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Reactor Containment Dependability Analysis in Safety Critical Nuclear Power Plants: Design, Implementation and Experience

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***Abstract*—The use of nuclear energy to generate electric power is crucial in meeting the high energy demand of modern economy. The dependability analysis of nuclear power plants has been a critical issue and the reactor containment is the most important safety structure acting as a barrier against the release of radioactive material to the environment. In this paper, we analyze the dependability of the reactor containment. We also propose a tool for design, implementation, and V&V to enhance the dependability of reactor containment through an integrated leakage rate test. Our practical experiences in the on-site tests are also discussed.**

Keywords- containment; leakage rate; ILRT; VLRT; V&V.

I. INTRODUCTION

Reactor containment is a critically engineered safety feature (ESF) in nuclear power plants (NPPs). The main function of containment is a leak-tight barrier against the release of radioactivity to the environment. The reactor confines the mass of radioactive materials inside the containment, which plays an important role in the recent nuclear crisis of Fukushima I Nuclear Power Plant in Japan. The study of the reactor containment dependability in this paper is crucial in addressing the safety concerns raised by the recent incident. A typical containment is illustrated in Fig. 1. The typical containment is consisting of a structure enclosing the reactor pressure vessel (RPV), suppression pool, electrical and mechanical penetrations, equipment access hatches, air lock doors and hatches, and seals and isolation valves. In the current Nuclear Reactor Commission (NRC) regulation, the Title 10 (10CFR50 Appendix J) specifies the integrated leakage rate test (ILRT) for pre-operational and periodic verification of the leak-tight integrity of the reactor containment [1].

Type A test, known as integrated leakage rate test (ILRT), adopts the Absolute Test Method using Ideal Gas Law to compute dry air masses in the containment. The Absolute Method assumes that the free air volume of containment is constant, i.e., changes of temperature and pressure are not significant enough to affect the containment structure. Several methods are proposed to compute leakage rate based on the Absolute Method. We adopt the standard Mass Point (MP) Method [2], [3]. Table I [4] shows the historical data of leakage rate and calculated leakage areas. Table I demonstrates that the ILRT is effective and the calculated lower bound of leakage area by which this test passes.

Type B test is used to measure leakage across containment boundaries such as penetrations, doors and hatches, and seals. Type C test is used to measure leakage of isolation valves. Type B and type C tests are also referred to as Local Leakage Rate Test (LLRT). The LLRT is called the penalty that shall be added to the 95% Upper Confidence Limit (UCL). Detailed explanation of UCL is given in Section III.

This paper mainly discusses the design and implementation of the ILRT. We conduct software verification and validation (V&V) on the procedure. We also present our practical experiences of operational NPP ILRT to validate the procedure.

II. BACKGROUND AND OVERVIEW

The main purpose of an ILRT is to establish the acceptance criteria, which assure that leakage through the reactor containment does not exceed allowable leakage rate and guarantee the integrity of containment. The regulation

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TABLE I. ILRT LEAKAGE AREA DATA

Reactor Name	Containment Volume ft.3	Leakage Rate wt%/24h	Area sq. in.
Brunswick-2	2.9E+05	1.25	0.0092
Brunswick-2	2.9E+05	6.4	0.047
Fitzpatrick	2.9E+05	0.545	0.0040
LaCrosse	2.6E+05	0.11	0.0007
LaCrosse	2.6E+05	0.62	0.0041
Surry-2	1.8E+06	0.3	0.014
Surry-2	1.8E+06	1.0	0.046

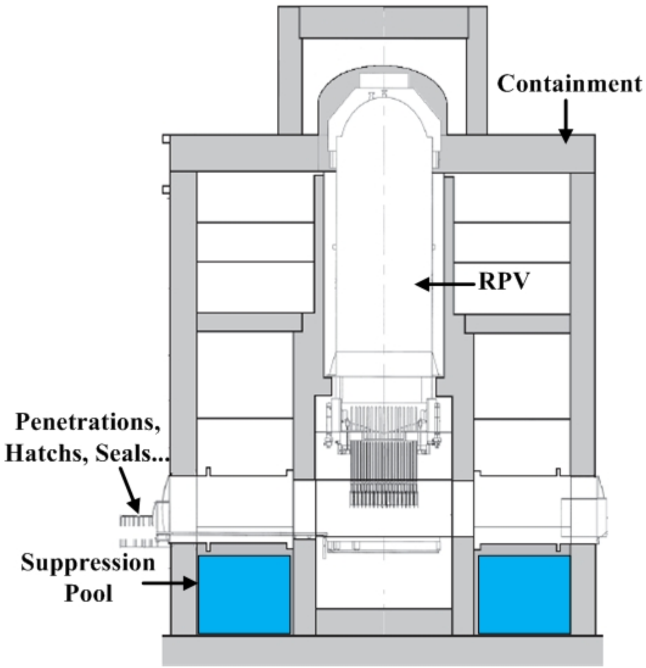

Figure 1. Overview of Reactor Containment

10CFR50 Appendix J, also referred to ANSI/ANS-56.8 [2][3], is the current regulation specifying the testing requirements for pre-operational and periodic verification of the ILRT [1]. The test procedure in the NPP specifies that the pre-operational test shall follow the criteria in [2] while the periodic operational test should follow those in [3]. The application we develop is based on the test procedure.

There exists literatures discussing the enhancement of reliability for containment through an ILRT [5][6]. In [5], the critical factors are considered in decision making to ensure containment reliability while [6] reviewed the ILRTs reported in USA and in European countries. They did not address the applicability of the ILRT. In this paper, we present a practical and thorough application for the ILRT design, implementation, and software V&V.

III. DEFINITIONS

We first define terminologies used in the following sections [1-3].

1. Data set: The set of readings from all test instruments at each time point of the data acquisition system (DAS).
2. Instruments: There are four kinds of instruments in the test.

   (1) Dry bulb temperature (thermal element) sensors detect the temperature in the containment.

   (2) Dew point temperature (dew cell) sensors detect the dew point in the containment used to calculate the saturate vapor pressure.

   (3) Pressure meters detect the absolute pressure in the containment.

   (4) Flow meters measure the flow in the containment.

   (5) Level sensors detect the water level in suppression pool.

   All the instruments are acquired by DAS periodically, i.e., every 5 minutes, during the test. Thermal element (TE) 、dew cell (DEW) and level instruments are acquired via Modbus protocol over TCP/IP while pressure and flow meters are acquired via RS232 protocol.

3. L_a (wt%/24h): The maximum allowable leakage rate at pressure P_a. L_a is 0.5%/24h according to the test procedure.
4. L_{am} (wt%/24h): Measured leakage rate at pressure P_a.
5. L_c (wt%/24h): The composite containment leakage rate measured after L_o is superimposed.
6. Leakage (kg): The quantity of fluid escaping from the containment.
7. Leakage rate (wt%/24h): The rate at which the leakage escapes from the containment at a specified test pressure.
8. L_o (wt%/24h): The known leakage rate superimposed on the containment during the verification leakage rate test (VLRT). L_o shall be between 0.75 L_a and 1.25 L_a.
9. L_t (wt%/24h): The maximum allowable leakage rate at pressure P_t. L_t shall be $L_a(L_{tm}/L_{am})$ if L_{tm}/L_{am} is not greater than 0.7, otherwise L_t is set as $L_a(P_t/P_a)$.
10. L_{tm} (wt%/24h): Measured leakage rate at pressure P_t.
11. Mass point analysis method: A standard method to calculate dry air mass in the containment utilizing the Ideal Gas Law in each data set during the test. This method relies upon a regression analysis (least squares fit) to the contained dry air mass with respect to time. The leakage rate is then determined from the ratio of the slope to the intercept of the line and is expressed as units of percent per 24 hours.
12. P_a (kPa): The peak containment internal pressure. P_a is 379.825 kPa according to the test procedure.
13. P_t (kPa): The reduced containment internal pressure. P_t should be less than P_a but no less than 0.5 P_a.
14. P_a ILRT: Peak pressure test shall be conducted at P_a and L_{am} shall be less than $0.75L_a$. The duration shall be at least 24 hours for a pre-operational test and at least 8

hours for a periodic test. A minimum of 30 data sets shall be recorded at approximately equal time intervals.

15. P_a VLRT: The verification test after P_a ILRT is conducted. The duration shall be at least 4 hours with a minimum of 15 data sets recorded at approximately equal time intervals. L_c shall be between (L_o+L_{am}-0.25L_a) and (L_o+L_{am}+0.25L_a).
16. P_t ILRT: Reduced pressure test shall be conducted at P_t and L_{tm} shall be less than 0.75L_t. The duration shall be at least 24 hours for a pre-operational test and at least 8 hours for a periodic test. A minimum of 30 data sets shall be recorded at approximately equal time intervals.
17. P_t VLRT: A verification test after P_t ILRT is conducted. The duration shall be at least 4 hours with a minimum of 15 data sets recorded at approximately equal time intervals. L_c shall be between (L_o+L_{tm}-0.25L_t) and (L_o+L_{tm}+0.25L_t).
18. Upper Confidence Limit (UCL): A value constructed from test data that places a statistical upper bound on the true leakage rate. UCL is calculated at 95% confidence level according to the test procedure.

IV. Design and Implementation

The trend of the Instrumentation and Control (I&C) systems in newly constructed NPP is to replace the obsolete analog hard-wired systems with the contemporary digital and distributed processor based systems [7]. The I&C system here is a distributed control information system (DCIS). TE and DEW readings are acquired via DCIS Gateway. Pressure and flow values are acquired from those meters located in the Test Cart. Modem acts as a converter between RS232 and fiber optic signal. Compared to [8], the enhanced system adds two workstations as illustrated in Fig. 2. The enhanced system has two main features: (1) DAS is used only to acquire data while the workstation serves as an interface for data analysis. (2) Since the acquisition process can not be interrupted and data shall be acquired periodically within the accuracy of 1min/24hr, the enhanced system is guaranteed to meet the criteria. The system structure is fault tolerant. Any single component failure can be tolerated. The application uses National Instruments LabVIEW™ to acquire data and to serve as an interface. We use VC++ to compute and analyze data and use MySQL™ database to store data. The application structure is illustrated in Fig. 3.

A. Design

We design six flows in this application. Test flow is the main flow involving the other five flows. Das flow is a process of data acquisition. P_t and P_a flows describe the processes in pressurization and stabilization ILRT periods. The P_t and P_a analysis flow describes the processes to calculate data sets, leakage rate, and curvature & data scatter limits.

The terminology in the design section such as methods in dry air mass calculation, Instrumentation Selection Guide (ISG), temperature & atmosphere stabilization, and curvature & data scatter limits will be described briefly in the implementation section.

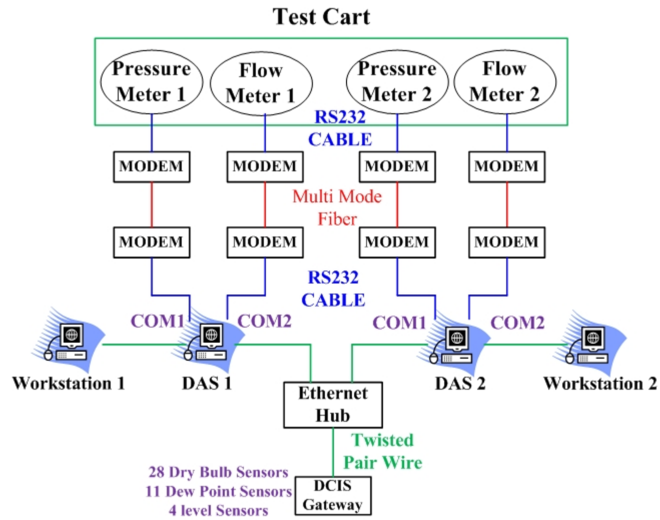

Figure 2. Illustration of Physical Structure

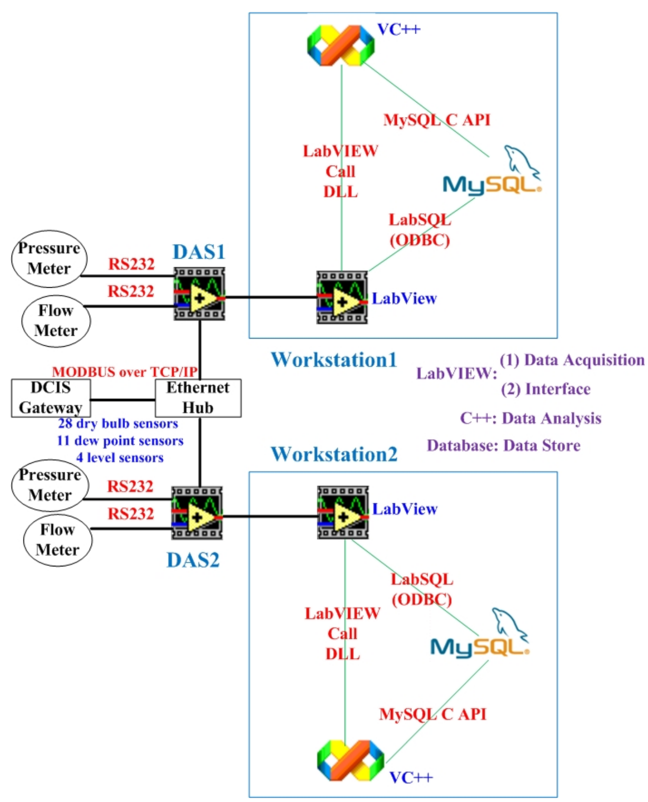

Figure 3. Illustration of Application Structure

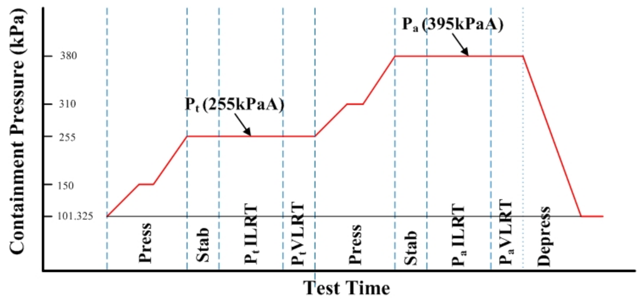

Figure 4. Test Time versus Containment Pressure

B. Implementation

The implementation follows the flows described in the design section. Fig. 4 depicts the practical trend of test time and containment pressure during the test. The following is the brief description of terminologies we implement in this application.

1. Absolute Method:

The Absolute Method uses Ideal Gas Law to compute dry air masses in the containment. Equation (1) provides an approximation that calculates saturate vapor pressure from dew point temperature, where DEW denotes average dew point temperature (℃). The dry air pressure (kPa) is then obtained by subtracting the saturation vapor pressure from the pressure meter reading. Equation (2) calculates dry air mass (kg) based on the Ideal Gas Law where M is a constant of 0.029 kg/mol; V denotes net free volume of the containment (litre); R is a constant of 8.31447 J/(K · mol); and TE denotes volume weighted thermal element temperature (℃).

$$Vapor = 0.089 \times 6.9 \times \exp(17.37 \times DEW \times 1.8/(DEW \times 1.8 + 430)) \quad (1)$$

$$Dry\_Mass = M \times Dry\_Press \times V/[R \times (TE + 273.15)] \quad (2)$$

2. ISG:

The ISG criteria are used to determine the ability of an I&C system and the value of ISG shall not exceed $0.25L_a$ [2]. ISG is adopted only in the pre-operational test.

3. Temperature Stabilization:

Upon completion of containment pressurization to the test pressure (P_a and P_t), the containment volume weighted TE temperature versus test time shall approach a straight line [2]. Temperature stabilization is adopted only in the pre-operational test.

4. Atmosphere Stabilization:

After the containment has been pressurized to test pressure (P_a and P_t), the containment atmosphere shall stabilize for at least four hours [3]. Atmosphere stabilization is adopted only in the periodic operational test.

5. Limit on Curvature:

The limit on curvature assures that the function relating containment dry air mass to time is either linear or the curvature of that function is within the bounds specified in [3]. Limit on curvature is adopted only in the periodic operational test.

6. Limits on Data Scatter:

The limits on data scatter of containment dry air mass shall provide a statistical test to evaluate whether the scatter of the air mass points about a regression line are within acceptable bounds specified in [3]. The limit on data scatter is adopted only in the periodic operational test.

V. Verification and Validation

The purpose of software V&V is to improve the reliability of computer programs especially in safety critical applications [9][10][11]. The V&V processes and activities are adopted in this procedure to achieve the functionality, effectiveness, and feasibility for enhancing the dependability of reactor containment in safety critical NPPs. The V&V activities of the V&V processes are the preparation of test plans, verification of software requirement specification (SRS), test plans, software design specification (SDS) and source codes, testing of the complete software and hardware system, and final documentation and deployment of the program. The V&V processes and activities in this application follow the standard for the nuclear industry as listed in table II [11].

TABLE II. V&V Process and Activity

Process	Activity
Initiation	Prepare test plan
Requirements Analysis	Verify requirements specification
	Verify test plan
Design	Verify design specification
	Verify updated test plan
Implementation	Verify source code
	Verify updated documentation
Testing	Build test cases
	Verify test results
Deployment	Verify final documentation
	Verify final deployment program

$\alpha + \beta = \chi$. (1) (1)

VI. Results

We present a practical operational NPP ILRT test case in this section by following the criteria in [3]. We discuss the analyses of the containment dependability in the tests in individual stages: pressurization, stabilization, ILRT and VLRT periods. Since this test case is performed as the periodic operational test, only the test pressure at P_a is needed (i.e. P_aILRT). The parameters are listed as follows: free air volume of containment is 57489.6 m^3; type B plus type C LLRT penalty is 0.0008%/day; and L_a is 0.1%/day.

A. Pressurization Period

In this period, the containment is pressurized to the test pressure P_a (i.e. 440kPa ≒ 4.36 standard atmospheric pressure). The pressurization rate (Pr) shall be within the following bound: (1) P<301.3kPaA => Pr < 20kPa/hr, (2) 301.3kPaA>P>451.3kPaA => Pr < 10kPa/hr.

B. Stabilization Period

Upon the completion of containment pressurization to the test pressure, the containment volume weighted TE temperature versus test time shall approach a straight line. The duration of this period shall be at least 4 hours. Atmosphere stabilization is adopted in this period. Figure 5 depicts the trend of TE versus time (data set number) during stabilization period. We observe that the volume weighted TE temperature decreases slowly as time increases.

C. ILRT Period

After the containment has been stabilized for at least 4 hours, the ILRT period starts. The duration shall last for at least 8 hours for periodic test and the interval between each data set is 15 minutes. Since the acquisition period is 5 minutes, we select data sets in an interval of 3 data sets. To pass ILRT, the measured 95% UCL plus LLRT penalty shall be less than 0.75 L_a. Figure 6 depicts the trend of leakage rate (L_{am}) and 95% UCL plus LLRT penalty versus time (data set number) during ILRT period. We observe that the dotted green line is below the limit (0.75L_a) from data set number 515.

D. VLRT Period

Finally, a verification test after P_a ILRT is conducted for at least 4 hours and the interval between each data set is 15 minutes. Since the acquisition period is 5 minutes, we select data sets in an interval of 3 data sets. L_o is the known leakage rate superimposed on the containment and L_o shall be between 0.75 L_a and 1.25 L_a. The actual L_o is 1.014 L_a in this test. L_c is the composite containment leakage rate measured after L_o is superimposed. To pass VLRT, L_c shall be between L_o+L_{am}-0.25L_a and L_o+L_{am}-0.25L_a. Figure 7 depicts the trend of composite leakage rate (L_c) versus time (data set number) during VLRT period. We observe that the dotted blue line (L_c) is within the acceptance region from data set number 615.

VII. Conclusion

We propose a practical application to analyze dependability of reactor containment in safety-critical nuclear power plants. In the proposed approach, we adopt different standards for pre-operational and periodic tests. The thorough design and implementation processes are also presented. Moreover, this paper also adopts software V&V processes and activities to support the application. Last but not least, a practical NPP test case is presented to validate the proposed application. Future work is to apply the test bed in other I&C systems for dependability analysis in safety-critical NPPs.

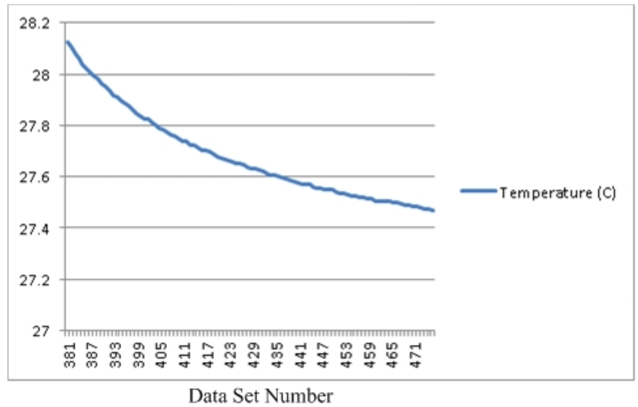

Figure 5. Trend of TE versus time (data set number) during stabilization period.

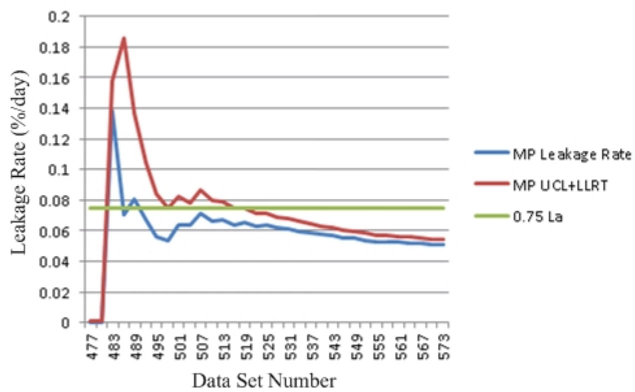

Figure 6. Trend of MP Leakage Rate (L_{am}), UCL+LLRT penalty versus time (data set number) during ILRT period.

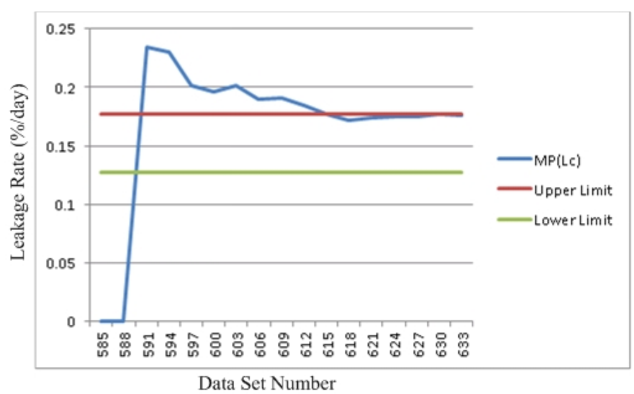

Figure 7. Trend of L_c versus time (data set number) during VLRT period.

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