive nights in March 2007, tracer gas inleakage tests were undertaken on the Control Room Envelope (CRE) of a two-unit PWR nuclear power plant in Japan. As noted above the CREEVS enters a neutral pressure operating mode on receipt of an emergency signal.

The CRE encompassed three levels. The Main Control Room, a Downstairs West and East Chart Room, a Restroom, and a Janitor Closet are located on the middle level. A schematic drawing of the MCR is provided in Figure 2. Note that the Chart Rooms, the Restroom and Janitor Closet are located in a north annex (top of Figure 2) to the MCR and are contained within the CRE.

An Upstairs West and East Chart Room are located on a level above the MCR and are coincident with the Downstairs West and East Chart Rooms. These rooms could be accessed via a stairwell contained within the CRE.

The Cable Spread Room is located one level beneath the MCR. Access to this room was via an external stairwell.

For the A-Train CREEVS, an initial test obtained only three sets of samples taken from thirty-one different locations at 30 minute intervals. Three additional tests were undertaken subsequently with five sets of samples taken 30 minutes apart from the same thirty-one different locations. A P&ID of the CREEVS is provided in Figure 3.

Tracer gas injection occurred over a sixty minute interval using 50 ml syringes filled with pure SF6. Twelve syringes of SF6 were injected into the return side of the CREEVS ductwork.

In an attempt to achieve acceptable mixing of the tracer gas within the CSR and to increase the initial tracer gas concentration in the CSR, six additional syringes were released directly into the CSR. Syringe injection was accomplished by walking around the CSR while slowly depressing the syringe plunger. Each syringe was emptied over a ten minute period. Such an injection strategy is useful to obtain dispersion of tracer gas within a poorly ventilated (and hence poorly mixed) volume that exhibits substantial inleakage such as the CSR.

Six mixing fans were used in the north area of the CRE to assist the mixing of tracer gas. In addition, to further facilitate mixing throughout the MCR a number floor tiles in the chart room area were removed and axial fan/flex duct systems were emplaced to provide air beneath the east and west chart room raised floor. Axial fan/flex duct air moving systems were also used to provide air above the drop ceiling in the MCR as well as above the drop ceiling in the east chart room, as well as the kitchen, bathroom and janitor closet.

Mixing of the tracer gas within the CSR presented an especially difficult experimental challenge since there was only a single supply and a single return duct located on the east end of the room. Accordingly eight mixing fans and six axial fan/duct systems were placed in the CSR to assist with tracer gas mixing.

Even with this large number of mixing fans the CRE was not well mixed. The standard deviation of the mean concentration at each sample time interval ranged from approximately 30 % to 35 % thereby confirming that tracer concentration was poorly mixed throughout the CRE.

A plot of tracer concentration data versus time for one of the tests is provided in Figure 4. Also shown is the “best fit” regression line for the particular test. All four tests showed a similar scatter in the concentration values obtained at each time.

The poor mixing shown in the tracer concentration data and illustrated in Figure 4 is the result of a large amount of air inleakage occurring into both the MCR and the CSR at localized portions of the CRE boundary. Preliminary “Calibration” tests undertaken on previous days disclosed the existence of significant inleakage at two MCR access doors as well as at cable penetrations on the south wall of the CSR.

Air samples were obtained using individual 50 ml disposable polypropylene syringes. Within much of the CRE air samples were taken directly as grab samples. Air samples from a number of locations above drop ceiling panels, at elevations above floor level, and at a number of locations within the CSR were obtained using a dedicated pump/manifold sampling system.

Tracer gas concentration analysis was performed by means of two channels of Gas Chromatograph (GC) equipped with a non-radioactive electron capture detector. Throughout the test the analyzers were operated by MHI personnel.

Each analyzer was individually calibrated prior to each test. Calibration was undertaken using three SF6 in air calibration mixtures (49.3 ppb, 20.33 ppb and 9.95 ppb). The calibration response data was used to calculate a specific calibration curve for each analyzer. Note that daily individual calibration is accepted analytical chemistry laboratory practice used for precision analyses of chemical constituents.

Both analyzers exhibited response drift during the course of each test. One analyzer exhibited daily drift ranging from 0.4 % to 2.3 % of full scale. The other analyzer exhibited daily drift ranging from 3.0 % to 11.1 %. Accordingly a drift correction was made for each concentration value prior to calculation of inleakage rates. Table 1 provides information on each gas analyzer.

As noted above, there was simply too much outside air entering the CRE in localized regions to allow substantial tracer gas mixing to occur. Thus, while it was possible to undertake concentration decay tests in the absence of good mixing, the resulting uncertainty in the regression value of air inleakage rate was much larger than that which would result in the case of better tracer gas mixing.

However, it turned out that the poor mixing was repeatable during each test. Comparison of the inleakage data for each test was then possible. Measured inleakage values for the four tests are provided in Table 2.

4.0 Differential Pressure Measurements

Except for the Cal-02 test, differential pressure between the MCR and various surrounding rooms were measured during each tracer gas air inleakage test. Differential pressures were measured using two Setra Model 370 Digital Barometers.

Initially, both barometers were placed next to each other on the floor of the MCR and the units were “zeroed”. One unit (the mobile unit) was then moved to various locations and the pressure values noted at timed intervals. The indicated pressure values of the unit remaining in the MCR (the stationary unit) were also recorded at timed intervals. The mobile unit was ultimately returned to the stationary unit and both readings were again noted. This allowed a correction to be made for drift between the responses of the two units.

Differential pressures were then calculated between the various locations by differencing the drift corrected values of the two digital barometers. In some cases, elevation corrections were made to the readings of the mobile barometer to ensure that the differential pressure relative to the floor of the MCR was obtained.

Table 3 provides the measured differential pressures for three A-Train air inleakage tests. A positive value for differential pressure implies that the Main Control Room is at a higher pressure than the measurement location.

Differential pressures are plotted in Figure 5. As can be seen by inspection of this plot, the differential pressure conditions for the three tests were essentially identical. This suggests that comparison of the measured inleakage values for the purposes of evaluating repeatability of the measured data is valid.

It is also apparent from this figure that a number of areas adjacent to the CRE are at a higher differential pressure than the CRE, i.e., the CRE differential pressure is negative relative to these areas. These areas are most likely a source of a great deal of the inleakage air measured in this test program.

5.0 Conclusions and Discussion

While the standard deviations of the mean concentrations during each test ranged from 30% to 35%, the 95 % Urss uncertainty values for the inleakage ranged from approximately 12% to 15%.

Measured inleakage values for the four tests are summarized in Table 4 along with the corresponding 95% uncertainty values. The mean of four tests yielded inleakage rates exhibiting a standard deviation of the mean of less than 2.5%.

To the authors’ knowledge this is the first time repeatability data for inleakage testing within the nuclear power generating community have been published.

Especially in light of the poor mixing attained in each test, the agreement between the four tests is gratifying. It would be useful to repeat a comparable testing sequence for pressurization CREEVS to investigate the repeatability of tracer gas testing for this operating mode also.

6.0 References

1. ASTM, Standard E 741-00, 2000 (Reapproved 2006), “Standard Test Method for Determining Air Change Rate in a Single Zone by Means of a Tracer Gas Dilution”, ASTM, Philadelphia, PA

2. Lagus, P.L., Taylor, J., Anderson, K., and Pearson, J.R., 2000, “Air Inleakage Testing at Crystal River Unit 3” in Proceedings of the 26th NRC/DOE Air Cleaning Conference, Richland, WA

3. Lagus, P.L., and Grot, R.A., 1996, “Control Room Envelope Unfiltered Air Inleakage Test Protocols" in Proceedings of the 24th NRC/DOE Air Cleaning Conference, Portland, OR

Table 1

Tracer Gas Analyzers

Manufacturer/Model	Detector Type	Analysis Range
J Science Ltd. Model G2800	Non-Radioactive ECD	50 ppb to 10 ppb*
J Science Ltd. Model GC7000	Non-Radioactive ECD	50 ppb to 10 ppb*

* Analyzer responded to concentration levels down to1 ppb, but no chromatograph calibration data was obtained for a 1 ppb calibration point.

Table 2

Measured Inleakage Values

Test	CREEVS Train	Inleakage Rate (m^3/min)
Cal-02	A	97
1	A	98
2	A	97
3	A	102

Table 3

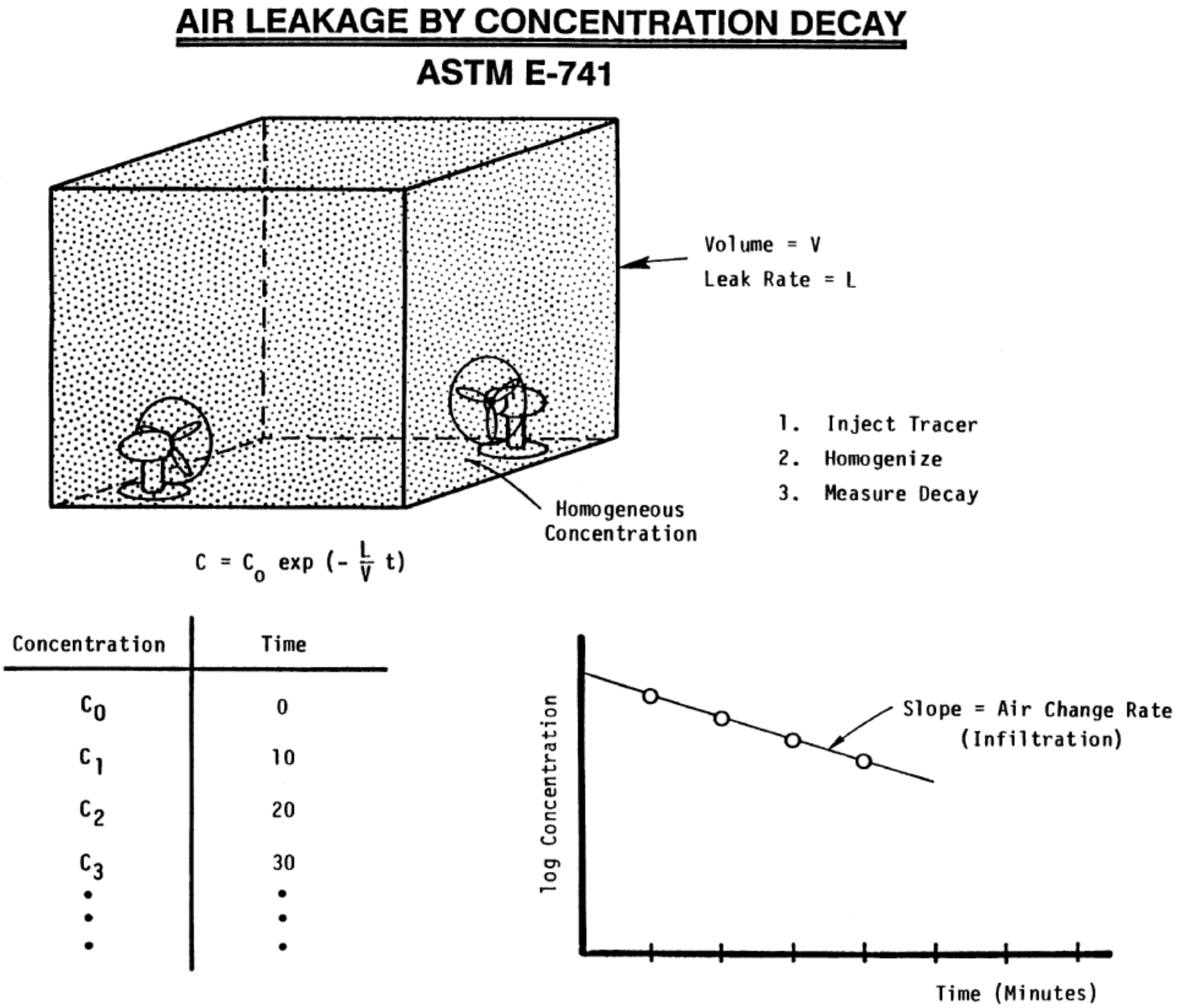
Differential Pressure Measurements
(mm H_2O)

STATION	TEST 1	TEST 2	TEST 3
EAST HALL @ 17.3m	-2.5	-2.6	-1.8
RAD AREA ENTR @ 23.8m	1.5	1.6	1.0
COOL RAD AREA @ 23.8m	1.6	1.6	1.2
TURBINE BLDG @ 17.3m	-3.3	-3.6	-2.8
WEST ALCOVE @ 17.3m	-2.7	-2.7	-1.5
WEST HALL @ 17.3m	-1.8	-2	-1.1
WEST LAND CSR @ 14m	NM	-1.1	0.3
CABLE SPRD RM @ 13.2m	0.6	0.8	1.2
2B BATT RM @ 7.7m	7.0	7.1	7.2
2A BATT RM @ 7.7m	6.6	6.4	6.4
U2 SWTCH GEAR RM @ 7.7m	4.8	4.9	5.1
SWG HALL @ 7.7m	-2.7	-3	-1.8
1B BATT RM @ 7.7m	7.7	7.7	8.0
1A BATT RM @ 7.7m	7.8	7.5	7.9
U1 SWTCH GEAR RM @ 7.7m	2.3	2.3	2.6
TURBINE BLDG @ 9.8m	-3.3	-3.5	-2.0

Table 4

Mean Inleakage Value with 95% Urss

Test	CREEVS Train	Inleakage Rate (m^3/min)	Urss (m^3/min)	Urss (%)
Cal-02	A	97	15	15.0
1	A	98	13	13.3
2	A	97	13	12.9
3	A	102	12	11.9
	Mean= **Std Dev=** **% Std Dev=**	**98.5 m^3/min** **2.38 m^3/min** **2.4 %**		



$$C = C_0 \exp\left(-\frac{L}{V} t\right)$$

Concentration	Time
C_0	0
C_1	10
C_2	20
C_3	30
•	•
•	•
•	•

Figure 1. Tracer Concentration Decay Test (ASTM E741)

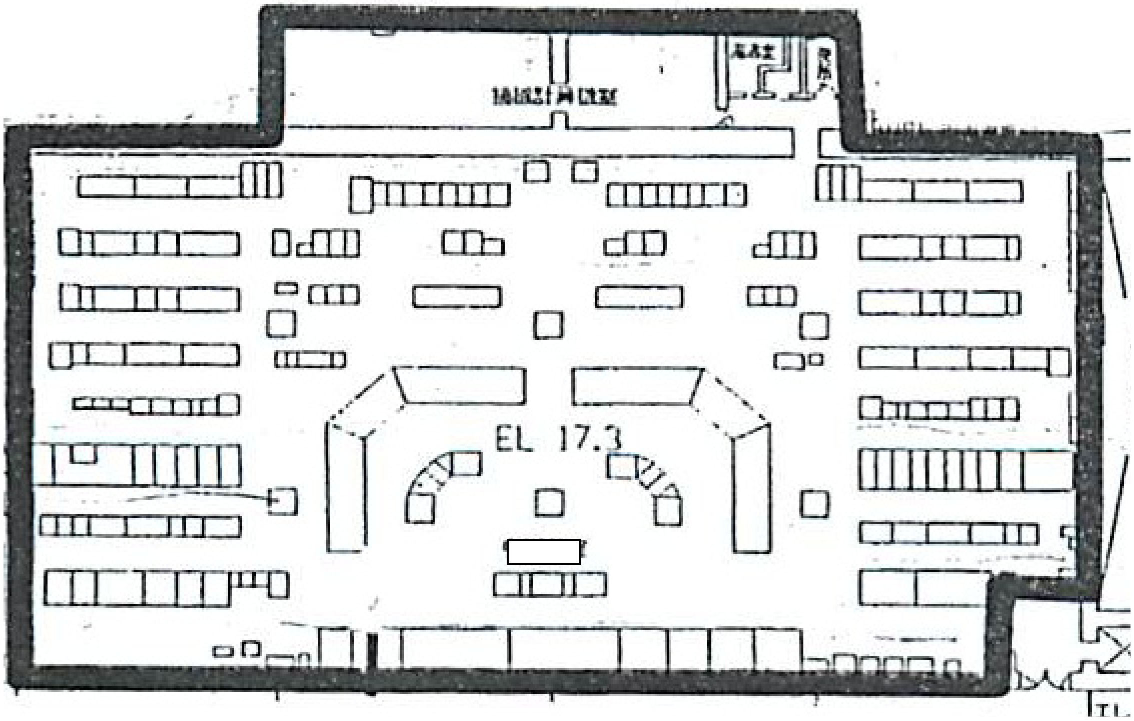


Figure 2. Plan view for MCR level of CRE (Note that north is “up” in Figure)

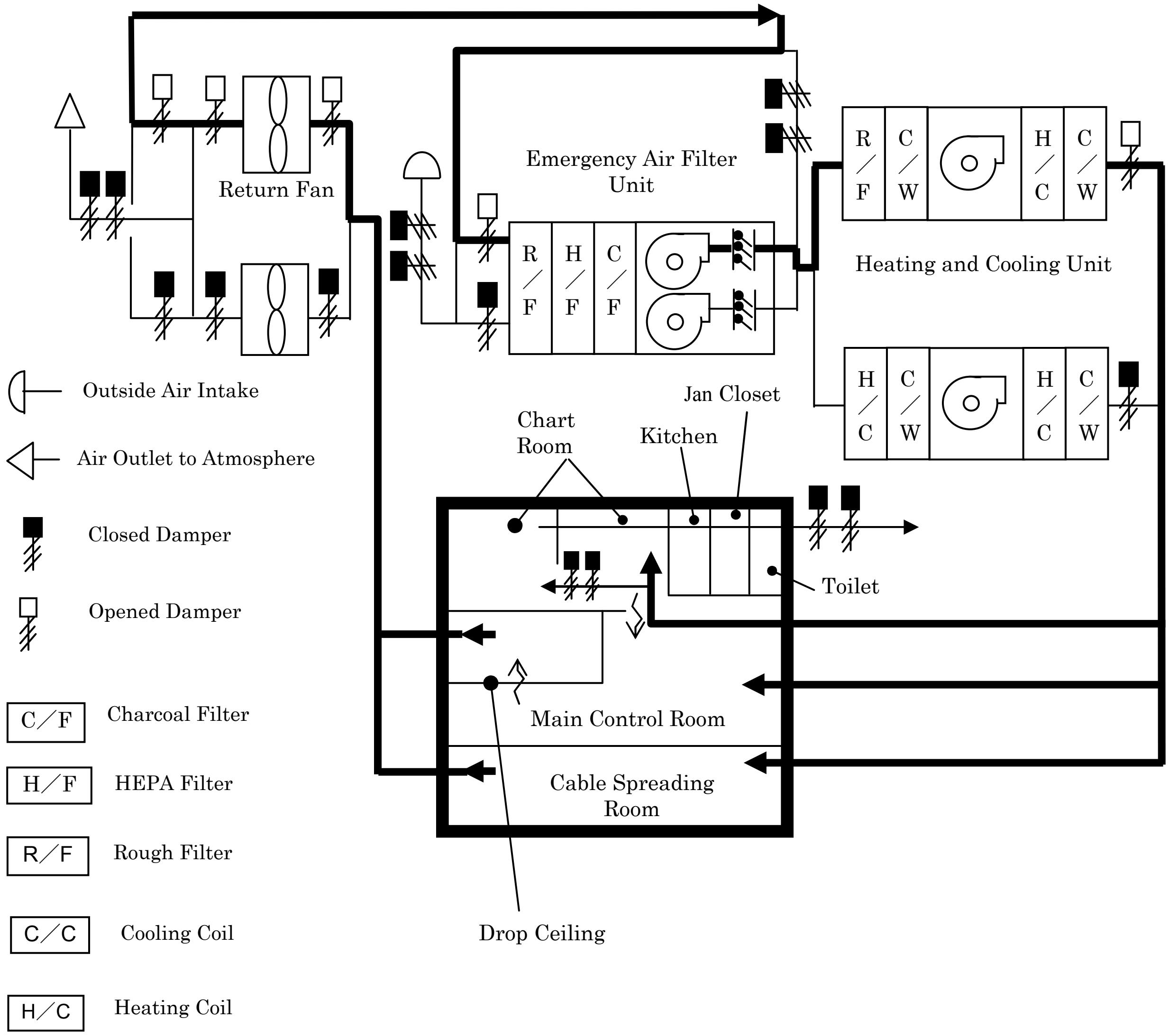


Figure 3. P&ID of CREEVS.

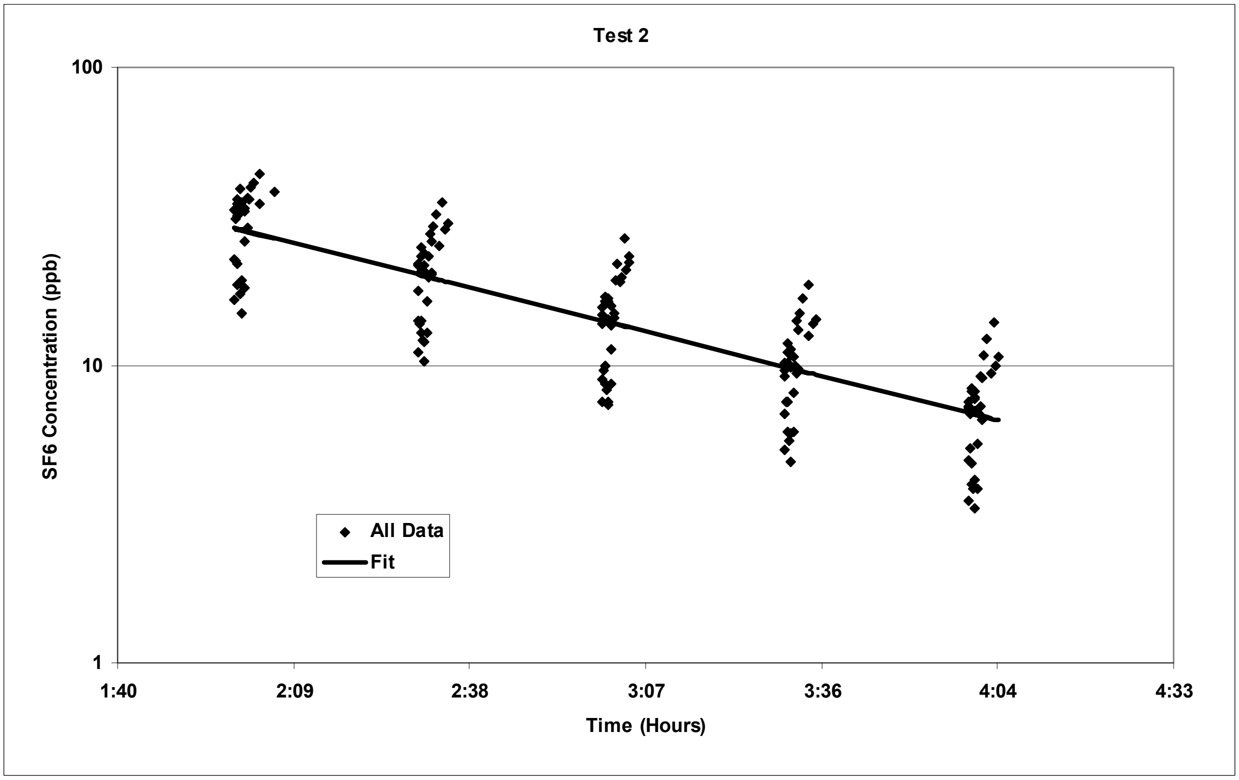


Figure 4. Plot of concentration data and “best fit” regression line.

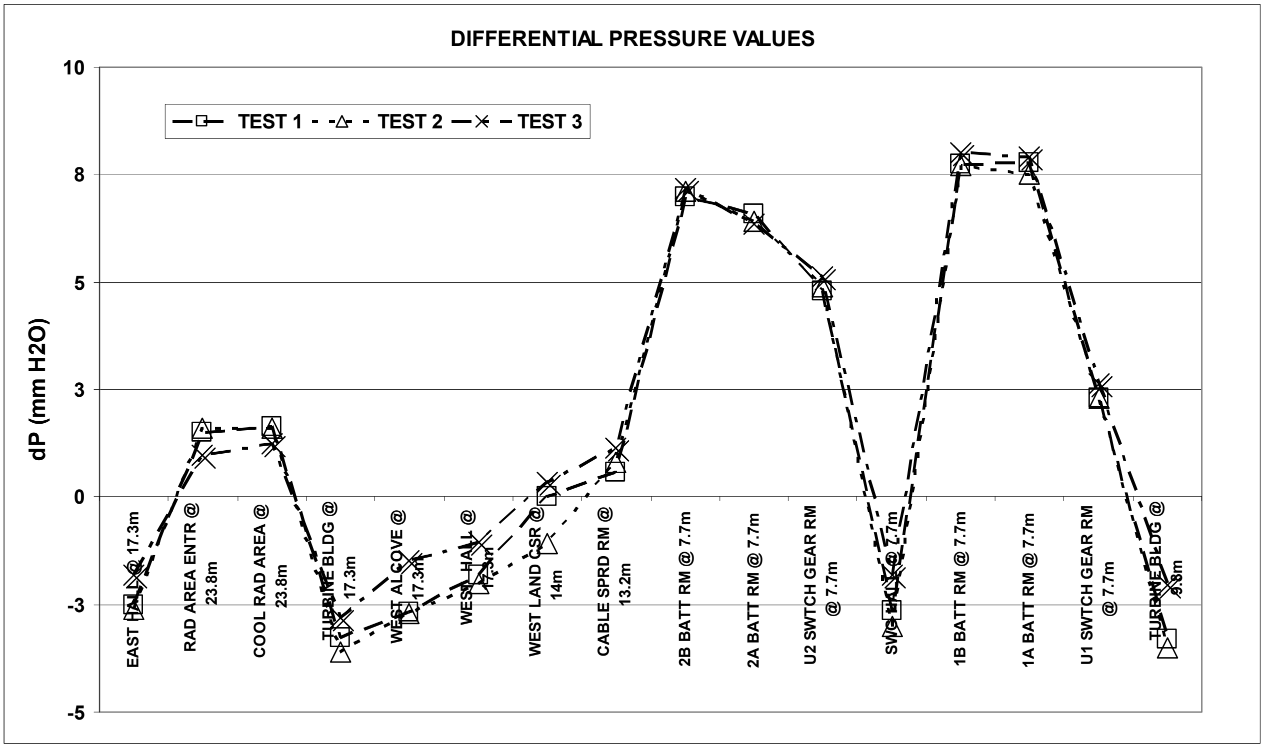


Figure 5. Plot of Differential Pressure measurements for three inleakage tests..

Neutral Pressure CREEVS Inleakage Measurements

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Japan’s Nuclear Power Industry

- In 2008 Japan became the third largest nuclear power user in the world with 53 nuclear reactors
- With all reactors operating, approximately 49,500 megawatts of power can be supplied
  - This represents 34.5% of Japan's electricity demand
- Both pressurized water and boiling water reactors are utilized within the Japanese nuclear power industry
- In response to a potential emergency condition, all Japanese plants isolate the CRE and the CREEVS enters a neutral pressure (recirculation) mode

Japan’s Nuclear Power Industry

(Cont’d)

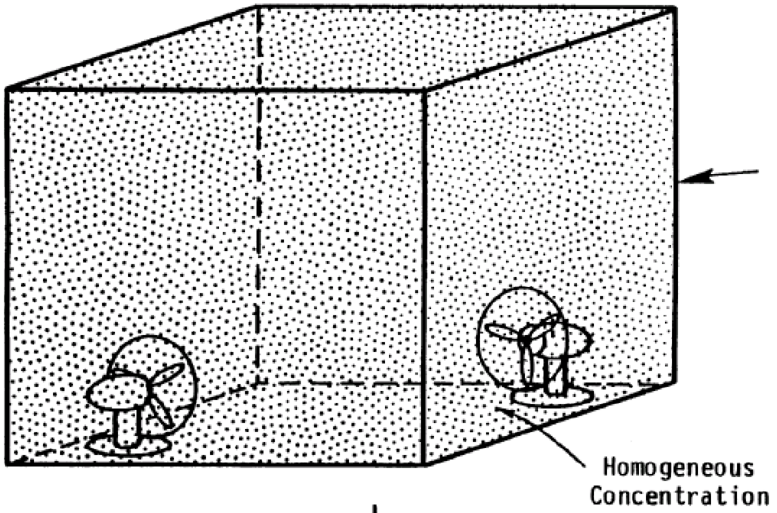
- Nuclear power plants are regulated by the Nuclear and Industrial Safety Agency (NISA) which is a part of the Ministry of Economy, Trade, and Industry (METI)
- Generic Letter 2003-01 and TSTF 448 created interest for an inleakage testing program similar to that being developed in the US.
- Mitsubishi Heavy Industries (MHI) was tasked to develop a program for inleakage measurement in those plants for which MHI provides support services

Objectives of Testing Program

- Measure Inleakage using ASTM E741 Concentration Decay Tests
- Understand the technical and logistical issues for tracer gas testing of inleakage in Japanese nuclear plants
- Develop procedures for future inleakage testing based on ASTM Standards
- Train MHI personnel in test techniques
- Investigate reproducibility of tracer gas inleakage measurement

AIR LEAKAGE BY CONCENTRATION DECAY

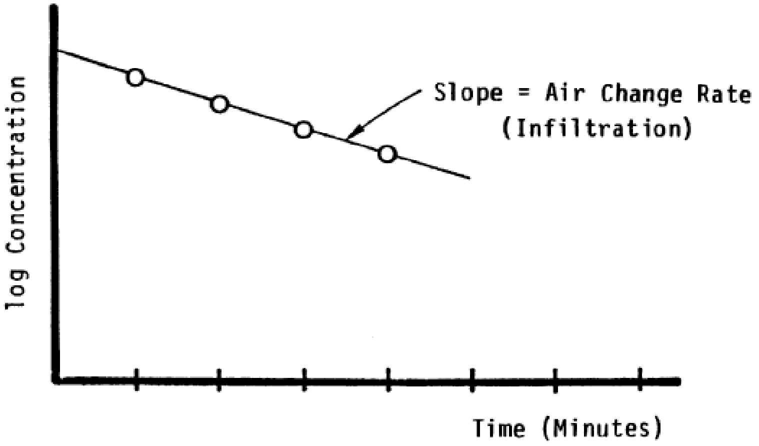
ASTM E-741



1. Inject Tracer
2. Homogenize
3. Measure Decay

$$C = C_o \exp\left(-\frac{L}{V} t\right)$$

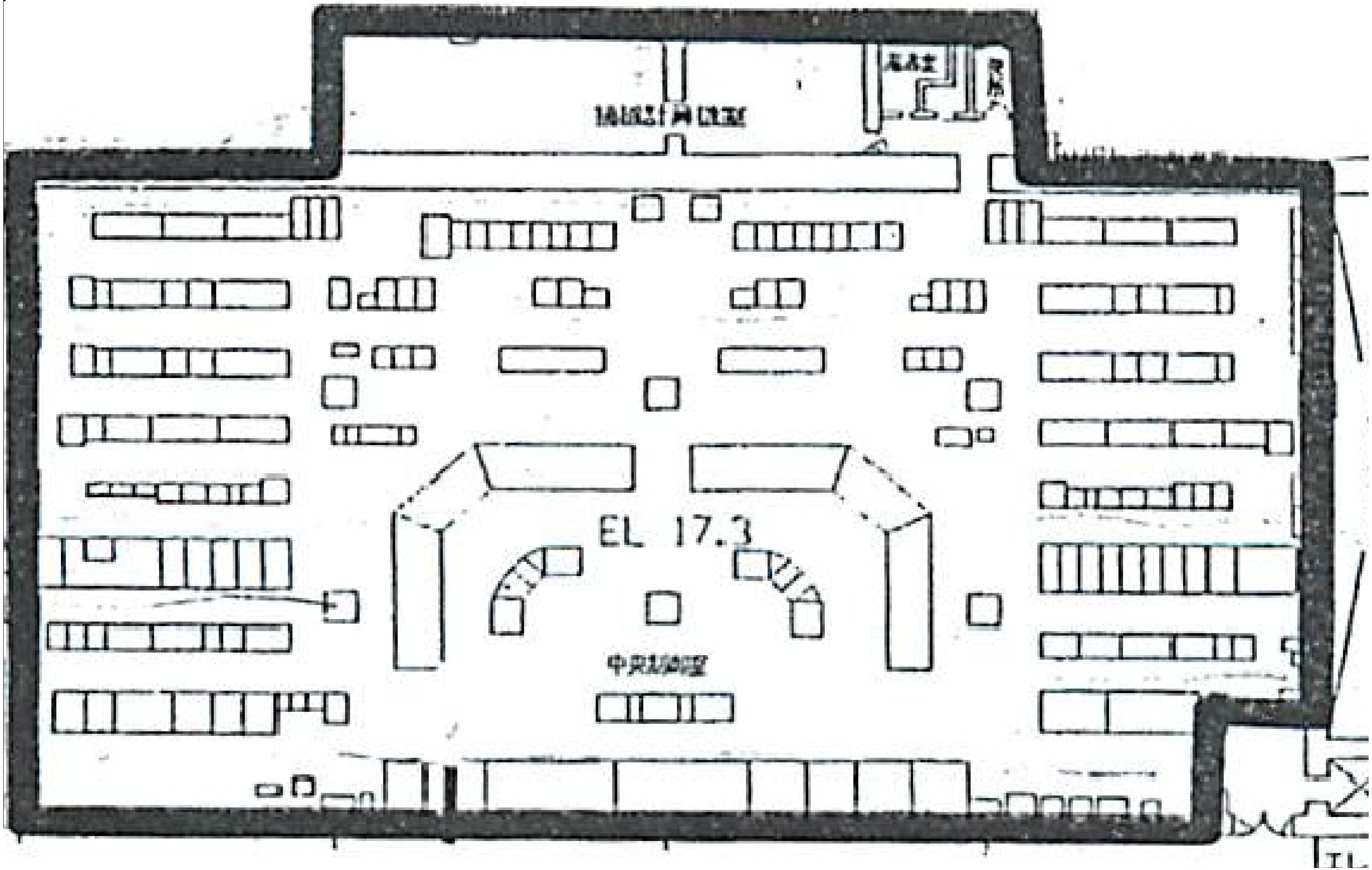
Concentration	Time
C_0	0
C_1	10
C_2	20
C_3	30
•	•
•	•
•	•



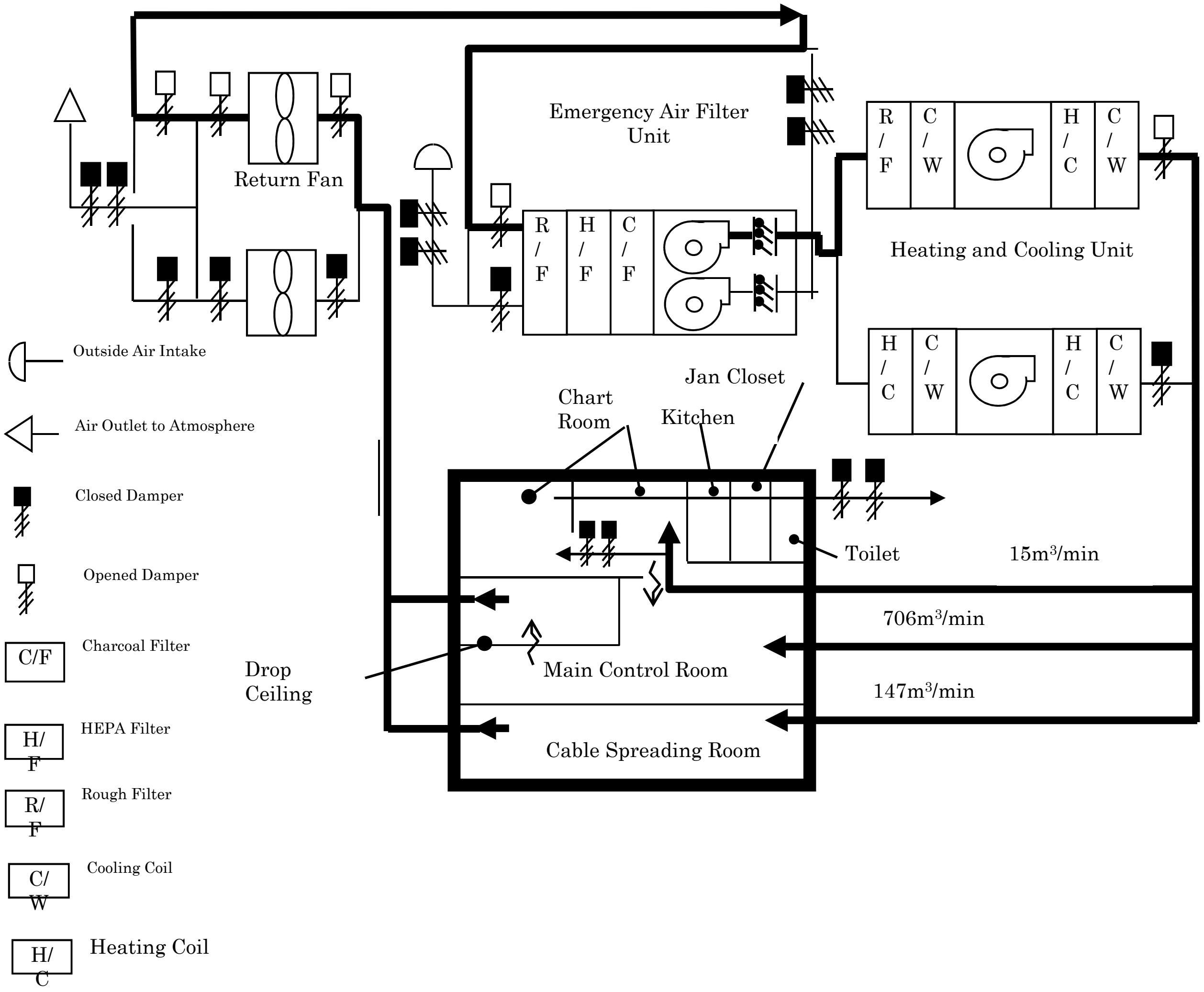
The CRE

- Dual Unit PWR
  - Located on Northern Coast of main island of Japan
- Three level CRE
  - Upper level annex
  - MCR
  - Cable Spread Room
- CRE isolates upon emergency signal
- Redundant CREEVS located outside the CRE
- CREEVS are neutral pressure (recirculation) systems

Main Level of CRE



P&ID

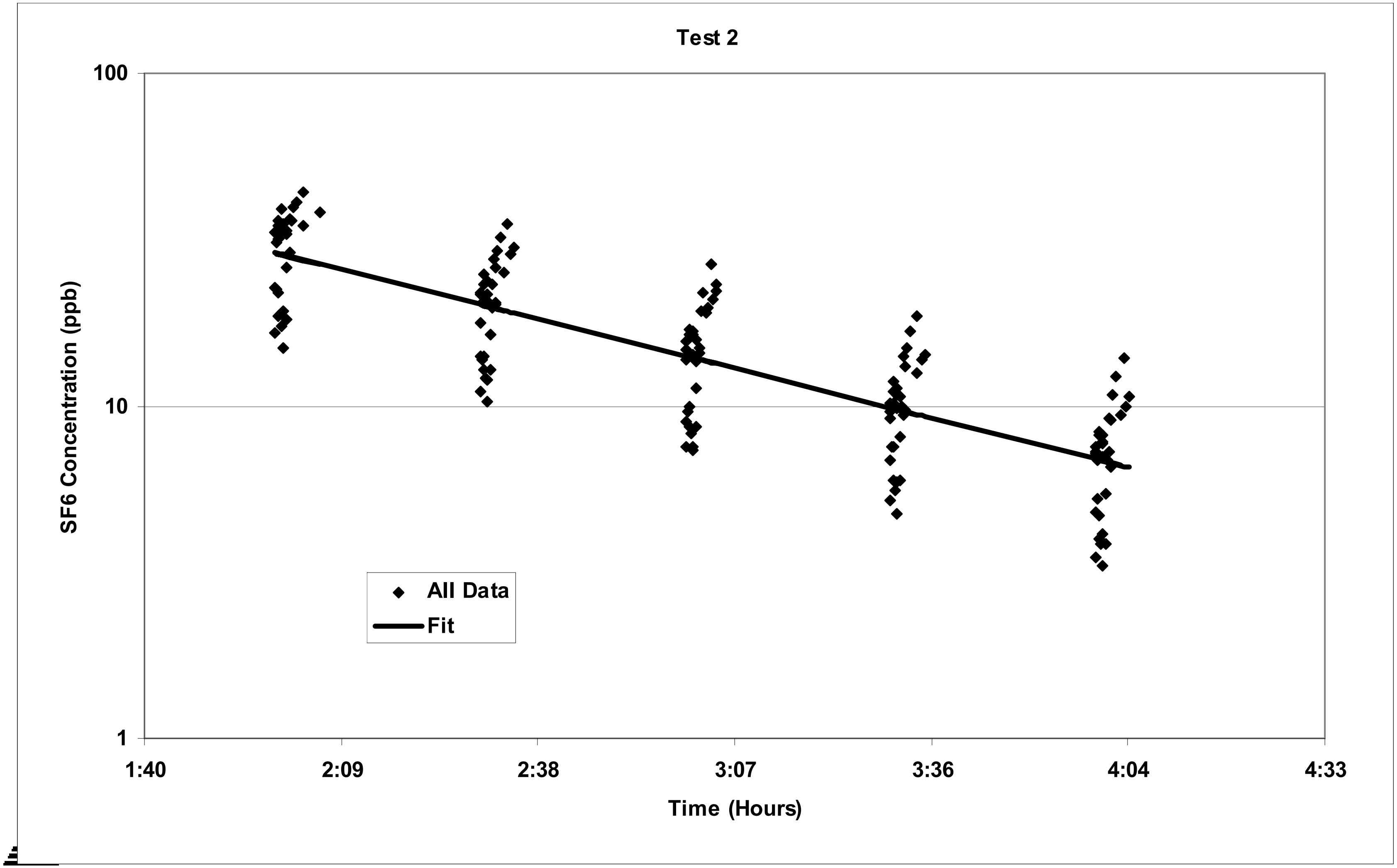

Return Fan
Emergency Air Filter Unit
R / F
H / F
C / F
R / F
C / W
H / C
C / W
Heating and Cooling Unit
H / C
C / W
H / C
C / W
Jan Closet
Chart Room
Kitchen
Toilet
15m³/min
706m³/min
147m³/min
Drop Ceiling
Main Control Room
Cable Spreading Room
Outside Air Intake
Air Outlet to Atmosphere
Closed Damper
Opened Damper
C/F
Charcoal Filter
H/F
HEPA Filter
R/F
Rough Filter
C/W
Cooling Coil
H/C
Heating Coil

Four Repeat Inleakage Tests

(A-Train)

- One test obtained samples from 31 different locations at three sample intervals 30 minutes apart
- Three subsequent tests obtained samples from the same 31 different locations at five sample intervals 30 minutes apart
- Differential pressures were measured relative to surrounding areas during each test
- Standard Deviation of Mean CRE concentration at any sample interval ranged from 30% to 35%
  - Poor Mixing of tracer gas

Concentration Decay Data



Origin of Concentration Scatter

- **Inleakage at MCR entry way doors**
- **Inleakage through penetrations in CSR walls**
  - **Exacerbated by differential pressure distribution**
- **Location of air distribution network in CSR**
- **Lack of air distribution to upper level of MCR annex during emergency operation**

ANSI/ASME Standard PTC 19.1 "Measurement Uncertainty"

- **Combines both Bias or Systematic Uncertainties of the measurement equipment with Random Uncertainties of the actual measured data**
- **Provides Confidence Limits (Chosen as 95%)**
- **Substitutes a calculational format for subjective "engineering judgment" uncertainty analysis**

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ANSI/ASME Root Sum Square Uncertainty Urss

$$U_{rss} = \pm\left[\left(B\right)^{2} + \left(t_{95} \bullet S\right)^{2}\right]^{1/2}$$

- B= Systematic Uncertainties (Bias) in Measurement Apparatus
- S= Standard Deviation of Measured data
- t95= Student’s “t” distribution value

95% Confidence Limits

- A 95 % confidence limit means that if a measurement is repeated 100 times, 95 times the resulting value will lie between the Lower and Upper Confidence Limit
- Mathematically the inleakage rate data in this paper are quantified as a value, L, plus or minus a 95% Confidence Limit (Urss)

$$\mathrm{L} - \mathrm{U}_{\mathrm{rss}} \leq \mathrm{L} \leq \mathrm{L} + \mathrm{U}_{\mathrm{rss}}$$

Decay Test Equations

$$C = C_0 \bullet \exp(-A \bullet t)$$

$$A = L_{INLEAK} / V$$

$$L_{INLEAK} = A \bullet V$$

Measured Inleakage Rates

CREEVS Train	Inleakage Rate (m^3/min)	Urss (m^3/min)	Urss (%)
A	97	15	15.0
A	98	13	13.3
A	97	13	12.9
A	102	12	11.9

Mean Inleakage Value

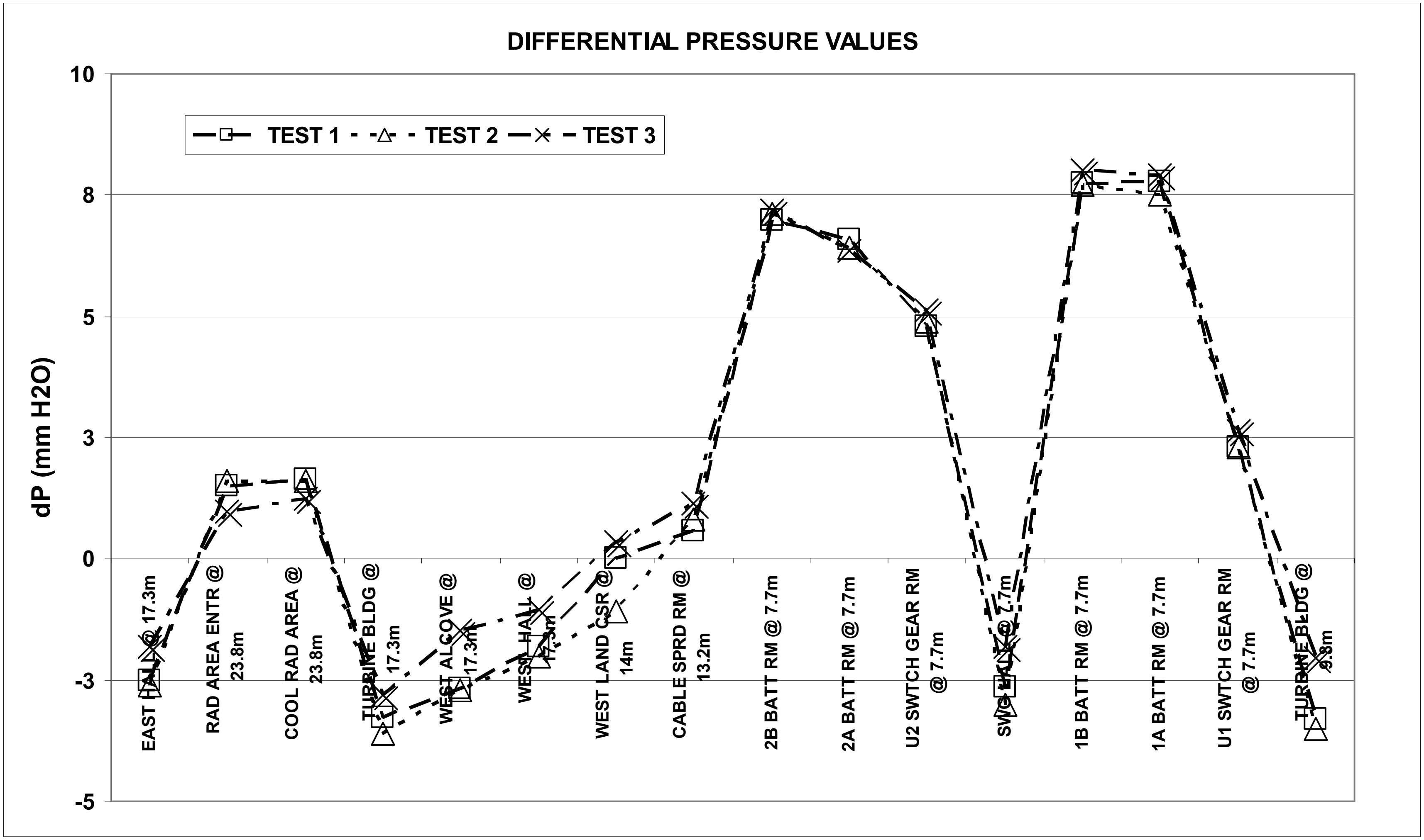
Mean=	98.5 m^3/min
Std Dev=	2.38 m^3/min
% Std Dev=	2.4 %

Major Assumption

The statistical analysis on the previous slide is valid only if the operation of the CREEVS and surrounding HVAC systems is (*__approximately) the same__*)

from test to test

dP Values for Three Tests



Conclusions

- In the nuclear power plant context, the Concentration Decay Test (ASTM E741) is extremely repeatable
- Even in the case of very poor mixing within the CRE, it is possible to extract useful inleakage information by repetition of the inleakage test
  - CREEVS and surrounding HVAC systems must provide similar differential pressures for each test
- Inleakage testing program is now ongoing in Japan