GUIDELINES NO. AERB/NPP/SG/O-15

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GOVERNMENT OF INDIA

A E R B S A F E T Y G U I D E

PROOF AND LEAKAGE RATE TESTING OF REACTOR CONTAINMENTS

ATOMIC ENERGY REGULATORY BOARD

AERB SAFETY GUIDELINES NO. AERB/NPP/SG/O-15

PROOF AND LEAKAGE RATE TESTING
OF
REACTOR CONTAINMENTS

Atomic Energy Regulatory Board
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FOREWORD

Activities concerning establishment and utilisation of nuclear facilities and use of radioactive sources are to be carried out in India in accordance with the relevant provisions of the Atomic Energy Act, 1962. In pursuance of the objective to ensure safety of members of the public and occupational workers, as well as protection of environment, the Atomic Energy Regulatory Board has been entrusted with the responsibility of laying down safety standards and framing rules and regulations for such activities. The Board has, therefore, undertaken a programme of developing safety standards, codes of practice and related guides and manuals for the purpose. These documents cover aspects such as siting, design, construction, operation, quality assurance, decommissioning and regulation of nuclear and radiation facilities.

Codes of practice and safety standards are formulated on the basis of internationally accepted safety criteria for design, construction and operation of specific equipment, systems, structures and components of nuclear and radiation facilities. Safety codes establish the objectives and set minimum requirements that shall be fulfilled to provide adequate assurance for safety. Safety guides elaborate various requirements and furnish approaches for their implementation. Safety manuals deal with specific topics and contain detailed scientific and technical information on the subject. These documents are prepared by experts in the relevant fields and are extensively reviewed by advisory committees of the Board before being published. The documents are revised when necessary, in the light of experience and feedback from users as well as new developments in the field.

The code of practice on 'Safety in Operation of Nuclear Power Plants' (AERB/SC/O) states the minimum requirements to be met during operation of nuclear power plants in India. This guide provides information on all aspects of proof and leakage rate testing of reactor containments. It is based on the current practices followed in Pressurised Heavy Water Reactors (PHWRs) as also Boiling Water Reactors (BWRs), but can also be applied to other types of reactors. In its drafting, relevant International Atomic Energy Agency (IAEA) documents, USNRC Regulatory Guides/ Standards, French Guidelines (RCC-G), Canadian Standards (CAN) and other relevant international documents as well as the current Indian practices being followed at various nuclear power plants, have been used extensively.

Consistent with the accepted practice, 'shall', 'should' and 'may' are used in the guide to distinguish between a firm requirement, a recommendation and a desirable option, respectively. Appendices are an integral part of the document, whereas annexures, footnotes, references/ bibliography and lists of participants are included to provide information that might be helpful to the user. Approaches for implementation, different to those set out in the guide, may be acceptable, if they provide comparable assurance against undue risk to the health and safety of the occupational workers and the general public and protection of the environment.

For aspects not covered in this guide, applicable and acceptable national and international standards, codes and guides should be followed. Non-radiological aspects, such as industrial safety and environmental protection, are not explicitly considered. Industrial safety is to be ensured through compliance with the applicable provisions of the Factories Act, 1948 and the Atomic Energy (Factories) Rules, 1996.

This guide has been prepared by specialists in the field drawn from Atomic Energy Regulatory Board, Bhabha Atomic Research Centre, Nuclear Power Corporation of India and other consultants. It has been reviewed by the Advisory Committee on Nuclear Safety.

AERB wishes to thank all individuals and organisations who have prepared and reviewed the draft in its finalisation. The list of persons, who have participated in this task along with their affiliations, is included for information.

(Suhas P. Sukhatme)
Chairman, AERB

DEFINITIONS

Acceptable Limits

Limits acceptable to for regulatory body accident conditions or potential exposure.

Acceptance Criteria

The standard or acceptable value against which the value of a functional or condition indicator is used to assess the ability of a system, structure or component to perform its design function or compliance with stipulated requirements.

Accident Conditions

Substantial deviations from operational states which could lead to release of unacceptable quantities of radioactive materials. They are more severe than anticipated operational occurrences and include design basis accidents as well as beyond design basis accidents.

Anticipated Operational Occurrences

An operational process deviating from normal operation which is expected to occur during the operating lifetime of a facility but which, in view of appropriate design provisions, does not cause any significant damage to items important to safety nor lead to accident conditions.

Commissioning

The process during which structures, systems and components of a nuclear and radiation facility, on being constructed, are made operational and verified to be in accordance with design specifications and found to have met the performance criteria.

Confidence Level (leakage rate)

The probability that the true leakage rate will not exceed the upper confidence limit.

Commissioning

The process during which structures, systems and components of a nuclear and radiation facility, on being constructed, are made functional and verified in accordance with the design specifications and to have met the performance criteria.

Conditioning of Waste

The processes that transform waste into a form suitable for transport and/or storage and or disposal. These may include converting the waste to another form, enclosing the waste in containers and providing additional packaging.

Consent

A written permission issued to the consentee by the regulatory body to perform specified activities related to nuclear and radiation facilities. The types of consents are 'licence', 'authorisation', 'registration' and 'approval', and will apply according to the category of the facility, the particular activity and radiation source involved.

Discharge (Radioactive)

Planned and controlled release of (gaseous or liquid) radioactive material into the environment.

Discharge Limits

The limits prescribed by the regulatory body for effluent discharges into atmosphere aquatic environment from nuclear/radiation facilities.

Disposal (Radioactive waste)

The emplacement of waste in a repository without the intention of retrieval or approved direct discharge of waste into the environment with subsequent dispersion.

Documentation

Recorded or pictorial information describing, defining, specifying, reporting or certifying activities, requirements, procedures or results.

Effluent

Any waste discharged into the environment from a facility, either in the form of liquid or gas.

Confinement

Barrier which surrounds the main parts of a nuclear facility carrying radioactive materials and designed to prevent or mitigate uncontrolled release of radioactivity into the environment during commissioning, operational states, design basis accidents or in decommissioning phase.

Construction

The process of manufacturing, testing and assembling the components of a nuclear or radiation facility, the erection of civil woks and structures, the installation of components and equipment, and the performance of associated tests.

Containment

(See ‘Primary Containment’/’Secondary Containment’/’Confinement’)

Containment Boundary

The outer limits of containment system.

Containment Isolation

The process of isolating the containment or boxing up the containment so that there is no direct path from the system available for the radioactivity to reach the environment.

Containment Structure

The concrete portion and embedded parts of the primary and secondary containment systems.

Containment Penetrations

Openings in the containment envelope provided for passage of personnel, materials, process piping and cables.

Design Pressure (containment)

The calculated peak containment internal pressure (P_a), as arrived at from the safety analysis of design basis accidents (e.g. MSLB, LOCA). While the pressure for leakage rate testing of the reactor containment will be based on LOCA, for proof testing the higher of the two pressures arrived at from MSLB or LOCA will be the governing pressure.

Dose Limit

The value of the effective dose or the equivalent dose to individuals from controlled practices that shall not be exceeded.

Embedded Part

Any structural member, plate, angle, channel, pipe sleeve or other section anchored to a concrete structure through direct bond or other anchors.

Integrated Leakage Rate Test (containment)

The leakage test performed on the containment by pressurising the same to particular leakage rate test pressure, and determining the overall integrated leakage rate.

Leakage

The quantity of fluid escaping from a leak.

Leak Tightness

The ability of a component to maintain leakage rate within a prescribed value.

Local Leakage Rate Test (containment)

The leakage test performed on the various containment penetrations, such as access airlocks, penetration seals with expansion bellows, cable seals and containment isolation valves.

Loss of Coolant Accident (LOCA)

An accident resulting from the loss of coolant to the fuel in a reactor due to a break in pressure retaining boundary of primary coolant system.

Main Steam Line Break (MSLB)

A break in steam pipeline which leads to discharge of high enthalpy steam.

Primary Containment

The principal structure of a reactor unit that acts as a pressure retaining barrier, after the fuel cladding and reactor coolant pressure boundary, for controlling the release of radioactive material into the environment. It includes containment structure, its access openings, penetrations and other associated components used to effect isolation of the containment atmosphere.

Reactor Building

The concrete containment structure that contains and supports the reactor and other related systems, such as the heat transport system, moderator system.

Resolution

The least entity discernible on the display mechanism.

Secondary Containment

The structure surrounding the primary containment that acts as a further barrier to limit the release of radioactive materials and also protects the primary containment from external effects. It includes secondary containment structure and its access openings, penetrations and those systems or portions thereof which are connected to the containment structure.

Structure

The assembly of elements which supports/houses the plants, equipment and systems.

Suppression Pool

A pool of water located at the lowermost elevation of the reactor building into which steam, resulting from LOCA/MSLB, is directly led and condensed to reduce the pressure in the primary containment.

Testing (QA)

The determination or verification of the capability of an item to meet specified requirements by subjecting the item to a set of physical, chemical, environmental, or operational conditions.

CONTENTS

1. INTRODUCTION

1.1 General

1.1.1 The containment of a Nuclear Power Plant (NPP) encloses completely the reactor core, reactor coolant system and other radioactive fluid-containing systems. The containment along with its associated engineered safety systems, keeps the radiation doses to the members of public within the limits specified by the Regulatory Body, both during normal operation and accident conditions. In order to assure structural integrity and leaktightness of the containment structures and associated systems, tests are conducted under specified conditions, prior to first criticality and also at specified time intervals during the life of NPP.

1.1.2 In the case of double containments, the primary cntainment (PC), also known as inner containment (IC), provides leaktightness against internal pressure, while the secondary containment (SC) also known as outer containment (OC), together with associated engineered safety features (ESFs) further minimises ground level releases by intecepting the leaks from PC.

1.1.3 Prior to first criticality of a NPP, the following tests shall be conducted:

i) proof test (PT), also known as structural integrity test (SIT) to demonstrate the structural integrity of all parts of the PC envelope under specified internal pressure.

ii) local proof test and local leakage rate test (LLRT) on airlocks, isolation devices and individual penetration assemblies such as those for piping, cables, etc. (wherever applicable), to determine and demonstrate that they satisfy the acceptance criteria.

iii) integrated leakage rate test (ILRT) to demonstrate that the leakage from the containment satisfies the acceptance criteria.

iv) for pressure suppression type of containment systems having V_1 (dry-well) and V_2 (wet-well) volumes, V_1 to V_2 integrity tests to estimate suppression pool bypass should be carried out.

v) leakage rate testing of secondary containment.

vi) test for maintenance of secondary containment negative pressure.

1.1.4 During the service life of the NPP, the tests specified under subsection 1.1.3, items (ii) to (vi) shall be conducted at specified intervals, at specific pressure and as per acceptance criteria given under section 6.0.

1.2 Objectives

1.2.1 The objective of this guide is to lay down guidelines for the proof testing and leakage rate testing of reactor containments with primary containment as prestressed concrete (PCC) and secondary containment as reinforced concrete (RCC) as applicable to the projects under contstruction and the projects planned. It covers both pre-operational and in-service tests, and includes frequency and suggested leakage rate calculational methodologies for LLRTs and ILRT, criteria for test acceptance, duration of testing, test pressure, minimum intrumentation requirements, temperature stabilisation criteria, guidelines for establishing correlation between leak rate and pressure and accounting for compressed air in-leakages.

1.2.2 Efforts should be made to implement the relevant sections of this guide for existing operating NPPs. However, wherever not possible, it should be examined on a case by case basis.

1.3 Scope

1.3.1 This guide presents pre-requisites, requirements for procedures, instrumentation requirements, acceptance criteria, leakage rate calculations and error analysis methods, reporting requirements, as applicable, for the following:

(i) proof testing of primary containment,

(ii) local leakage rate tests (LLRTs) of airlocks, isolation devices and individual penetration assemblies,

(iii) pre-operational primary containment integrated leakage rate testing (PC-ILRT),

(iv) pre-operational secondary containment leakage rate testing (SC- LRT),

(v) pre-operational V_1 to V_2 integrity testing, and

(vi) periodic in-Service testing of primary containment, secondary containment, V_1 to V_2 integrity testing.

1.3.2 The guide also gives typical numbers for some of the parameters as indicative values. These are based on experiences with previous tests conducted on the existing NPPs. Some of these numbers may change in future.

2. CONTAINMENT PROOF TEST

2.1 General

2.1.1 The objective of containment proof test (PT), is to demonstrate the ability of the containment to withstand the test pressure corresponding to the design basis accidents (DBAs), e.g. LOCA or MSLB and to demonstrate elastic behaviour of the containment as per the design intent. In case of double containments, the PT is carried out for primary containment only. The requirements spelt out in this section will apply to projects under construction and projects being planned.

2.1.2 The proof test shall be done prior to first criticality. This test is to be conducted in two parts, viz. local proof tests (wherever applicable), and proof test of entire primary containment.

2.1.3 Following any major modification to containment structure, affecting its structural integrity, either a local proof test or a full proof test of the structure, if so desired by the regulatory body, should be conducted.

2.1.4 Proof test should also be conducted following any severe loading arising from elevated pressure differentials, resulting from accidents or from severe environmental effects (e.g. earthquake above OBE level).

2.2 Pretest Requirements

2.2.1 The PT should be conducted only after completion of construction work of containment envelope.

2.2.2 A visual check should be carried out before the PT to check the containment structure and its appurtenances.

2.2.3 Checklist shall be prepared to ensure that all prerequisites and instrumentation are completed.

2.3 Test Procedure

A detailed test procedure shall be prepared covering all aspects of test and made available at site prior to commencement of test.

2.4 Test Pressure

2.4.1 For pre-operational PT, the test pressure, Pt shall satisfy the following:

$P_t = KP_a$

where, P_a is the containment design pressure determined from the safety analysis of DBAs (e.g. LOCA[1] MSLB,[2] etc.) and K is the constant based on the liner used. Presently K = 1.15 for steel-lined containments, and K = 1 for containments without metallic liner.

2.4.2 The proof test pressure should be attained in stages consisting of at least four nearly equal pressure increments.

2.5 Test Medium

Test should be carried out using atmospheric air free from oil, excessive humidity and other contaminants.

2.6 Entry

2.6.1 Personnel entry into pressurised containment is not encouraged; however, entry may be necessary for identification of certain leakages which otherwise cannot be detected from outside. For this purpose, provisions for entry into the containment in early stages of pressurisation (say, upto 0.15 kg/cm^2g) may be made. Accordingly, a crew comprising appropriate personnel shall be trained and qualified (see Annexure I) to make entry into the containment under pressurised condition, satisfying the Atomic Energy (Factories) Rules, 1996. It is desirable that at least two airlocks are kept operable for entry into the containment. Airlocks shall be appropriately modified to function as compression/ decompression chamber at controlled rate. Communication in airlock and medical facilities at the site shall be available, both during acclimatisation and the time of entry.

2.6.2 To obviate the need for entry into the containment in case of an incident of fire, inflammable materials if any, kept inside the containment should be removed.

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1 In the context of this guide, this refers to doble-ended-guillotine (DEG) rupture of one of the primary heat transport system headers (in case of PHWRs) or DEG in main reactor coolant pipeline (for other reactors)

2 In the context of this guide this refers to double-ended-guillotine rupture in one of the main steam lines

2.7 Duration

The pressure at each inspection stage of the test shall be maintained for a minimum duration of half an hour before any measurements and records are taken.

2.8 Instrumentation

2.8.1 The instrumentation given in this section includes the minimum requirements. Additional instrumentation may be provided by the designer, if required by special and case-specific considerations.

2.8.2 The first reactor containment of each series should be instrumented in detail to measure the global as well as local behaviour (e.g. deflections, strains, etc.) of the containments for comparison with the design analysis results. Subsequent containments in the same series at the same site, should be instrumented for global response measurement. However, level of detailed instrumentation required for first containment of existing series at a new site may be less elaborate than that for the first containment of the series.

2.8.3 The power supply for instrumentation should be backed up by an uninterrupted power supply package.

2.9 Parameters for Measurements

2.9.1 The instrumentation shall be designed to measure the following responses:

(i) Global Behaviour

- settlement of the containment with respect to external benchmark
- inclination of the containment
- radial and vertical deformations

(ii) Local Behaviour

- strains
- tension in the pre-stressing cable (as an alternate, indirect method of assessing the tension in the pre-stressing cable may be used, e.g. monitoring of strains in the structure at appropriate location in the general section)

2.9.2 In addition, monitoring of crack patterns, crack widths and lengths should be done.

2.10 Locations of Measurements

2.10.1 Settlement/Inclination of containment should be measured at least at 4 locations around the containment with respect to predetermined reference point outside the containment structure.

2.10.2 Instrumentation to measure the differential settlement of basemat should be placed evenly distributed at the stressing gallery (applicable to non-rocky sites).

2.10.3 Vertical deformation of the containment under the effect of pressure during proof test should be measured at 4 locations on the containment at ring-beam level and at suitable locations on the dome (such as steam generator openings, crown). The vertical line of measurement on the containment should not run along the buttress of the horizontal prestressing cable.

2.10.4 Radial deformation under the effect of pressure should be measured at 5 elevations (between basemat and ring beam) with 4 azimuthal points at each elevation.

2.10.5 Strain[3] should be meassured at a number of representative locations, including locations of maximum stress points, such as :

- i) large openings/penetrations (diameter greater than three times the wall thickness or 2.0 m, whichever is less, e.g. SG openings and Airlocks),
- ii) representative regions where penetrations/openings are closely spaced,
- iii) basemat-containment wall junctions,
- iv) connection between internal structure of reactor building and ICW,
- v) wall and dome springing level,
- vi) representative locations around anchorage/ribs of prestressing cables,
- vii) crown of dome,
- viii) region where material properties change and where time difference of two consecutive concrete pours is significantly more than time limit given in construction specifications and
- ix) regions of major discontinuities not covered above.

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[3] Strain need not be measured at locations wherever the predicted strain values are too low to give meaningful data (e.g. less than 50 mΘ in case of current generation PHWR containments, using electric resistance strain).

2.10.6 For single containments, measurements of temperature variations across the wall should be made to take account of temperature variations due to solar radiation.

2.10.7 The tension in the unbonded prestressing cable shall be measured at least at 4 vertical tendons. Locations for the measurements shall be determined on the basis of the following considerations:

i) The loss of tension is mainly due to tendon creeping, but also depends upon the deferred shrinkage and creeping of concrete, as well as the thermal conditions affecting the structure. In addition, it is necessary to know the variation of friction between the tendon and its conduit, as the tensions beneath the active end and beneath the passive end tend to balance each other over a period of time.

ii) The various considerations normally result in measuring instruments being fitted with each group of tendons. However, the horizontal tendons and dome tendons are normally tensioned by their ends, thus preventing any measurement of friction variation. Consequently the measurement should be done on the vertical tendons.

As an alternative to direct measurement of tension in tendons, the indirect method of assessing the tension in the pre-stressing cable may be used, e.g. monitoring of strains in the structure at appropriate locations in the general section.

2.11 Precision

Precision of the instruments shall conform to the requirements of test specification.

2.12 Calibration

The instruments shall be calibrated as applicable in accordance with test specification for expected range of operation.

2.13 Redundancy

Instrumentation required as per section 2.10.5 should have redundancy commensurate with the reliability of the strain gauges, depending on possible damage during construction and for possible instrument drifting. Initial measurements should be made to verify and demonstrate proper performance of the instrumentation provided for the test, so as to establish the baseline data for taking into account the diurnal variations.

2.14 Acceptance Criteria

2.14.1 The containment shall be accepted, provided the following criteria are satisfied:

i) measurements carried out demonstrate an elastic behaviour of the structure as defined in item (iii) below.

ii) the behaviour of the structure should be in accordance with the structural design analysis as defined in item (iv) below.

iii) residual displacements at the points of maximum predicted radial and vertical displacements at the completion of depressurisation or up to 24 hours later, shall not exceed for PCC containments or prestressed directions of partially pressurised containments, by 20 % of measured or predicted displacements at maximum test pressure, whichever is greater, plus 0.01" (0.25 mm) measurement tolerance [12].

iv) the measured displacements at test pressure at points of predicted maximum radial and vertical displacements, do not exceed predicted values by more than 30 % plus measurement tolerance.

v) no visible signs of distress.

2.15 Test Reports

Test report for each test should be prepared. The report should highlight the following:

records,

visual inspection,

verification, and

anomalies

2.16 Records

Observations and measurements shall be recorded at atmospheric pressure and at all stages of pressurising and depressurising for each test performed.

2.17 Visual Inspection

2.17.1 The containment should be visually inspected for any signs of distress during proof test, in addition to the inspection requirements given in test specifications.

2.17.2 Crack patterns, their widths and lengths at representative locations (viz. high stress areas, i.e. near major penetrations, e.g. MAL, EAL, near areas of changing material properties and near dome and springing level should be mapped. Locations on the outside surface of the PC should be mapped before pressurisation, at full pressure and at end of the test after depressurisation. Locations on the inside surface (e.g. suppression pool floor, cylindrical wall, near MAL opening) should be mapped before and after the proof test.

2.17.3 The integrity of non-metallic liner shall be confirmed and recorded at atmospheric pressure after the test.

2.18 Verification

Test results should be evaluated and documented to include:

i) comparison between the measured global behaviour and the predicted global behaviour of containment, determined from the design calculation

ii) for first Unit of existing series, comparison of measured stress and stress determined by design analysis

2.19 Anomalies

Any significant departure in the actual behaviour and the behaviour predicted and other anomalies shall be reported and explained. These should be satisfactorily resolved by the designers.

2.20 Retest

If the test results do not satisfy the acceptance criteria, the necessary modifications or repairs, or both, shall be implemented and the containment retested. If any local compartment does not pass the proof test, necessary repairs shall be carried out. A local proof test can be considered acceptable, provided the compartment under test is loaded in a manner not significantly differing from that in an integral proof test. Otherwise, a repeat proof test of the containment should be conducted.

3. PRE-OPERATIONAL PRIMARY CONTAINMENT LEAKAGE RATE TESTING

3.1 General

Two types of tests shall be done:

(i) Local leakage rate tests (LLRT) on:

- airlocks,
- penetration seals with expansion bellows,
- cable penetration seals, and
- containment isolation valves

(ii) Integrated leakage rate test (ILRT)

The requirements spelt out in this section will apply to projects under construction and projects being planned.

3.2 Sequence of Pre-operational Tests

ILRT of PC shall be conducted following a proof test. However, it is permissible to conduct both PT and ILRT together in one pressurisation campaign, if all the prerequisites for both the tests are met. ILRT is normally conducted following completion of LLRTs. If an ILRT is conducted after installation of a temporary sealing on a leak path, then following normalisation of the leakage path, LLRT shall be conducted on this path and leakage rate determined from this path is to be added to the ILRT results.

Secondary containment leakage rate test is also to be carried out prior to ILRT of PC to facilitate estimation of percentage of PC leakage rate bypassing the secondary containment.

3.3 Local Leakage Rate Test (LLRT)

3.3.1 Pretest Inspection

Prior to local leakage rate test, the relevant components and the appurtenances of the containment should be visually examined for any damages.

3.3.2 Test Specifications

The local leakage rate test should be conducted in accordance with the approved test specifications. Test specifications should include the following:

3.3.2.1 A list of various components and appurtenances covered in the test programme, e.g. airlocks and their seals, cable seal penetrations, penetrations with expansion bellows, containment isolation valves in lines constituting direct communication between containment and outside atmosphere.

3.3.2.2 Test parameters, e.g. test pressure, specified leakage rate, test methodology for individual leak paths.

3.3.2.3 Conceptual description of test setup e.g. pressurisation/depressurisation facilities, relief provisions.

3.3.2.4 Specifications of test instruments and their accuracy.

3.3.2.5 Method of calculation of leakage rate and error.

3.3.3 Test Procedure

A detailed procedure shall be prepared covering all aspects of test and made available at site prior to commencement of the test.

3.3.4 Test Pressure

Local leakage rate test shall be conducted at pre-operational integrated leakage rate test pressure [P_{PO}] (as defined in subsection 3.4.2). To the extent possible, local leakage rate tests shall be conducted by pressurising the components/appurtenances such that the direction of pressure is same as that during the post-accident condition. Conducting the test with direction of pressure differing from that of post-accident condition shall be adequately justified.

3.3.5 Test Medium

LLRT should be conducted using atmospheric air free from oil, excessive humidity and other contaminants.

3.3.6 Test Method

Local leakage rate test shall be conducted by one of the following methods, depending on the test volume involved :

(i) absolute pressure method,

(ii) flow rate method, and

(iii) any other approved method.

3.3.7 Test Duration

Duration of local leakage rate test should be based on reliability and accuracy of the results. In the event, flow rate method is used, the test should be conducted for a duration that allows flow to be monitored under stabilised conditions. For absolute pressure decay method, the duration shall be not less than 15 minutes.

3.3.8 Acceptance Criteria and Retesting

The sum of computed or measured local leakage rates (all local leakage rate test results, including for airlocks) shall be within 60 % of maximum allowable leakage rate (MALR) for PC. However, any gross leakage from any individual penetration should be investigated and rectified.

If the above is not met, then the LLRT shall be repeated after completion of necessary repairs/modifications.

3.3.9 Leakage Rate Computation and Error Analysis

When the absolute pressure method is used, the leakage rate computation may be done either by mass plot method or a two-point method. The leakage rate shall be reported as:

Local leakage rate = L_L+ *L_L

where L_L=local leakage rate (sm^3/h) and

*L_L= error in local leakage rate calculation (sm^3/h)

The error analysis for local leakage rate calculations may be done only for major containment openings/penetrations.

For flow makeup method, the compensating flow rate as determined from the flow totaliser and elapsed time may be reported.

Details of local leakage rate compuation and error analysis are given in sections A.5 and B.7 of Appendices A and B respectively.

3.3.10 Test Instrumentation

Typical instrumentation required for LLRT is given in Annexure II.

3.3.11 Reporting of Results

The test results should be documented in all respects in a manner to permit comprehensive review and analysis. It should also permit the use of this experience for future tests. The report should include the following:

i) summary, results/conclusions,

ii) measured leakage rates alongwith calculated error estimates,

iii) test specifications, deviations/exceptions from test specifications/ requirements, and

iv) summary tabulation of test results for all local leak paths, including comments/remarks regarding healthiness of leak paths. Indicate any repairs carried out and date of test.

3.4 Integrated Leakage Rate Test

3.4.1 Pretest Inspection

Before commencement of ILRT, checklists shall be prepared to ensure that all prerequisites have been completed and the containment system is as close as possible to that during the reactor operation. A visual inspection shall be made of the passive as well as active parts of the containment to ensure that no defects exist in the containment boundary that may jeopardise the safety of the structure or successful completion of test. Checklist shall include a list and types of repairs carried out on the containment that may have a bearing on containment leak-tightness, their locations and the areas covered by repairs.

3.4.2 Test Pressure

Subsequent to completion of proof test and prior to the first criticality of the reactor, ILRT shall be conducted at pre-operational integrated leakage rate test pressure (ILRTP), P_{PO} where P_{PO} is the pressure based on calculated maximum peak containment pressure, following postulated double-ended break in the primary heat transport system.

ILRT shall also be conducted at the pressure specified for periodic in-service leakage rate test, and at least at two other well-spread intermediate pressures, to enable obtain a correlation between the containment pressure and the leakage rate.

3.4.3 Test Medium

ILRT shall be conducted using atmospheric air free from oil, excessive humidity and other contaminants.

3.4.4 Test Method

ILRT shall be conducted by the method of absolute pressure in the containment after deducting the partial pressure of water vapour from the total pressure (i.e. the sum of gauge pressure and atmospheric pressure).

3.4.5 Entry

See Section 2.6.1 for details.

3.4.6 Test Duration

The duration of ILRT should be based on the considerations of allowable leakage rate and the accuracy of computed leakage rate determined, based on the test instrumentation and the data recording frequency. In any event, the duration of ILRT should be at least 6 hours after stabilisation. During rundown, data should be collected every 15 minutes or earlier. The duration of 6 hours may be shortened if the error analysis indicates that overall error with shortened test duration is within 10% of allowed/observed leakage rate (see equation A.10). However, a minimum of 20 data points should be recorded. For superimposition of known leaks for verification of leakage rate monitoring, the duration of ILRT should be at least 3 hours.

3.4.7 Test Specifications:

The ILRT should be conducted in accordance with approved test specifications. The test specifications should include the following:

i) test parameters such as test pressure, test volume, allowed leakage rates, test duration, test methodology,

ii) conceptual description of test setup e.g. pressurisation/ depressurisation facilities, relief provision,

iii) required status of various relevant systems and components during the test. This should include a list of all temporary installations and the programme of their post- test normalisation,

iv) specification of test instrumentation and accuracy. Locations of temperature sensors in reactor building for monitoring dry and wet-bulb temperatures,

v) methods for calculation of leakage rate and error analysis and data rejection condition (criteria),

vi) arrangement for compression and decompression facilities and programme of personnel qualification for inspection of containment/ leak detection under overpressure condition,

vii) a programme of pretest visual inspection, and

viii) method of containment isolation before starting pressurisation. In case containment is isolated by a method other than actuation of isolation logic, acceptability of the test results should be justified.

3.4.8 Test Procedure

A detailed procedure covering all aspects of test should be prepared and made available at site before commencement of test.

3.4.9 Acceptance Criteria and Retesting

The containment shall be considered acceptable if the computed integrated leakage rate is within 75% of the maximum allowable leakage rate (MALR) specified in technical specifications for operation of NPP. Results of local leakage rate tests, if any, conducted subsequent to ILRT on blanked penetrations, should be added to ILRT results.

If the above is not met, the test (ILRT) shall be repeated after completion of necessary repairs.

3.4.10 Assessment of Compressed Air In-leakage

During the integrated leakage rate test, the various compressed air systems should be isolated from containment using two isolation valves in series with interspace vented to atmosphere. In case compressed air system has to remain charged within containment, an assessment of compressed air inleakage shall be made by atleast one of the following methods:

i) use of precision flowmeters in the compressed air lines, and

ii) absolute pressure method either before or after the ILRT, with compressed air system configuration same as during the ILRT

The method at item (i) above is preferred, since measurement precision is more accurate. However, if precision flowmeter is not available, then the method at item (ii) above should be used.

3.4.11 Leakage Rate Computation and UCL Calculation

The absolute pressure method is used for the leakage rate compuation (see Appendix A). An upper confidence limit (UCL) shall be set on the calculated leakage rate by this method, such that there is only 5 % chance that the actual containment leakage rate exceeds the reported UCL value. This is expressed as the upper limit of the 95 percent confidence level of the leakage rate (for details of the calculations and equations, see Appendix A). An approximation of this value is generally adequate and shall be determined as given in equation (A.11) of Appendix A.

For flow makeup method, the compensating flow rate as determined from the flow totaliser and elapsed time may be reported.

Details of leakage rate computation are given in Appendix A.

3.4.12 Pressure and Temperature Stabilisation

After pressurisation and before starting ILRT, pressure and temperature should be stabilized in the containment. After cutting off compressed air injection, temperature reading should be taken at regular interval. ILRT can be started upon meeting the criterion that the rate of change in air temperature averaged over the last hour does not deviate by more than 0.3°C/h from the average rate of change over the last four hours. However, if pressurisation/ depressurisation rate is relatively small (less than 10% per hour), then the following criterion may be used: the average rate of change in containment average air temperature computed over the last hour does not deviate by more that 0.15°C/h from the change measured over the last two hours.

3.4.13 Test Instrumentation

3.4.13.1 Selection of Instrumentation

The instrumentation shall be specified and selected as per the instrumentation selection guide (ISG) given in Appendix C.

Annexure IV gives typical instrumentation details for ILRT of PC.

3.4.13.2 Calibration

The instruments shall be calibrated, as applicable, in accordance with test specifications for their expected range of operation.

3.4.13.3 Dry and Wet Bulb Temperature Measurement

The dry/wet-bulb temperature sensors should be distributed such that they yield reliable and representative results. For this purpose all compartments having a volume of 5% or more of total containment free air volume shall have independent sensors, such that the weighted average temperature of containment volume can be assessed. For compartments having large volumes, independent sensors shall be provided to take care of spatial variation in temperature. A temperature survey shall be conducted to decide the distribution of sensors in various compartments of containment and further, within the compartments to decide the sensor locations. As far as practicable, sensors should be located at the centre of the volumes represented by them, away from the direct heat sources/sinks.

For wet-bullb temperature measurement it shall be ensured that the water supply to the wicks is adequate for the entire duration of test with adequate margin and an air velocity of 4.5m/s or more is maintained over the wick throughout the test at various overpressure conditions.

It shall be ensured that the system is free from drift for the duration of the test. The cabling for the temperature measurement may be of permanent type such that before a test, the sensors can be easily installed and test conducted.

3.4.13.4 Equipment/Instrument Operability and Verification

The equipment/instrument (e.g. fan for wet-bulb temperature measurement) which would have to operate under overpressure condition should be tested for satisfactory operation in a pressurised enclosure. The correct functioning of instruments for measurement of temperature/dew point (both before and after the test) should be established by conducting local measurements, using instruments of comparable accuracy.

After the ILRT, the combined operation of ILRT instrumentation should be verified by superimposition of a known out-leakage (or in-leakage) approximately equal to measured leakage rate. The duration of the super-imposition test should be one half of the duration of ILRT.

3.4.14 Reporting of Results

The test results should be documented in all aspects in a manner to permit a comprehensive review and analysis. It should also permit use of this experience for the future test. The report should include the following:

i) summary, results/conclusions,

ii) results of ILRT covering computed leakage rates alongwith UCL values; results of verification tests,

iii) test specifications, deviations/exceptions from test specifications/ requirements,

iv) status of relevant systems and components during the test,

v) instrumentation used and their calibration status,

vi) list of various leak paths identified during ILRT and repair work carried out, if any,

vii) post-test examination/inspection,

viii) test data, and

ix) log of events.

4. PRE-OPERATIONAL SECONDARY CONTAINMENT LEAKAGE RATE TESTING

4.1 General

The following tests are to be conducted:

i) positive pressure leakage rate test of the space between outer 2 doors of main and emergency airlocks (applicable to containment with 3 doors as a part of secondary containment)

ii) a positive pressure secondary containment integrated leakage rate test (SC- ILRT)

iii) tests to demonstrate maintenance of negative pressure in SC

The requirements spelt out in this section will be applicable to projects under construction and projects being planned.

4.2 Pretest Inspection

Prior to any test, secondary containment should be visually examined (doors, penetrations, etc.) to ensure that there is no visual damage to the appurtenances.

4.3 Positive Pressure Leakage Rate Test of Secondary Containment Space of Main and Emergency Airlocks

Pre-operational positive pressure test of SC space of MAL and EAL should be conducted at a pressure P_{SO} (see for details section 4.4.1).

4.4 Secondary Containment Leakage Rate Test (SC-LRT)

4.4.1 Positive Pressure Test

Pre-operational positive pressure test, subsequent to completion of construction and prior to first criticality of the reactor, SC-LRT should be conducted at pre-operational leakage test pressure, P_{SO}, where P_{SO} is higher of the following:

i) calculated maximum peak secondary containment pressure following postulated double ended break in the primary heat transport system,

or

ii) the pressure which enables effective leak search and successful leakage rate testing (typical value is 200 mm WC)

4.4.2 Negative Pressure Test

Following the pre-operational positive pressure LRT, a negative pressure maintenance test should be conducted to demonstrate the maintenance of specified negative pressure, with the secondary containment recirculation and purge system operating as per the design.

4.5 Test Medium

The positive pressure test should be conducted using atmopheric air free from oil, excessive humidity and other contaminants.

4.6 Test Method

Leakage rate test at positive pressure should be conducted either by absolute pressure method or flow rate method with constant gauge pressure.

The negative pressure test should be conducted by demonstrating maintenance of vacuum in SC, in the specified range, and by monitoring the corresponding average purge flow.

4.7 Test Duration

The duration of positive pressure test by absolute pressure method should not be less than 1 hour.

In case of flow make-up method, the test shall be conducted at least for 15 minutes.

The duration of the negative pressure test should be such that reliable indication of the purge rate can be established. As a minimum, the duration of test should be for 5 cycles of operation of purge damper.

4.8 Test Specifications

The tests shall be conducted in accordance with the approved test specifications. The test specifications shall include the following :

4.8.1 Test parameters such as test volume, pressure, allowable leakage rate, test duration, test methodology for airlocks, positive and negative pressure tests.

4.8.2 Conceptual description of test setup, e.g. pressurisation/depressurisation facilities and relief provisions.

4.8.3 The programme of pretest visual inspection.

4.8.4 Method of containment isolation before starting pressurisation. In case containment is isolated by a method other than actuation of isolation logic, acceptability of the test results should be justified.

4.8.5 Required status of various relevant systems and components during the test should be taken into account. This should include a list of all temporary installations and the programme for their post-test normalisation.

4.8.6 Specifications of test instruments and their accuracy.

4.8.7 Method of calculation of leakage rate as per the specifications.

4.9 Test Procedure

A detailed procedure shall be prepared covering all aspects of the test and made available at the site before commencement of the test.

4.10 Acceptance Criteria and Retesting

The secondary containment LRT shall be considered acceptable if:

a) negative pressure is maintained as per station technical specifications,

and

b) the computed leakage rate is within the maximum allowable leakage rate (MALR) as specified in technical specifications for operation of NPP.

If any of the above is not met, then the corresponding test shall be repeated after completion of necessary repairs.

4.11 Assessment of Compressed Air In-Leakage

During the ILRT of secondary containment, the compressed air systems supplying air to SC should be isolated. In case compressed air system has to remain charged within containment, an assessment of compressed air in-leakage should be made by any one of the following methods:

a) use of precision flowmeter in the compressed air lines, and

b) absolute pressure method, either before or after the LRT with compressed air system configuration same as during the LRT.

4.12 Leakage Rate Computation

When absolute pressure method is used, the leakage rate computation may be done either by mass plot method or two-point method.

For flow makeup method, the compensating flow rate as determined from the flow totaliser and elasped time may be reported.

The leakage rate computation is based on a polynomial fit of the observed air mass versus time. Details of leakage rate computation are given in Appendix D.

4.13 Test Instrumentation

4.13.1 Selection of Instrumentation

The instruments should be selected as per specifications. The inaccuracy of the instruments selected should not be more than ±5 % in the selected range. A typical list of instruments including their range and accuracy is given in Annexure IV.

4.13.2 The instruments shall be calibrated, as applicable, in accordance with test specifications for their expected range of operation.

4.14 Reporting of Results

The test results should be documented in all aspects so as to permit comprehensive review and analysis. It should also permit use of this experience for the future test. The report should include the following:

i) summary, results/conclusions,

ii) results of positive pressure test indicating measured leakage rate alongwith calculated error estimate,

iii) results of vacuum maintenance test,

iv) results of positive pressure leakage rate test of secondary containment space of main and emergency asirlocks (if not separately reported) ,

v) test specifications, deviations/exceptions from test specifications/requirements,

vi) status of relevant systems and components during the test,

vii) instrumentation used and their calibration status,

viii) list of various leak paths identified during the test and repairs carried out, if any ,

ix) test data, and

x) log of events.

5. PRE-OPERATIONAL VOLUME V_1 TO V_2 INTEGRITY TESTING

5.1 General

The following tests should be conducted:

(i) a positive pressure leakage rate test to evaluate the effective suppression pool bypass area between V_1 and $V_{2,}$ and

(ii) test to demonstrate, maintenance of measurable negative pressure in V_1 with respect to V_2, with normal ventilation and purge from V_1 operating

5.2 Pre-test Inspection

Prior to commencement of V_1-V_2 integrity testing, all V_1-V_2 barriers such as doors and their seals, joints in floors and walls, isolation valves, cable and other penetrations, pressure equalisation devices shall be visually inspected and examined to ensure their completeness for intended operation as per the design.

5.3 Leakage Rate Test

5.3.1 Positive Pressure Test

The differential pressure for the test should be sufficiently high to permit effective leak search. Typcial test pressure value of V_1 is 200 mm of WC with respect to V_2.

5.3.2 Negative Pressure Test

Following the pre-operational positive pressure leakage rate test, a negative pressure test should be conducted on V_1 to demonstrate measureable vacuum in V_1 with respect to V_2 with all compressed air systems charged and with normal ventilation in V_2 on (typical value will be around 15 mm WC). The level of vacuum should include margins for chronic water leakage in volume V_1 from various systems and small spills expected during online refuelling operation.

5.4 Test Medium

The positive pressure test should be conducted, using atmospheric air free from oil, excessive humidity and other contaminants.

5.5 Test Method

The positive pressure test may be conducted either by absolute pressure method or flow rate method with constant gauge pressure The negative pressure test may be conducted by maintenance of measurable negative pressure in V_1, with normal ventillation in V_2 and design purge flow from V_1.

5.6 Test Duration

For positive pressure test, the test may be continued till the differential pressure between V_1 and V_2 becomes essentially zero or 30 minutes whichever is less.

For negative pressure test, the duration should be sufficiently large to achieve stable conditions.

5.7 Test Specifications

The tests shall be conducted in accordance with the approved test specifications. The test specifications shall include the following :

5.7.1 Test parameters such as test volume, test pressure, equivalent bypass area, test duration and test methodologies.

5.7.2 Required status of various relevant systems and components during the test and their impact on the leaktightness. This should also include a list of all temporary installations and the programme of their post-test normalisation.

5.7.3 Specifications of test instruments and their accuracy.

5.7.4 The programme of pretest visual inspection.

5.8 Test Procedure

A detailed test procedure shall be prepared covering all aspects of the test and be available at site before commencement of test.

5.9 Acceptance Criteria and Retesting

5.9.1 The calculated bypass area between V_1 and V_2 shall not exceed the design specified value (typical value for current generation 220 MWe PHWR is of the order of 0.02 m^2). Test shall be repeated after necessary repair of the V_1-V_2 barriers, if this is not met. Acceptance of deviation from specified value would require adequate justification.

5.9.2 Test shall be repeated after necessary repairs if a measurable negative pressure cannot be developed in volume V_1.

5.10 Leakage Rate Computation

Leakage rate computation for V_1-V_2 integrity test by absolute pressure method may be done by two-point method on the basis of which, the bypass area calculation will be done.

Details of computation are given in section A.3 of Appendix A.

5.11 Test Instrumentation

A typical list of instruments used including their range and accuracy is given in Annexure V.

5.12 Reporting of Results

The test results should be documented in all aspects in a manner to permit comprehensive review and analysis. It should also facilitate use of the experience for future tests. The report should include the following:

i) summary, results/conclusions,

ii) results of positive pressure test, indicating measured leakage rate and assessed bypass area,

iii) results of negative pressure maintenance test,

iv) test specifications, deviations/exceptions from test specifications/ requirements,

v) status of relevant systems and components during the test,

vi) list of various leak paths identified during the test and repairs carried out, if any ,

vii) test data, and

viii) log of events.

6. IN-SERVICE TESTING OF CONTAINMENT

6.1 General

A programme of periodic in-service testing of the containment should be established to ensure that the functional design requirements are met during the entire operating life of the NPP. In order to achieve this, different types of in-service leakage rate tests are carried out on primary as well as secondary containments and on V_1-V_2 barriers in the primary containment. Appropriate provisions should be available to conduct the periodic in-service ILRT on primary containment upto pre-operational ILRTP [(P_{PO}), see Section 3.4.2] at any time during the life of the NPP.

The requirements spelt out in this section will be applicable to projects under construction and projects being planned.

6.2 Test Program

The following sequence of in-service test programme should be carried out:

(i) visual inspection of the primary and secondary containments, including various penetrations and V_1-V_2 barriers, etc.,

(ii) local leakage rate testing of airlocks, penetration seals with expansion bellows, cable seals and containment isolation valves in specified system,

(iii) integrated leakage rate test of primary containment at reduced pressures and full pressure (ILRTP) at appropriate intervals,

(iv) positive pressure test of SC and test to demonstrate maintenance of negative pressure in SC, and

(v) positive pressure test of V_1-V_2 barriers and test to demonstrate maintenance of negative pressure in V_1 with respect to V_2 .

6.3 Visual Inspection Programme

6.3.1 A visual inspection programme should be carried out, covering the following aspects once every 4 years:

(a) inspection of the primary and secondary containment structures (including concrete/metallic parts, non-metallic and organic parts),

(b) left-in instruments required for containment monitoring,

(c) inspection around major embedded parts/penetrations, and

(d) inspection of V_1-V_2 doors, hinges and sealings.

6.3.2 A detailed visual inspection programme covering the following aspects should be carried out, once every 8 years, prior to conducting the full pressure ILRT on PC:

(a) inspection of the primary and secondary containment structures, including concrete/metallic parts, etc.,

(b) left-in instruments required for long-term structural behaviour monitoring ,

(c) inspection around major embedded parts/penetrations,

(d) inspection for leakages from barriers such as caulking compounds, expansion joints/seals used around penetrations,

(e) any weak concrete patches revealed during operation,

(f) non-destructive tests like, schmidt hammer test, carbonisation, ultrasonic pulse velocity (USPV) etc. on representative areas of the PC, and

(g) inspection of V_1-V_2 doors, hinges and sealings.

6.3.3 Irrespective of what is stated in sections 6.3.1 and 6.3.2, however, after any abnormal event, following occurrence of any severe environmental load, the containment should be subjected to a detailed visual examination.

6.3.4 Based on the inspection as above, inspection reports should be prepared and major repairs be carried out with written down procedures, if required.

6.4 Periodic Local Leakage Rate Test

Following the pre-operational test, local leakage rate tests should be conducted once every 2 years at pre-operational test pressure unless otherwise required by station technical specifications, taking into account the wear and tear of components during normal operation. LLRT should be carried out on piping penetrations with bellows and cable penetrations, isolation dampers (actuated by containment isolation signal). However, airlocks should be leak tested once every year and after every seal change. Containment isolation dampers should be leak tested once every year.

6.5 Periodic In-Service Integrated Leakage Rate Tests of Primary Containment

6.5.1 Test Pressures for Periodic ILRT

6.5.1.1 The following are the test pressures (P_t) to be adopted for the periodic ILRT based on the frequency of the tests:

i) $P_t = P_{PO}$, for first ILRT, to be conducted 4 years after first criticality

ii) $P_t = 0.33\ P_{PO}$, for subsequent tests to be conducted once in 4 years

iii) $P_t = P_{PO}$, for tests to be conducted once in 8 years. During this test special care is to be taken of the instruments/equipment housed inside the containment for their pressue-withstand capability. During this test, rundown data should also be taken at 0.33 P_{PO}

Any deviations from the above, shall be subject to review and approval of the regulatory body.

During the above tests, data should also be collected from permanent left-in instruments for long-term structural behaviour monitoring.

6.5.2 Frequency and Acceptance Criteria for ILRT of PC

6.5.2.1 Following the first criticiality of the reactor, periodic in-service leakage rate tests should be conducted at a pressure as specified in section 6.5.1 (ii), at a frequency of once in 4 years.

6.5.2.2 In case the 4 year test results indicate leakage rate in excess of 90 % MALR value, then necessary repair works should be completed and the containment should be retested so as to bring back the leakage rate within 90 % MALR value.

6.5.2.3 Nothwithstanding what is stated in sections 6.5.1.1 (i) and (ii) and 6.5.2.1, ILRT of PC should be conducted at pre-operational test pressure (P_{PO}) once in 8 years. If the 8 years ILRT test results indicate leakage exceeding 75 % MALR value (as specified in technical specifications for operation of NPP), then the leaktightness of PC should be brought below 75% MALR through appropriate remedial measures before startup of the reactor.

6.5.3 The need to conduct the structural integrity test and/or ILRT at full pressure following the completion of major repairs, resulting from severe deterioration or damage and prior to reinstating the containment to service, should be based on the review of the extent of the repairs done.

6.6 Leakage Rate Specifications for Periodic LLRTs and ILRT of Primary Containment

The aforesaid in-sevice LLRTs and ILRTs should be conducted in accordance with the approved test specifications.

The test specifications should include the following:

i) test parameters such as test pressure, test volume, allowed leakage rates, test duration, test methodology, etc. for both integrated and local leakage rate tests,

ii) conceptual description of test setup e.g. pressurisation/ depressurisation facilities, relief provision,

iii) required status of various systems and components during the test. This should include:

(a) a list of all temporary installations and the programme of their post-test normalization, and

(b) the status of various systems for maintenance of cold shutdown condition,

iv) specifications of test instrumentation and accuracy as well as locations of temperature sensors in reactor building for monitoring dry and wet-bulb temperatures, and

v) methods for calculation of leakage rate and error analysis and data rejection condition.

6.7 Periodic Leakage Rate Test of Secondary Containment

6.7.1 Negative Pressure Test

Following the first criticality of the reactor, in-service periodic test at negative pressure should be conducted once every 2 years to demonstrate the maintenance of specified negative pressure, with secondary containment purge system operating as per design.

6.7.2 Positive Pressure Test

Following the first criticality of the reactor, inservice periodic test at positive pressure [(P_{SO}), see section 4.4.1] should be conducted once every 4 years at pre-operational test pressure or at a pressure suitably chosen for successful leak search and integrated test. If the negative pressure test as specified in section 6.7.1 is not successful, then a positive pressure test should be conducted for effective leak search.

6.8 Periodic Integrity Test of V_1 & V_2

6.8.1 Negative Pressure Test

Following the first criticality of the reactor, in-service periodic negative pressure test should be conducted for V_1-V_2 barriers once every 2 years, in the same manner as for pre-operational test. Test should be repeated, if specified vacuum could not be developed in V_1 after carrying out necessary repairs.

6.8.2 Positive Pressure Test

Following the first cirticality of the reactor, in-service periodic leakage rate test at positive pressure should be conducted for V_1-V_2 barriers once every 4 years at pre-operational test pressure (see Section 5.3.1). If the test results indicate that the calculated bypass area between V_1 and V_2 exceeds the specified value, then the test should be repeated after necessary repairs.

6.9 Leakage Rate Computation

The methodology for leakage rate calculations for the above said periodic in-service leakage rate tests of primary and secondary containtments, periodic in-service local leakage rate testing of various penetrations and access airlocks and periodic in-service V_1-V_2 integrity testing should be as per the respective clauses spelt out in the aforesaid sections of this guide.

6.10 Test Instrumentation

The instrumentation required for conducting the various periodic in-service tests as mentioned above, should be on the same lines as spelt out in the relevant sections on pre-operational tests given in this guide.

6.11 Reporting of Results

The above periodic in-service LLRT and ILRT of PC, SC and volume V_1 and V_2 as applicable, should be documented in all aspects so as to permit comprehensive review and analysis of the test results. The report should include the following, as applicable to the respective tests:

i) summary, results/conclusions,

ii) results of integrated positive pressure test, indicating measured leakage rates alongwith UCL values,

iii) results of negative pressure maintenance test,

iv) test specifications, deviations/exceptions, if any, from test specifications/ requirements,

v) status of relevant systems and components during the test,

vi) instruments used and their calibration status,

vii) list of various leak paths identified during the test,

viii) post-test examination/inspection,

ix) test data,

x) log of events, and

xi) recommendations for future tests .

APPENDIX-A

INTEGRATED LEAKAGE RATE CALCULATIONS

A.1 General

This guide requires that absolute pressure method be used to gather data and the mass plot technique to compute the leakage rates from primary and secondary containments and their associated appurtenances. For PC, the results from the mass plot analysis can be verified by superimposition of known in-leakage or out-leakage during the rundown. The absolute pressure method is a direct application of perfect gas law equation and for calculating the air mass. It is assumed that changes in temperature and pressure are not sufficient to significantly change the free air volume of the containment during the test.

A.2 Mass Plot Technique

In this technique, data from an absolute system is reduced to a contained mass of air by application of the perfect gas law. The test data consists of time series of independent values of contained air mass. If it is assumed that the leakage rate is constant with time, then the data can be analysed by the method of linear least squares. The slope of this line will then give the rate of change of air mass with time, which can be used to get the leakage rate.

A.2.1 Air Mass Calculation

The air mass in the test volume is derived from the perfect gas law as follows:

$$PV = mRT \qquad \text{(A.1)}$$

or

$$m = 9.81E{+}4\ (P_a + P_b - P_v)\ V/(RT) \qquad \text{(A.2)}$$

where m = mass of dry air, kg

P_a	=	gauge pressure of air in test volume, kg/cm^{2}g
P_b	=	atmospheric pressure of air, kg/cm^{2}a
P_v	=	vapour pressure of air in test volume, kg/cm^2 a
9.8 E+4	=	conversion factor, kg/cm^2 to N/m^2
V	=	free air in space in test volume, m^3
R	=	gas constant for air 8314.4 joules/kg-mole- ^{o}K 288.7 joules/kg-^{o}K (1kg mole of air = 28.8 kg)
T	=	average temperature of air in the containment/test volume

If the test volume is free from any water vapour source and the test duration is relatively small, so that ‘T’ does not change appreciably, then equation A.2 will reduce to:

$$m = 9.81E+4\ (P_a + P_b)\ V/(RT) \tag{A.3}$$

Plot the computed containment air mass against time; assuming that the change in leakage rate is not significant but there is slight change in pressure over the duration of the test, a linear least square line can be fitted through these points. The basis for using the least square method is to arrive at the calculated leakage rate with smallest variance, provided the data is free from bias. The fitted least square line can be written as:

$$m = A\mathit{k} + B \tag{A.4}$$

The least square constants A and B are given as:

$$A = \frac{n(\sum \phi_i m_i) - (\sum m_i)(\sum \phi_i)}{n(\sum \phi_i^2) - (\sum \phi_i)^2} \tag{A.5}$$

$$B = \frac{(\sum m_i)(\sum \phi_i^2) - (\sum \phi_i m_i)(\sum \phi_i)}{n(\sum \phi_i^2) - (\sum \phi_i)^2} \tag{A.6}$$

where

n = the total number of readings (observations)

m_i = air mass at any time N_i, kg

A = slope of the least square fit line (leakage rate, kg/h)

B = intercept of the least square fit line [i.e., the initial mass of air in the test volume/containment, kg]

N_i = time elapsed between first observation and the i^{th}observation in hours(N_1=0)

A.2.2 Calculation of Leakage Rate

Calculate the leakage rate from the formula given below using the equations for the least square fit constants A and B (see equations A.5 and A.6). Each N_i is the elapsed time between clock time at which the initial reading is taken and the clock time at which the ith reading is taken. Thus, $N_1 = 0$ in all test situations, N_2 is the length of the time elapsed before the next reading, and so on.

The leakage rate is expressed as the ratio of the rate of change of mass and the mass in the containment at time N_1=0. Since values of N_i have the units of hours and the percentage hourly leakage rates are desired, then the mass point leakage rate is expressed as a positive number by computing the fractional leakage rate in percentage of the contained air mass and is given by:

L_{am} = (-100)(A/B) % of contained volume leaking per hour (A.7)

L_{am} is also called as the estimate of the percentage measured leakage rate as determined from the least square slope and intercept

The least square fit mass leakage rate L_m can be given by the slope of this line as:

L_m = (-) A kg/h (or equivalent sm^3/h) (A.8)

A.2.3 Calculation of Upper Confidence Limit (UCL)

With reference to the least square fit air mass equation A.4, if a total of n observations are made, then the slope (leakage rate; if negative then it will be out-leakage, if positive, then it will be in-leakage) and intercept of this line are given by equations A.5 and A.6.

The estimate of common standard deviation, 'S' (following from 'equally variable' assumption) of the air masses with respect to the least square fit line is given by ANSI/ANS-56.8:1981 as:

$$S=\left[\frac{\Sigma\left(m_i-\overline{m}_i\right)^2}{n-2}\right]^{0.5} \tag{A.9}$$

Where, $m_i = A_i + B$

Constants A and B are given by Equations (A.5 & A.6)

The standard deviation of the slope of the least square fit line can be written as :

$$S_A=\pm\left(\frac{n}{n\Sigma\phi_i^2-(\Sigma\phi_i)^2}\right)^{0.5} S \tag{A.10}$$

An approximate upper limit of the 95 percent confidence on the true leakage rate can be given as :

Upper Confidence Limit (UCL) = L_{am} + 100$t_{0.95}$ (S_A/B) (A.11)

where,

L_{am}, is the measured percentage mass point leakage rate = (-100) (A/B)%/h.

S, is the estimate of standard deviation of measured mass from least squares line,

S_A, is the estimate of standard deviation of slope of least square line,

$t_{0.95} = \dfrac{1.6444d_F + 3.5283 + 0.85602/d_F}{d_F + 1.2209 - 1.5163/d_F}$, is the student's t distribution,

and d_F is the degrees of freedom, given as :

$d_F = n - 2$

A.2.4 Containment Gauge Pressure

Containment gauge pressure is measured at some representative locations e.g. pump room, MAL lobby. If the pressure is measured by more than one pressure gauge, then the arithmetic mean of the readings should be taken.

A.2.5 Barometric Pressure

Read the barometric pressure, P_b and convert the reading to kg/m^{2}a.

A.2.6 Temperature Measurement (Dry and Wet Bulb)

Temperature measurement, both dry bulb and wet bulb are carried out (at various locations, see Section 3.4.13.3) as follows:

- note down the total RTD resistance R_i for the sensor I_I
- deduct the lead wire resistance R_l from R_i to arrive at the net RTD resistance, $R_n=R_i-R_l$
- read the temperature (^{o}C) from the calibration curve of RTD. Interpolate the temperature, if necessary

Calculate the average containment air temperature, both 'dry bulb' and 'wet bulb', from the following formula:

Dry bulb temperature is:

$$T_d = \Sigma f_i T_{di}$$

where

T_d = average wet bulb temperature of containment air

T_{di} = area dry bulb temperature indicated by i^{th} sensor

f_i = weighting factor for i^{th} sensor

Wet bulb temperature is:

$$T_w = \Sigma f_i T_{wi}$$

where

T_w = average dry bulb temperature

T_{wi} = area wet bulb temperature

f_i = weighting factor for i^{th} sensor

A.2.7 Vapour Pressure

Calculate the saturation pressure of vapour at wet bulb temperature T_w from:

$$P_{sat(T_w)} = 1.03 \times 10^{-3} \exp\left(56.8883 - \frac{6891.3}{T_{wa}} - 5.32 \ln T_{wa}\right),$$

provided T_w lies between

10° C and 40° C, and T_{wa} = Wet bulb temperature, $^\circ K = 273 + T_w$

and , $P_{sat(T_{wa})}$ = Saturation pressure of vapour at T_{wa}, kg/cm^2

Calculate, the partial pressure of vapour from:

$$P_v = P_{sat(T_w)} - \frac{P_T \ (T_d - T_w)}{1500} \ ,$$

where

$P_{V'}$ = partial pressure of vapour, kg/cm^2g

P_T = total pressure of air and vapour mixture = $P_a + P_b$ kg/cm^2a.

Calculate average value of vapour pressure from

$P_{V''} = \Sigma f_i P_{V_i''}$ kg/cm^2g.

If temperature measurement (dry or wet) for a particular location has been faulty as revealed from the verification (see section A.2.8) or otherwise from examination of data, then readings of this location can be rejected and those of neighbouring regions can be used with suitable modification in weighting factors.

A.2.8 Hygrometer Readings

Note down the area dew point temperature T_i from the hygrometer and calculate the area vapour pressure. This is used for verifying the above vapour pressure measurements at atmospheric pressure. Compare

the calculation from dry/wet bulb measurement for verification.

A.2.9 Air Mass

Calculate air mass from:

$m = 9.81x10^4(P_a+P_b-P_V)\ V/(RT)$

m = containment air mass, kg.

A.2.10 Time

Note down the 'point of time' corresponding to each set of reading of P_a, P_b and T. Readings may be taken at an interval of 10 or 15 minutes. The chronometers used for this purpose should be synchronised before the test and subsequently once a day during the test.

A.3 Calculation of Bypass Leakage Area (V_1 to V_2 Integrity Test)

Leakage rate calculated by two-point method would be the leakage rate at the volume V_1 pressure i.e., $P_{1av} = (P_1+P_2)/2$,

where P_1 and P_2 are the pressures at the beginning and end of rundown. Volume V_2 pressure is kept as atmospheric during the test.

Hence, the following parameters are available for the calculation of bypass area:

P_{1av}, P_2 and Q, where,

P_{1av} is the average pressure of volume V_1 (N/m^2)

$P_{Vol\ 2}$ is the pressure of volume V_2 (N/m^2)

Q (sm^3/h) is the leakage rate from volume V_1 to V_2 to be calculated by two-point method.

Now bypass area can be calculated by the following orifice equation:

$$Q = A.k \sqrt{\frac{2P_{1av}\gamma}{(\gamma-1)}\left[1-\left(\frac{P_{Vol2}}{P_{1av}}\right)^{\frac{\gamma-1}{\gamma}}\right]} \text{ sm}^3/\text{h}$$

where

A = bypass area between V_1 to V_2, m^2 (A.12)

k = discharge coefficient (assumed 0.6 for coservative estimation of leakage area)

g = c_p/c_v = 1.4 (for air)

A.4 Leakage Rate Calculation by Two-Point Measurement

A.4.1 General

In case there is no gross leakage from a test volume, the leakage rate from this volume can be calculated on the basis of the initial pressure conditions before the start of the pressure rundown and pressure condition, after some time interval or at the end of the test.

A.4.2 Two-Point Equations

The mass of contained air at the beginning and end of the test can be written as:

$m_1 = P_1V/ RT_1$; $m_2 = P_2V/ RT_2$

where the test volume V is constant.

The mass loss is then given by:

$$\text{mass loss} = m_1 - m_2 = \left(\frac{P_1}{T_1} - \frac{P_2}{T_2}\right)\frac{V}{R} \qquad \text{(A.13)}$$

The mass loss can be converted to a volume loss rate at standard condition

since:

$m = P_sV_s / RT_s$

or

$V_s = mRT_s / P_s$

and thus leakage rate in standard volume units become :

$$L = (V_{s1} - V_{s2})/\phi = \frac{1}{\phi}\left(\frac{m_1 RT_s}{P_s} - \frac{m_2 RT_s}{P_s}\right) = \frac{RT_s}{P_s\phi}(m_1 - m_2) \qquad \text{(A.14)}$$

or

$$L = \frac{V\,T_s}{P_s\phi}\left(\frac{P_1}{T_1} - \frac{P_2}{T_2}\right) sm^3/h \qquad \text{(A.15)}$$

For computing % fractional leakage rate Eq. (A.15) is to be divided by V_{s1}. In which case,

$$L_{am} = \frac{100}{\phi}\left(1 - \frac{P_2\,T_1}{P_1\,T_2}\right)\%/h \qquad \text{(A.16)}$$

where

$P_{1,2}$ = test volume pressures at the beginning and end of the test $(=P_a+P_b-P_v)_{1,2}$, kg/cm^2g

$P_{a1,2}$ = containment/test volume gauge pressures at the beginning and end of the test, kg/cm^2g

$P_{b1,2}$ = atmospheric pressure at the beginning and end of the test, kg/cm^2 a

$P_{v1,2}$ = partial pressure of vapour in containment test volume at the beginning and end of test, kg/cm^2 a

P_s = standard pressure (14.697 psia), 1.033 kg/cm^2 a

T_s = standard temperature, 293 K

$T_{1,2}$ = containment/test volume average air temperature at the beginning and end of test, K

L = leakage rate of dry air, sm^3/h

V = free air volume of test area, m^3

f = test duration (time between data points), hours

Error analysis calculations should be done as per section B.2.

A.5 Local Leakage Rate Calculation

For determination of local leakage rates, where the test volumes are small and are free from a source of water, the vapour pressure may be assumed to remain constant. If the duration of the test is small and the leakages are low, the temperature of the test volume also may be assumed to remain constant. Then equation A.15 in such a situation will reduce to:

$$L_L = \frac{VT_s}{P_a T}(P_1 - P_2) \qquad \text{(A.17)}$$

where

$P_1 = (P_a + P_b)_1$; and

$P_2 = (P_a + P_b)_2$

APPENDIX-B

ERROR ANALYSIS

B.1 General

The uncertainty in the estimated value of L_{am} is assessed in terms of the standard deviation of A and B (equations A.5 and A.6) and their co-variance, followed by the computation of an upper limit of the 95th confidence level for L_{am}. The symbols used in the analysis are as follows:

List of Symbols used:

L	=	leakage rate, sm^3/h
L_m	=	measured leakage rate as given by slope of the least square fit line, kg/h or sm^3/h
L_{am}	=	percentage measured leakage rate as given by the slope of the least square fit line, %/h
V	=	free volume of test area, m^3
T_s	=	standard temperature, K
f	=	duration of test, hours
P_s	=	standard pressure, 1.033 kg/cm^2 a
P_a	=	gauge pressure in containment/test volume, kg/cm^2 g
P_b	=	atmospheric pressure kg/cm^2 a
P_v	=	partial pressure of vapour in containment test volume, kg/cm^2 a
P_T	=	net total pressure of dry air (P_a+P_b-P_v), kg/cm^2 a at temperature T ^{0}K
T	=	average temperature of containment/test volume air, K
ISG	=	instrumentation selection guide

e	=	error associated with measurement of a parameter (such as pressure, temperature, humidity etc.)
Var (y)	=	variance of general function f(y) = $[\sigma(y)]^2$
Var (x)	=	variance of a variable x
Var (x_1x_2)	=	co-variance of (x_1+x_2)

The instrumentation errors are combined using a root-sum-square-formula i.e. if, in the basic leakage rate equation, the error in measurements is $3e_1$ at point 1 (beginning of the interval) and $3e_2$ at point 2 (end of the interval), then combined error will be:

$$= [(3e_1)^2 + (3e_2)^2]^{0.5}$$

$$= (2 \quad 3e^2)^{1/2}, \text{ where } 3e_1 = 3e_2 = 3e \text{ .} \qquad \text{(B.1)}$$

The effect of systematic errors has been neglected as it can be shown that a fixed error (not changing with time or absolute value of the variable being measured), unless the absolute value of the error is a sizeable fraction of the absolute value of the variable being measured, does not have a significant contribution in overall error.

For a function $y = f(x_1,x_2,x_3\ldots..)$

$$\text{Var (y)} = \left(\frac{\partial y}{\partial x_1}\right)^2 \text{Var } (x_1) + \left(\frac{\partial y}{\partial x_2}\right)^2 \text{Var } (x_2) + 2\left(\frac{\partial y}{\partial x_1}\right)\left(\frac{\partial y}{\partial x_2}\right) \text{Covar } (x_1x_2) + \ldots \qquad \text{(B.2)}$$

Neglecting the covariances (which will be very small),

$$\text{Var (y)} = \left(\frac{\partial y}{\partial x_1}\right)^2 \text{Var } (x_1) + \left(\frac{\partial y}{\partial x_2}\right)^2 \text{Var } (x_2) + \ldots\ldots \qquad \text{(B.3)}$$

B.2 Error in Two Point Measurement

From Equation (A.15), it can be seen that L can be written as :

$$L = f(P_{a_1}, P_{a_2}, P_{b_1}, P_{b_2}, P_{v_1}, P_{v_2}, T_1, T_2) \qquad \text{(B. 4)}$$

Therefore Var(L) can be written similar to the Equation (B.3) as above :

$$\mathrm{Var}(L) = \left[\frac{\partial L}{\partial P_{a_1}}\right]^2 (e_{P_{a_1}})^2 + \left[\frac{\partial L}{\partial P_{a_2}}\right]^2 (e_{P_{a_2}})^2 + \left[\frac{\partial L}{\partial P_{b_1}}\right]^2 (e_{P_{b_1}})^2 + \left[\frac{\partial L}{\partial P_{b_2}}\right]^2 (e_{P_{b_2}})^2 +$$
$$\left[\frac{\partial L}{\partial P_{V_1}}\right]^2 (e_{P_{V_1}})^2 + \left[\frac{\partial L}{\partial P_{V_2}}\right]^2 (e_{P_{V_2}})^2 + \left[\frac{\partial L}{\partial T_1}\right]^2 (e_{T_1})^2 + \left[\frac{\partial L}{\partial T_2}\right]^2 (e_{T_2})^2$$

where, $\mathrm{Var}(x) = (e_x)^2$

As the random error in measurements at points 1 and 2 are the same :

$$(e_L)^2 = (e_{P_a})^2 \left[\left(\frac{\partial L}{\partial P_{a_1}}\right)^2 + \left(\frac{\partial L}{\partial P_{a_2}}\right)^2\right] + (e_{P_b})^2 \left[\left(\frac{\partial L}{\partial P_{b_1}}\right)^2 + \left(\frac{\partial L}{\partial P_{b_2}}\right)^2\right] +$$
$$(e_{P_V})^2 \left[\left(\frac{\partial L}{\partial P_{V_1}}\right)^2 + \left(\frac{\partial L}{\partial P_{V_2}}\right)^2\right] + (e_{P_T})^2 \left[\left(\frac{\partial L}{\partial T_1}\right)^2 + \left(\frac{\partial L}{\partial T_2}\right)^2\right]$$

By using Equation (A.15) for L and taking partial derivations of L with respect to each of the parameters, the following equations are obtained :

$$\frac{\partial L}{\partial P_{a_1}} = \frac{VT_s}{\phi\, P_s}\left(\frac{1}{T_1}\right)$$
$$\frac{\partial L}{\partial P_{a_2}} = -\frac{VT_s}{\phi\, P_s}\left(\frac{1}{T_2}\right)$$
$$\frac{\partial L}{\partial P_{b_1}} = \frac{VT_s}{\phi\, P_s}\left(\frac{1}{T_1}\right)$$
$$\frac{\partial L}{\partial P_{b_2}} = \frac{VT_s}{\phi\, P_s}\left(\frac{1}{T_2}\right)$$
$$\frac{\partial L}{\partial P_{v_1}} = -\frac{VT_s}{\phi\, P_s}\left(\frac{1}{T_1}\right)$$
$$\frac{\partial L}{\partial P_{v_2}} = \frac{VT_s}{\phi\, P_s}\left(\frac{1}{T_2}\right)$$

$$\frac{\partial L}{\partial T_1} = -\frac{VT_s}{\phi\, P_s}\left(P_a + P_b - P_V\right)_1\left(\frac{1}{T_1^{\,2}}\right) = -\frac{VT_s}{\phi\, P_s}\left(\frac{P_{T_1}}{T_1^2}\right)$$

$$\frac{\partial L}{\partial T_2} = \frac{VT_s}{\phi\, P_s}\left(P_a + P_b - P_V\right)_2\left(\frac{1}{T_2^{\,2}}\right) = \frac{VT_s}{\phi\, P_s}\left(\frac{P_{T_2}}{T_2^2}\right)$$

Therefore,

$$e_L^{\,2} = \left(\frac{VT_s}{\phi\, P_s}\right)^2\left[e_{P_a}^{\,2}\left(\frac{1}{T_1^{\,2}} + \frac{1}{T_2^{\,2}}\right) + e_{P_b}^{\,2}\left(\frac{1}{T_1^{\,2}} + \frac{1}{T_2^{\,2}}\right) + e_{P_V}^{\,2}\left(\frac{1}{T_1^{\,2}} + \frac{1}{T_2^{\,2}}\right) + e_T^{\,2}\left(\frac{P_{T_1}^{\,2}}{T_1^{\,4}} + \frac{P_{T_2}^{\,2}}{T_2^{\,4}}\right)\right]$$

(B.7)

During primary containment leakage rate test, the absolute pressure changes very little, the vapour pressure is very small compared to the absolute pressure and the contaiment temperature is nearly constant over the test period. Hence, the following assumptions can be made :

$P_{T_1} = P_{T_2} = P_T$; $T_1 = T_2$; $P_{a_1} + P_{b_1} - P_{v_1} = P_{a_2} + P_{b_2} - P_{v_2} = P_T$

Therefore,

$$e_L^{\,2} = \left(\frac{VT_s}{P_s T}\right)^2 2\left[e_{P_a}^{\,2} + e_{P_b}^{\,2} + e_{P_V}^{\,2} + \left(\frac{e_T P_T}{T}\right)^2\right]$$

or

$$e_L = \pm\left(\frac{VT_s}{P_s T}\right)\sqrt{2}\left[e_{P_a}^{\,2} + e_{P_b}^{\,2} + e_{P_V}^{\,2} + \left(\frac{e_T P_T}{T}\right)^2\right]^{\frac{1}{2}} sm^3/h \qquad \text{(B.8)}$$

In case one does a similar calculation using Equation (A.16), then :

$$e_L = \pm\frac{100}{\phi}\left[2\left(\frac{e_P}{P}\right)^2 + 2\left(\frac{e_T}{T}\right)^2 + 2\left(\frac{e_{Pv}}{P}\right)^2\right]^{\frac{1}{2}} \%/h \qquad \text{(B.9)}$$

This does not include the human error in noting down the value of the variables and error due to non-representative measurement.

Whereas e_{Pa} and e_{Pb} in the above equation are specified for the instruments, e_{PV} and e_T are to be determined in the following manner:

Measurement of temperature involves use of RTD and multimeter for reading the resistance and hence,

$e_T = [(e_{RTD})^2+(e_{multimeter})^2]^{0.5}$ (B.10)

where

e_{RTD} = random error in temperature detected by RTD, ^oC

$e_{multimeter}$ = random error in resistance reading by multimeter converted to temperature, ^oC

In case multiple sensors are used for measurement of temperature, T, then weighted average temperature is to be calculated and error found as follows:

$$T = f_1T_1 + f_2T_2 + f_3T_3 + ... \qquad \text{(B.11)}$$

Then, $\frac{\partial T}{\partial T_1} = f_1;......\frac{\partial T}{\partial f_n} = f_n$, etc.

or

$$\mathrm{Var}[T] = \left(\frac{\partial T}{\partial T_1}\right)\mathrm{Var}(T_1) + \left(\frac{\partial T}{\partial T_2}\right)\mathrm{Var}(T_2) + ... \qquad \text{(B.12)}$$

Assuming that $\mathrm{Var}(T_1) = \mathrm{Var}(T_2) = ...$

Therefore,

$$\mathrm{Var}[T] = [f_1^{\,2} + f_2^{\,2} + ...]\mathrm{Var}[T]$$

P_V can be written as:

$$P_V = P_{sat\,(TW)} \qquad \frac{P_T\,(T_d - T_w)}{1500} \qquad \text{(B.13)}$$

where

P_V = saturation pressure of steam at T_w, kg/cm^{2}a

P_T = total air pressure in containment ($P_a + P_b$), kg/cm^{2}a

T_d = dry bulb temperature

T_W = wet bulb temperature

Then,

$$e_{P_V}^{\;2} = \left(\frac{\partial P_V}{\partial P_{sat}}\right)^2 e_{P_{sat}}^{\;2} + \left(\frac{\partial P_V}{\partial P_T}\right)^2 e_{P_{sat}}^{\;2} + \left(\frac{\partial P_V}{\partial T_d}\right)^2 e_{T_d}^{\;2} + \left(\frac{\partial P_V}{\partial T_W}\right)^2 e_{T_W}^{\;2} \tag{B.14}$$

Taking the partial derviatives of P_V then:

$$\frac{\partial P_V}{\partial P_{sat}} = 1; \frac{\partial P_V}{\partial P_T} = -\left(\frac{T_d - T_W}{1500}\right)$$

$$\frac{\partial P_V}{\partial T_d} = -\frac{P_T}{1500}, \text{ and } \frac{\partial P_V}{\partial T_W} = \frac{P_T}{1500}$$

$$\therefore e_{P_V}^{\;2} = e_{P_{sat}}^{\;2} + \left(\frac{T_d - T_W}{1500}\right)^2 e_{P_T}^{\;2} + \left(\frac{P_T}{1500}\right)^2 e_{T_d}^{\;2} + \left(\frac{P_T}{1500}\right)^2 e_{T_W}^{\;2}$$

or

$$e_{P_V} = \pm\left[e_{P_{sat}}^{\;2} + \left(\frac{T_d - T_W}{1500}\right)^2 e_{P_T}^{\;2} + \left(\frac{P_T}{1500}\right)^2 e_{T_d}^{\;2} + \left(\frac{P_T}{1500}\right)^2 e_{T_W}^{\;2}\right]^{0.5} \tag{B.15}$$

where

$e_{T_d}^{\;2} = (e_{RTD})^2 + (e_{multimeter})^2$; $e_{T_W}^{\;2} = (e_{RTD})^2 + (e_{multimeter})^2$

B.3 Data Rejection Criteria

Data rejection for the calculation of leakage rate from the measured air mass in the containment at the specified time interval is to be carried out in accordance with ANSI/ANS-56.8:1981 described as follows:

An outlying observation or an outlier is a data point, which is widely different from the remaining observations in the data set. The outlier could be caused by instrument error, error in reading the measurement or numerical error in calculating the mass of air. The standard error of the residual (difference between the measured air mass and air mass obtained from least square fit), in case of regression analysis, varies with time and is given by:

$$s_i = S\sqrt{1 - \frac{1}{n} - \frac{\left(\phi_i - \bar{\phi}\right)^2}{\Sigma\left(\phi_i - \bar{\phi}\right)^2}} \qquad \text{(B.16)}$$

This is for the i^{th} observation where

s_i= standard error of the i^{th} residual r_i

r_i= i^{th} residual = m_i(measured) - m_i(from least square fit)

k_i= point of time

n= number of observations

$$\bar{\phi} = \frac{1}{n}\Sigma\phi_i$$

$$\therefore\ S = \sqrt{\frac{\Sigma\left(m_i - m_i'\right)^2}{(n-2)^2}}$$

S= standard deviation of measured air mass, is given as:

Compute the residual r_i=m_i-m_i and standard error s_i for each i^{th} value and divide r_i by s_i to obtain standardised residual. Compare this standardised residual with the limiting ratios given in Table B.1 below (ANSI-56.8, Table-B1). If this value exceeds the table value, then m_i is declared as an outlier.

TABLE B.1

CRITICAL DEVIATION RATIOS OR DATA REJECTION FOR A ONE-SIDED STATISTICAL TEST

No. of Observations	5 % Rejection Level	1 % Rejection Level
4	1.41	1.41
5	1.71	1.73
6	1.92	1.97
7	2.07	2.16
8	2.19	2.31
9	2.28	2.43
10	2.35	2.53
11	2.43	2.64
12	2.48	2.70
13	2.52	2.76
14	2.57	2.80
15	2.61	2.87
16	2.64	2.92
17	2.68	2.96
18	2.71	2.99
19	2.74	3.03
20	2.76	3.06
21	2.79	3.09
22	2.82	3.12
23	2.84	3.15
24	2.85	3.17
25	2.89	3.19
26	2.90	3.21
27	2.92	3.23
28	2.93	3.25
29	2.95	3.26
30	2.96	3.28
31	2.97	3.29
32	2.99	3.31
33	3.00	3.32
34	3.01	3.33
35	3.02	3.34

CRITICAL DEVIATION RATIOS OR DATA REJECTION FOR A ONE-SIDED STATISTICAL TEST (Contd.)

No. of Observations	5 % Rejection Level	1 % Rejection Level
36	3.03	3.35
37	3.04	3.36
38	3.06	3.37
39	3.07	3.38
40	3.08	3.39
41	3.09	3.40
42	3.09	3.40
43	3.10	3.41
44	3.11	3.42
45	3.12	3.42
46	3.13	3.43
47	3.14	3.44
48	3.15	3.44
49	3.15	3.45
50	3.16	3.46
51	3.17	3.46
52	3.17	3.47
53	3.18	3.47
54	3.18	3.48
55	3.19	3.48
56	3.19	3.49
57	3.20	3.49
58	3.20	3.50
59	3.21	3.50
60	3.21	3.50

For leakage rate tests in which data are collected at equal intervals of time, equation (B.16) can be written as:

$$s_i = S\sqrt{1-\frac{1}{n}-\frac{\left(i-\bar{i}\right)^2}{\sum\left(i-\bar{i}\right)^2}} \quad \text{and} \quad \bar{i} = \frac{1}{n}\sum i = \frac{n+1}{2}$$

Substituti ng the value of $\bar{i}$,

$$\therefore \quad s_i = S\sqrt{1-\frac{1}{n}-\frac{12\left(i-\bar{i}\right)^2}{n\,(n+1)\,(n-1)}} \tag{B.17}$$

B.4 Local Leakage Rate Error Equation

As given in equation A.17, the local leakage rate equation can be written as:

$$L_L = \frac{VT_s}{P_s}\left(\frac{P_1}{T_1} - \frac{P_2}{T_2}\right), \text{ where } P_{1,2} = (P_a + P_b - P_v)_{1,2}, \text{provided } T_1 = T_2$$

Thus $L_L = f(P_1, T_1, P_2, T_2, \phi\, V, T_s, P_s)$

As derived already (see equation B.7), the Var (L_L) can be written as:

$$\mathrm{Var}(L_L) = e_{L_L}{}^2 = \left(\frac{\partial L_L}{\partial P_1}\right)^2 e_{P_1}{}^2 + \left(\frac{\partial L_L}{\partial P_2}\right)^2 e_{P_2}{}^2 + \left(\frac{\partial L_L}{\partial T_1}\right)^2 e_{T_1}{}^2 + \left(\frac{\partial L_L}{\partial T_2}\right)^2 e_{T_2}{}^2 + \left(\frac{\partial L_L}{\partial \phi}\right)^2 e_{\phi}{}^2 + \left(\frac{\partial L_L}{\partial V}\right)^2 e_{V}{}^2 \qquad \text{(B.18)}$$

Taking the partial derivatives of L_L with respect various parameters as above:

$$\frac{\partial L_L}{\partial P_1} = \frac{VT_s}{P_s T_1}$$

$$\frac{\partial L_L}{\partial P_2} = \frac{VT_s}{P_s T_2}$$

$$\frac{\partial L_L}{\partial T_1} = -\frac{VT_s P_1}{P_s \phi}\frac{1}{T_1{}^2}$$

$$\frac{\partial L_L}{\partial T_2} = \frac{VT_s P_2}{P\phi}\frac{1}{T_2{}^2}$$

$$\frac{\partial L_L}{\partial \phi} = \text{assumed zero}$$

$$\frac{\partial L_L}{\partial V} = \text{assumed zero}$$

and thus

$$\mathrm{Var}(L_L) = \left(\frac{VT_s}{P_s\phi}\right)^2 \left[\frac{e_{P_1}{}^2}{T_1{}^2} + \frac{e_{P_2}{}^2}{T_2{}^2} + \frac{P_1{}^2}{T_1{}^4} e_{T_1}{}^2 + \frac{P_2{}^2}{T_2{}^4} e_{T_2}{}^2\right]$$

The local leakage rate error can now be written as:

$$\delta L_L = [\mathrm{Var}(L_L)]^{\frac{1}{2}} = \left\{\left(\frac{VT_s}{P_s T_1}\right)^2 e_{P_1}{}^2 + \left(\frac{VT_s}{P_s T_2}\right)^2 e_{P_2}{}^2 + \left(\frac{P_1 VT_s}{T_1{}^2 P_s}\right)^2 e_{T_1}{}^2 + \left(\frac{P_2 VT_s}{T_2{}^2 P_s}\right)^2 e_{T_2}{}^2\right\}^{\frac{1}{2}}$$

(B.19)

APPENDIX-C

INSTRUMENTATION SELECTION GUIDE (ISG)

C.1 General

The below listed instrumentation selection guide (ISG) formula is an acceptable method to measure the ability of an instrumentation system to calculate the integrated leakage rate of a primary reactor containment system. The ISG formula is not based on a statistical analysis of leakage rate calculations, but is a recommended method for instrumentation selection. The instrumentation errors are combined here, using root-sum-square-formula. The ISG computed is not added to the value of calculated leakage rate, but is used for instrument selection only.

C.2 Instrumentation Selection

The value of the instrumentation selection guide (ISG) shall not exceed $0.25L_{am}$ prior to the test, for the purpose of instrumentation selection. If, during the test, some of the multiple instruments/sensors (e.g. temperature sensors) are lost, this guide may be used for deciding on extending the duration of the test. For detailed guidance on ISG, see ANSI/ANS56.8, Appendix G [11].

C.3 Instrumentation Selection Guide Formula

ISG = Instrumentation selection guide

L_{am} = leakage rate, percent per hour

k = test duration, hours

P = containment atmosphere, total absolute pressure

P_V = containment atmosphere, partial pressure of vapour

T = containment atmosphere, weighted absolute dry bulb temperature

e	=	error associated with measurement of change in a given parameter (in case of multiple measurements of a given parameter, the total measurement system error, ‘e’ is divided by the square root of the number of sensors used to measure the given parameter)

From equation (B.9), it can be seen that:

$Var(L_{am}) = d^2(L_{am})$, or standard deviation of L_{am} can be written as:

$$\delta\, L_{am} = ISG = \pm \frac{100}{\phi}\left[2\left(\frac{e_P}{P}\right)^2 + 2\left(\frac{e_P}{P}\right)^2 + 2\left(\frac{e_{P_V}}{P}\right)^2\right]^{\frac{1}{2}} \%/h \qquad \text{(C.1)}$$

APPENDIX-D

LEAKAGE RATE CALCUATIONS FOR SECONDARY CONTAINMENT

D.1 General

Estimation of leakage by applying two-point method is generally accepted, when the readings of pressure rundown are frequent and also the pressure drop during two consecutive readings is small. In such a case, a plot for leakage vs pressure can be prepared by applying the approach of best curve fitting. Estimation of leakage rate by using the two-point method (first and last reading) can only be used when it is ensured that leakage rate does not change with pressure (i.e. when the change in pressure over the time-frame considered is not significant).

D.2 In order to avoid the uncertainty with regard to the behaviour of leakage, a generalised approach to plot mass vs time is adopted. This approach is in line with the technique used in estimating leakage rate from primary containment. In case of primary containment, the leakage rate is calculated by drawing a straight line plot for mass vs time by using least square curve fitting method, whereas for secondary containment, because of higher leakage rate, a polynomial fit of second or higher order will satisfy the variation of air mass with time.

The slope of the plot at any pressure obtained from this mass vs time by using best fitted curve method, will give the leakage rate at that pressure.

D.3 Method

Following set of measurements will be required for the above purpose:

- temperature at various locations in order to estimate mean containment air temperature (T_{av}),
- barometric pressure (P_b),
- volume of containment (V),
- pressure of containment at some fixed time interval during rundown (P_c), and
- R-Universal gas constant.

Step 1:

Mass of air at time t : $m(t) = (P_a+P_b)/(R\cdot T_{av})$

From this step estimate mass of air in containment at various points of time.

Step 2:

Fit a curve of type : $m(t) = a_0+a_1t+a_2t^2$

It has been observed from experience that a polynomial of second order gives best curve for mass vs time for secondary containment and V1-V2 leakage test. Least square fit for second order polynomial can be made by using appropriate curve fitting methods.

If the polynomial plot of second order does not match well with the mass points at various times, a polynomial for third order may be tried for better match. Appropriate curve fitting techniques may be adopted.

The leakage rate can be calculated by differentiating the equation of air mass with respect to time and putting the time equal to half of the rundown time for the purpose of leakage rate to be specified at the average pressure of rundown.

ANNEXURE-I

SELECTION AND TRAINING OF PERSONNEL FOR WORKING IN PRESSURISED ENVIRONMENT

I.1 General

Entry of personnel in the pressurised containment is envisaged upto a pressure of 0.15 kg/cm^2g for leak search, to supplement leak detection/ search from outside the PC, especially areas which may not have easy access from outside.

For entry into pressurised RB (upto 0.15 kg/cm^2g), applicable industrial safety requirements should be followed. Personnel should be selected and acclimatised for working in pressurised conditions. Rate of pressurisation and depressurisation should be controlled. Adequate medical facilities should also be available prior to start of the test.

I.2 Communication

Install telephone sets and electric bells in airlocks and the containment. In addition provide walkie-talkie sets to each group of crew entering the airlock/containment under hyperatmospheric pressure.

I.3 Qualification of Crew

A list of the qualified crew alongwith means of identification should be available at the test control room from where the entry into the containment is to be controlled.

I.4 Training

Train each crew for:

i) conducting the soap bubble test-preparation of soap solution, duration within which the soap solution should be used up; application of soap solution on various surfaces and joints, estimation of leakage rate from the size of soap bubbles; and the generation rate[4]**,**

Note: [4] Application of soap solution on the inner surface may not be of any use. However, the same crew will also conduct leak searches outside the containment alongwith the regular crew and this training will be useful there.

ii) detection of leakage from hissing sound and fire fighting if any required,

iii) use of smoke to detect leak path,

iv) use of ultrasonic leak detectors, and

v) estimation of individual leakages using various equipment and instruments.

ANNEXURE-II

TYPICAL INSTRUMENTATION REQUIREMENTS FOR LOCAL LEAKAGE RATE TESTING

Sr. No.	Parameter to be Measured	Name of the Instrument	Specification of the Instrument	No.
1.	Measurement of pressure	Pressure gauge	Range : 20% higher than test pressure Accuracy : ± 0.5% of FS	

ANNEXURE-III

TYPICAL INSTRUMENTATION REQUIREMENTS FOR PRIMARY CONTAINMENT INTEGRATED LEAKAGE RATE TESTING

Sr. No.	Parameter to be Measured	Name of the Instrument	Specification of the Instrument	No.
1.	Measurement of absolute pressure of primary containment for leakage calculation	Digital pressure gauge	Range : 20% higher than the proof test pressure Accuracy : ± 0.05% of full scale	1
2.	Measurement of dry bulb temperature of primary containement	RTD	Range : 0-60^{0}C Accuracy : ± 0.8^{0}C	21
3.	Measurement of wet bulb temperature of primary containment	RTD	Range : 0-60^{0}C Accuracy : ± 0.8^{0}C	21
4.	Display of temperature	Temperature scanner	Range : 0-60^{0}C Accuracy : ± 0.2% of full scale	1
5.	Flow measured during super-imposition	Air flow meter	0-250 sm3/h Accuracy : ± 2% of full scale	1
6.	Measurement of pressure of primary containment for outsided display	Pressure gauge	Range : 20% higher than the proof test pressure Accuracy : ± 2% of full scale	1
7.	Measurement of relative humidity	Hand held hygrometer	Range : 10% to 95% Accuracy : ± 2% of full scale	1

Note : The instrument specifications given here are approximate and slight variations could be there in the instrumentation actually used for test, which would be taken into account in the error estimate.

ANNEXURE-IV

A. TYPICAL INSTRUMENTATION REQUIREMENTS FOR SECONDARY CONTAINMENT LEAKAGE RATE TESTING

Sr. No.	Parameter to be Measured	Name of the Instrument	Specification of the Instrument	No.
1.	Measurement of absolute pressure of secondary containment for leakage calculation	Digital pressure gauge or water manometer	Range : 0-12000 mm of WC Accuracy: ± 0.05% of full scale L.C.=2 mm of WC Water manometer: Range: 0 to 400 mm of WC Resolution: 1 mm of WC Accuracy: 2m of WC(parallax and human self error)	1
2.	Measurement of dry bulb temperature of secondary containment	RTD (½ class-B tolerance) (IS-2848)	Range: 0-60^{0}C Accuracy: ± 0.2^{0}C	2
3.	Display of temperature	Temperature	Range: 0-60^{0}C Accuracy: ± 0.2% of full scale	1

B. TYPICAL INSTRUMENTATION REQUIREMENTS FOR SECONDARY CONTAINMENT VACUUM MAINTENANCE TEST

Sr. No.	Parameter to be Measured	Name of the Instrument	Specification of the Instrument	No.
1.*	Measurement of pressure of secondary containment w.r.t. atmosphere	Pressure transmitter through COIS	Range: -40 to +10 mm of WC Accuracy: ± 1% of full scale	1

Note : The instrument specifications given here are approximate and slight variations could be there in the instrumentation actually used for test, which would be taken into account in the error estimate.

* This pressure transmitter reads pressure in gauge as another end of it is exposed to service building atmosphere.

ANNEXURE-V

A. TYPICAL INSTRUMENTATION REQUIREMENTS FOR VOLUME V_1 AND V_2 POSITIVE PRESSURE TESTING

Sr. No.	Parameter to be Measured	Name of the Instrument	Specification of the Instrument	No.
1.	Measurement of pressure of volume V1 for leakage calculation	Digital pressure gauge	Range : 0-12000 mm of WC Accuracy: ± 0.05% of full scale	1

B. TYPICAL INSTRUMENTATION REQUIREMENTS FOR VOLUME V_1 AND V_2 NEGATIVE PRESSURE TESTING

Sr. No.	Parameter to be Measured	Name of the Instrument	Specification of the Instrument	No.
1.*	Measurement of pressure of volume V1	Pressure transmitter	Range : -250 to +250 mm of WC Accuracy : ± 0.5% of full scale	1
2.*	Measurement of pressure of volume V2 w.r.t. SB	Pressure transmitter	Range : -250 to +250 mm of WC Accuracy : ± 5% of full scale	1

Note : The instrument specifications given here are approximate and slight variations could be there in the instrumentation actually used for test, which would be taken into account in the error estimate.

* These pressure transmitters read pressure in gauge as another end of it is exposed to service building atmosphere.

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SPECIAL DEFINITIONS

Computed Leakage Rate

The leakage rate value calculated from a pressure rundown test carried out on the containment and associated appurtenances.

Containment System

System consisting of the primary and secondary containments (including its extensions and appurtenances) and the following systems:

(i) Containment Isolation System

(ii) Energy Management System

(iii) Radionuclide Management System, and;

(iv) Combustible Gas Control System

Integrated Leakage Rate Test Pressure (ILRTP)

The pressure to which the containment is pressurised to conduct an integrated leakage rate test. It will be different for the type of reactor considered, depending on the design basis accident scenario.

Maximum Allowable Leakage Rate (MALR)

It is the maximum allowed leakage rate L_a, at design basis pressure P_a, as specified in the Station Technical Specifications, for either primary or secondary containment.

Upper Confidence Limit (UCL)

A calculated value obtained from sample data with the intention of placing a statistical upper bound on the true leakage rate. In this guide, UCL is calculated at 95 percent probability.

Volume V_1 (dry-well)

Those areas inside primary containment housing all the high enthalpy systems of the reactor system.

Volume V_2 (wet-well)

Those areas inside primary containment and not forming part of volume V_1,but including the suppression pool.

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PROVISIONAL LIST OF SAFETY CODE GUIDES AND MANUAL ON OPERATION OF NUCLEAR POWER PLANTS

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AERB/SG/O-14	Life Management of Nuclear Power Plants
AERB/NPP/SG/O-15	Proof and Leakage Rate Testing of Reactor Containments
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