Suitability Study of On-Line Leak Tests for CANDU Single-Unit Containment Buildings

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Abstract

CANDU reactor containment buildings are checked for integrity every five years. An on-line test could be performed more often, thereby reducing long-term unavailability of the containment system. A test procedure which accounts for operational factors is proposed. A theoretical error analysis is performed to study the effect of test parameters on the accuracy and sensitivity of the test. It is found that leak rates greater than 5% per day can be detected in less than one day. The target 0.5% per day requires tests longer than five days and the leak detection is complicated by operational factors. A test of two to three days will allow the detection of a 1% leak. It is also shown that a system modification which draws instrument air from inside the reactor building would allow the detection of a 0.5% leak rate in less than 12 hours.

Résumé

L'étanchéite de l'édifice de confinement des centrales de type CANDU est testée à tous les cinq ans. Un test pouvant être conduit durand l'opération de la centrale permettrait une vérification plus fréquente de l'étanchéité et reduirait le risque de défaillance du système de confinement. On propose une procédure d'un test qui tiend compte des facteurs opérationels. On présente une analyse théorique de l'erreur afin d'étudier l'effet des paramètres de contrôle sur la précision et la sensibilité du dit test. On démontre que des taux de fuite supérieurs à 5% par jour peuvent être détectés en moins d'un jour. L'objectif de 0.5% par jour ne peut être mesuré en moins de cinq jours et le calcul est compliqué par la presence des facteurs dûs à l'opération du réacteur. Un test d'une duré de deux à trois jours permettrait la détection d'un taux de 1% par jour. On démontre également qu'il est possible de détecter un taux de fuite de l'ordre de 0.5% par jour en moins d'un jour si le système d'air d'instrumentation est modifié de façon à tirer sa source de l'intérieur du bâtiment.

Introduction

The nuclear industry recognises safety as a top priority. One of the safety features of a CANDU reactor is the containment building in which it is housed.

These concrete containment buildings are checked for integrity at the commissioning of the plant and subsequently every five years. During these tests, the reactor is shutdown and the building pressurized to design pressure. A single-unit building must hold this pressure with an allowable leakage of 0.5% of the building volume per day.

Since these tests are only done every five years, it is possible that a leak could develop and go undetected until the next test. A leak test that could be performed during plant operation would allow more frequent tests. Frequent tests would ensure the continued reliability of the containment system.

The objective of this work is to investigate the suitability and feasibility of such tests for a CANDU single-unit containment building. A review of past efforts shows the importance of operational factors. This report presents a proposed test procedure which considers these factors, and gives a theoretical study of test performance. The parameters affecting leak tests are given and data is provided to allow the choice of a set of test conditions based on the objectives of the utility.

Theory of Leakage

Leak tests done below design pressure will show a lower leak rate. This result may, however, be used to determine the leakage rate at design pressure. The relationship between leak rate and pressure is needed. This relationship depends on whether the flow is laminar or turbulent. The flow regime is dependent on the leak path geometry, which is never known *a priori*.

Leak rate is also affected by air ingestion [Toossi, 1981], temperature, and other factors. For these reasons a relationship between the leak rate at low pressure and that at design pressure must be customized to a particular containment building. The rela-

Keywords: containment, leakage, tests.

Table 1: Summary of Previous Leak Rate Test Results

Station	Type of containment	Test pressure (kPag)	Model used	% Lr and error (95% conf)
Pickering[a]	multi-unit	+41.4	L α ΔP	0.18–0.54% / hr
Gentilly-1[a]	single	+117	L α $\Delta P^{1/2}$	0.28 ± 16% / day
		+41	L α $\Delta P^{1/2}$	0.25 ± 22% / day
USA's[b]		345–415	L α $\Delta P^{1/2}$	0.02–0.16% / day
Pickering A[c]	multi-unit	+41	L α $P_u^2 - P_d^2$	0.44% / hr
Bruce A[c]	multi-unit	+69	L α $P_u^2 - P_d^2$	0.25% / hr
Pickering A[d]	multi-unit	+13.8	n.a.	1.2 ± 11.5% / hr
Bruce B[e]	multi-unit	+69	L α $P_u^2 - P_d^2$	0.20 ± 10% / hr
Lepreau[f]	single	+124	n.a.	0.225 ± 0.8%/day

[a]Smith, 1987; [b]Brown, 1975; [c]Zakaib, 1982; [d]Zakaib, 1984; [e]Zakaib, 1985; [f]Harvey, 1982.

tionship can only be found if a low-pressure test immediately precedes or follows one at design pressure.

Review of Test Methods

Many methods have been proposed for testing containment integrity. Some tests have been performed and some are in the development stage. They may be grouped into the following categories:

1. External test methods such as external tracer detection, which can only give an indication that a leak is present [Spletzer, 1986].
2. Design-pressure leak rate tests [Zakaib, 1982; Smith, 1975; Whyle, 1984; Zakaib, 1985].
3. Positive lower-pressure leak rate tests, performed at different pressures and for different periods of time [Spletzer, 1986; Zakaib, 1984].
4. Tests at vacuum [Zakaib, 1984].
5. Continuous on-line monitoring, which is performed during normal operation [Zakaib, 1984].
6. Tracer gas monitoring and a mass balance over the reactor building [Spletzer, 1986; Zakaib, 1984; Boyd, 1986].

All of the above methods except 1 calculate leakage based on a mass balance using the ideal gas law. Leak rates are calculated using a linear regression analysis of the data [Zakaib, 1982; Smith, 1975; Zakaib, 1985; Zakaib, 1984; Brown, 1975]. Some results of these tests, which have been performed at various conditions, are summarized in Table 1. As can be seen from this table, none of the stations have attempted leak rate tests to detect small leaks (0.5% per day) at low pressure (less than 20 kPag).

Suitability of Previous On-Line Test Methods

For obvious reasons, full-pressure tests cannot be performed on line. External detection techniques are not suitable, since they are not quantitative.

Tests at reduced negative or positive pressures, with or without a tracer gas, can give acceptable results in a relatively short time for large leaks only. For leaks on the order of 0.5% of the contained air per day, much longer tests are required, and operational factors may significantly affect the calculated leak rate. Therefore a valid test for single-unit containment systems must take into account the errors due to system operation, as well as aim at reducing the instrument error. On-line monitoring will be discussed later in this paper.

Leakage testing for a single-unit CANDU building is then narrowed to a mass balance-based test, either with or without a tracer gas.

Operational Considerations

Safety

For an operating plant, there are factors which will affect any mass balance-based leakage test. The foremost of these factors is how the test will affect the safety systems inside the reactor building.

A leak test will most likely involve either a positive or negative change in the pressure inside the reactor building. If the building pressure rises above 3.45 kPa, then the high reactor building pressure trip point will be reached. It is important that the reactor trip when the pressure inside the bulding rises by 3.45 kPa.

It follows that if the building pressure is changed by ΔP, then the reactor trip point must be changed by ΔP. To ensure that this safety feature is at no time bypassed, it will be necessary to change the building pressure slightly by dP, and then change the trip point inside the reactor building by dP, thus bringing the building and trip point to the desired pressures in steps and together. The implications of this change in the trip point on the safety analysis would have to be studied.

This procedure will take time. As an example, it should take 16 hours to increase the pressure of the building and the trip point to 10 kPa, and another 16 to reduce the pressure to normal operation at the end of the test (NBEPC staff estimate). The same procedure must be followed at the end of the test so that at no time is the difference between the containment building pressure and the trip point set value greater than 3.45 kPa.

The dousing system is activated at 14 kPa, and it would be best to keep the test below this pressure. This should not be a difficult constraint to meet. It should be noted that any change in pressure in the building may change the relief pressure of the moderator relief devices and the pressure of the moderator system. Small changes in building pressure will not significantly affect moderator operation.

Air Flows

Air flow is difficult to measure accurately, particularly in large-diameter piping systems. It is therefore best to shut off all non-critical air flows into and out of the reactor building. These include the ventilation system inlet and outlet, emergency air, breathing air, and drier purges. The instrument air flow cannot be shut off, as it is required to operate. A short description of this system will be helpful.

Air is drawn from the turbine building, compressed, dried, and distributed through an instrument air header. One arm of this header penetrates the containment boundary to supply all of the instrument air requirements for the reactor building. This pipe discharges into three holding tanks from which air is drawn as required.

The instrument air flow can be measured easily with the installation of a vortex meter in the feed line. The pressure in this line is known to vary, but it must be maintained constant for a leak test. This can be achieved with the installation of a pressure regulator with the vortex meter.

A small instrument air system inside the reactor building would also solve the problem of measuring this air flow. A compressor and a drier would be required. No measurement of the air flow would be needed since no air would be added to the building.

D_2O Recovery System

If all of the air flow out of the building is stopped, the relative humidity inside the building will rise due to leaks, water vapour in the air inlet, and various other sources. Some of this water may be D_2O. There are now eight fans which draw air from inside the building through driers and discharge the dry air back into the building. The continuous purge in this system draws air from the discharge of the other driers through a ninth drier, DR 5A / B, and exhausts to the atmosphere. This is the D_2O recovery system.

This is a closed loop system with the exception of the purge. Since no air is added, it will not affect the calculations if it is left running while a test is being done. This will help to keep the tritium levels low inside the reactor building. One possible concern is that in a vacuum test the fans may be starved. Account can be made of the change in moisture content between the air inlet and discharge by close monitoring of the relative humidity inside the building.

If a tracer gas is used, then its absorption properties in the drier bed must be considered. If it is absorbed, then the driers would have to be stopped for the duration of the test, or tracer concentration measured at the inlet and discharge of the driers. A further concern would be the effect of absorbed tracer gas on the operation of the driers.

Air Lock

Access to the reactor building may be required through one of two air locks. Entry is made through one door, and then that door is closed and the pressure equalized. Exit is through a second door. This process allows escape / ingress of air. The volume of the air lock is known and the pressure on each side of it is measured, which allows a calculation of the volume or weight of air change.

Fuelling Machine

If the test is to take more than a few days, the reactor may need to be refueled. During the refuelling procedure, there is a time when the refuelling machine is connected to the spent fuel discharge bay. At this time, there is a connection between the two buildings through a 0.635-cm orifice. Air will flow between the two buildings at a rate determined by the difference in pressure of the two rooms, and it will flow all the time that the machine is connected. This amounts to about 10 minutes for each refuelling.

Since the pressure in both the reactor building and the spent fuel discharge bay are measured, and the exact total time that the machine was connecting the two buildings can be recorded, then the amount of air added / lost can be calculated.

When the fuelling machine removes a fuel bundle from the reactor, about one litre of D_2O is spilled on the floor. This is one source of water ingress to the reactor building. Some of the water will be removed as liquid (a negligible volume relative to the volume of the reactor building) and some of it will vaporize. The vaporized D_2O is monitored by relative humidity measurements.

Other Considerations

Pressure gradients inside the building exist. These should be minimized, particularly for those rooms which have the containment boundary as one of their walls. Local pressure gradients will cause an error in leakage rate calculation. All doors that can be left open should be opened, to reduce these gradients and allow for mixing.

Temperature, too, will vary with location inside the building. It is important, then, to measure temperature in as many areas as feasible. The thermocouples that are used for the full pressure leak test are sufficient for this measurement. Proper mixing is also required, so all of the fans inside the building should be on.

Changing the pressure inside the building may affect some of the equipment. The pressure and vacuum ratings for that equipment would have to be checked.

Proposed Test Procedure

The proposed test procedure is based on a mass balance done at a relatively constant pressure. The building is brought to a specified pressure, either positive or negative, and kept at that pressure by removing the same amount of air through the drier purge system as is added by the instrument air system. As an example, consider a test done at a positive pressure of 10 kPa. Tests at negative pressures and with a tracer gas are similar (see Figure 1).

Before the test begins, drier DR 5B should be shut off and the automatic swing mechanism on DR 5A/B stopped. This will allow air to purge only through DR 5A. Allow the packing inside the drier to become saturated such that the dew point of the air entering and leaving the drier is the same. This is to ensure that no water is either added or removed by this drier.

As many of the interior doors as possible should be opened and all of the fans turned on. This will allow for proper mixing and minimize local gradients.

The ventilation outlet and inlet valves should be closed. The ventilation system must be shut off as it is not feasible to measure flows in this system with any degree of accuracy. The breathing and emergency air systems should also be shut off at this time.

Driers DR 1–4, DR 7–8, and DR 9–10 all have purges from the D_2O recovery system. These must be shut off so that the only purge from these driers is through DR 5A.

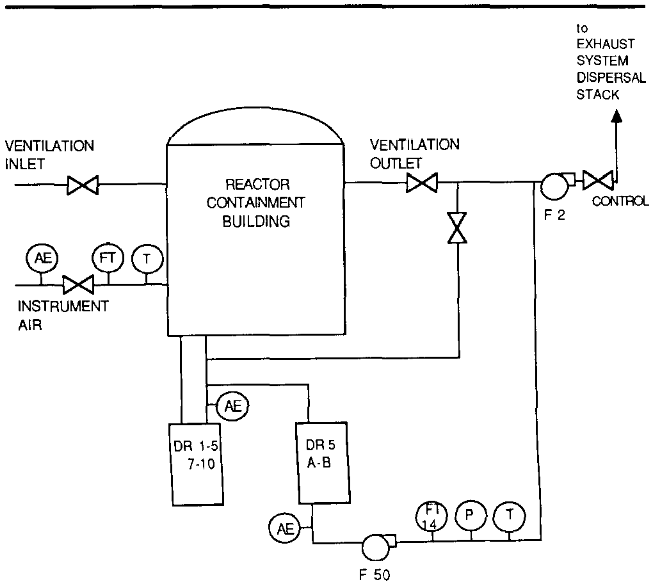

Figure 1 Leak test set up.

The purge through drier DR 5A should be shut off. This now stops all flows out of the building. Pressure will rise as the instrument air is still flowing into the building. A rise of about 1 kPa every three hours is expected [Ventzek, 1985] if the instrument air flow is the only air into the building and is operating normally. It is possible to increase this rate by loading up the air compressor or adding a portable air compressor. Once the pressure has increased about 2 kPa, the reactor trip point will have to be raised by the same amount. The increase in pressure must be accompanied by increases in the trip point.

Once the building pressure is 10 kPa, and the reactor trip point is set at 13.45 kPa, the discharge valve on fan F2 is opened. This valve is used to control the pressure inside the reactor building at the 10 kPa pressure. The only air flow into the building now is the instrument air, and the only out flow is through the drier purge. Fan F2 is used to draw the vacuum for a vacuum test.

The test is now ready, and data acquisition begins. Entry into the building should be minimized, and all entries logged. Fuelling should be delayed as long as possible, and also logged.

A similar procedure using a tracer gas has previously been proposed [Boyd, 1986]. In this case the building is pressurized. The gas is then injected and a transient mass balance is done on the tracer gas to determine the leak rate.

Data Acquisition

Leak rate is calculated from a mass balance around the containment building. The basic mass balance equation is:

$$Lr \times \Delta t = (m_{in} - m_{out})\,\Delta t + \Delta M + M_{fm} + M_{al} = y, \qquad (1)$$

where Lr is the leakage rate in kg/unit time, and m is the mass flow of air in or out of the building in the same units. M is the mass in kg of air added to the containment building by either the connection of the fuelling machine to the spent fuel discharge bay (subscript fm), or due to entries through the air lock (subscript al), both since the time t. ΔM is the change of the mass of the air inside the building and is equal to the mass of the air at time t minus the mass of the air at the start of the test ($M-M_0$).

Measurements to be taken are: temperature, pressure, and relative humidity inside the reactor building; temperature, pressure, and flow rate of the instrument air inlet and the drier purge outlet; and the dew point on either side of DR 5B. If the test uses a tracer gas, instrument air flow will not be measured but concentration of the gas must be recorded. Fuelling and air lock openings must be recorded so that corrections for air ingress/outflow may be made.

Temperature, pressure, and relative humidity inside the reactor building should be measured as in the commissioning test, and averaged to give a T, Pt, an RH for each time interval. This will allow the calculation of the mass of air inside the containment building at each time interval, using the ideal gas law.

The partial pressure of the water vapour inside the building is found from:

$$P_w = P_{wv} \times RH/100, \tag{2}$$

where P_w is the partial pressure of water in the air, P_{wv} is the vapour pressure of water at the average temperature in the containment building, and RH is the average relative humidity inside the containment building.

The partial pressure P of the air in the building is:

$$P = Pt - P_w. \tag{3}$$

The mass of air inside the containment building is then calculated from:

$$M = \frac{P \times V \times MW}{R \times T}, \tag{4}$$

where M is the mass of air in the containment building in kilograms, P is the partial pressure of the air in the building in kPa, R is the universal gas constant, T is the average temperature in the building in degrees Kelvin, and MW is the molecular weight of the air.

Pressure, temperature, flow rate, and relative humidity of the instrument air inlet and the purge outflow measurements allow for the calculation of the mass inflow and the mass outflow. These data are taken frequently and integrated over the chosen time interval to give a total change in mass/time interval. The mass flow of air into the building is calculated as:

$$m_{in} = Q_{in} \times \frac{P_{in} \times 298.15}{101.325 \times T_{in}} \times 1.185, \tag{5}$$

where Q_{in} is the air flow rate in cubic metres per unit time and P_{in} and T_{in} are the absolute air pressure and temperature of the instrument air. 1.185 is the standard density of air in kilograms per cubic metre.

The air flow out is calculated as:

$$m_{out} = Q_{out} \times \frac{298.15 \times P_{out}}{101.325 \times T_{out}} \times 1.185, \tag{6}$$

where P_{out} is the pressure of the air out through the drier purge. If the fuelling machine or airlock have been operated in the given time interval, the air lost or added due to this procedure can be calculated. For the air lock, the calculations are as follows:

$$M_{al} = \frac{V_{al} \times P \times MW}{R \times T}. \tag{7}$$

V_{al} is the volume of the air lock, MW is the molecular weight of the air, and P is the partial pressure of the air. The air partial pressure calculation depends on

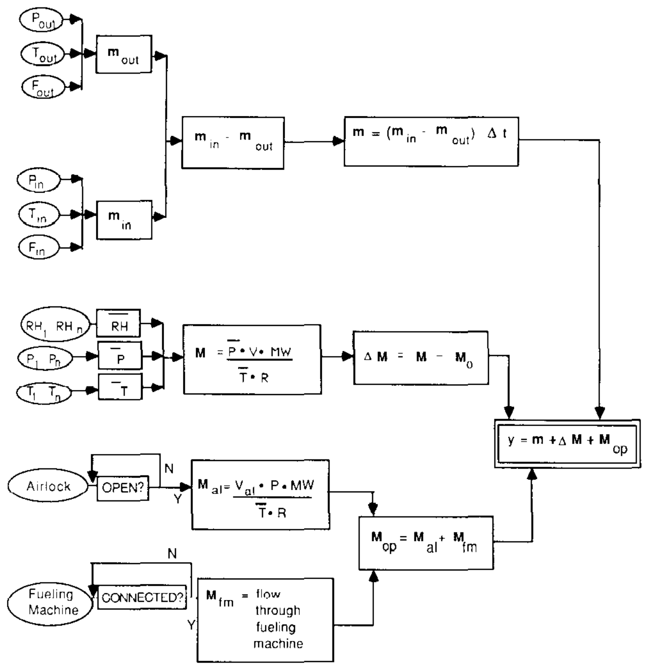

Figure 2 Flow chart of leak rate calculations.

whether the building is being entered or exited. If the containment is being entered then the air has a partial pressure associated with the ambient conditions outside, as outside air is being added. If the internal door is opened first, then air is leaving the building and the partial pressure is that of the air inside the containment. Calculations for the fuelling machine are basic fluid dynamics, based on flow through an orifice.

The air added to the building, the air removed from the building, and the weight inside are calculated. By mass balance then, a leakage rate can be calculated. One leakage rate is calculated for each time interval, and the 'true' leakage rate is known from a linear regression done over the period of the test (see Figure 2).

Error Analysis and Results

A mass balance performed on the reactor building uses the measurement of flows and contained mass to determine a leak rate. Because this leak rate may be very small (0.5% of the contained air per day, at 124 kPag), its detection is limited primarily by the accuracy of the measurements. Therefore, the first step in determining the suitability of a particular test is to examine the error obtained under various test and operating conditions.

In this section, two tests are considered: the tracer gas and the absolute mass method. A theoretical error analysis is performed in an attempt to predict the effect of test pressure and duration on the sensitivity of the techniques.

Sources of Error

As mentioned earlier in this report, there are two main

Table 2: Test Instrumentation

Instrument name and brand	*Error*
Mensor quartz manometer	±0.010% R ±0.002% FS
Digital humidity analyzer	±0.3 °C
RTD thermometer	±0.025 °C
Gas chromatograph	±0.1 %
Vortex meter	±1.0% R
Flow meter (exhaust)	±3.0% R

types of errors which affect measurements of containment leak rates: operational and instrument errors. Operational factors that are important to consider are those which lead to mass transfer in or out of the building in a way which is not accounted for by flow measurement. Important factors include the air locks, the fuelling machine and the instrument air storage tanks. A secondary but significant factor is the fluctuation of atmospheric conditions. This question will be considered later.

In the test procedure proposed, an operational transfer term can be calculated, then applied to the mass balance equation. The quantity calculated enters the mass balance as a correction term which must be added, unless there is no entry of the reactor building and no refuelling is done. Because it is a correction factor, errors on the operational terms are of second order and they are difficult to evaluate.

The other source of error, the accuracy of the instruments, can be estimated from the known calibrated error of the component. In our theoretical analysis, only this source will be considered. During the actual test, errors can be continuously monitored by calculating the standard deviation of the accumulated data. Similarly, the test reproducibility cannot be accurately estimated except by repeating the actual test.

The instruments used and their associated specified accuracy are reported in Table 2.

Mathematical Expressions

For both methods of leak rate measurement, the expression relating the physical measurement to the leak rate stems from the basic mass balance equation:

$$m_{in} - m_{out} + \frac{dM_{acc}}{dt} = Lr, \quad (8)$$

which, integrated over time, becomes

$$y = (m_{in} - m_{out})t + M_{acc} = Lr \times t, \quad (9)$$

where M_{acc} is an accumulation term which accounts for the operational factors. M_{acc} is the sum of the operational terms M_{fm} and M_{al}, and the term ΔM in equation 1.

A regression analysis can be performed using equation 9, with y plotted against time. This method appears to be the most accurate way to analyze the data [Koegh, 1985]. Lr, the leak rate, becomes the slope of the y versus t plot, which can be calculated by the least square method:

$$Lr = \frac{n\,\Sigma(y \times t) - \Sigma y \times \Sigma t}{n\,\Sigma(t^2) - (\Sigma t)^2}, \quad (10)$$

where n is the number of data taken. The error on the slope is then given by:

$$\sigma = (\alpha)\, S_{yt} \left[\frac{1}{\Sigma(t - t_{ave})^2}\right]^{1/2}, \quad (11)$$

where S_{yt} is the standard error of estimate [Lipson, 1973], and α is a constant depending on the confidence interval desired; $\alpha = 1$ or ≈ 2 for 68% and 95% confidence intervals, respectively.

In fact, σ is data-dependent, and it can be rigorously calculated only from the actual experiment. However, using the known accuracy of the instrumentation, it is possible to estimate the overall experimental α. AECL, 1977 treats this question in more detail. For our purpose, the instrumentation specifications will be used to predict the actual experimental error.

In this case, the standard error of estimate can be evaluated by the expression:

$$S_{yt}^2 = \sigma_y^2 = \sigma_{in}^2\,(t)^2 + \sigma_{out}^2\,(t)^2 + \sigma_{Macc}^2 \quad (12)$$

where σ is the standard deviation of the measurement. M_{acc} contains a change in the contained mass term, where the mass is calculated using the ideal gas law:

$$M_{acc} = a \times P / T + M_{op}, \quad (13)$$

where a is a constant. Therefore,

$$\sigma_{Macc}^2 = 2 \times a^2 \times [(\sigma_P / P)^2 + (\sigma_T / T)^2]. \quad (14)$$

Equation 12 contains a time dependent term, which can be averaged over the time of the test, to give:

$$(\sigma_{in}^2 + \sigma_{out}^2) \times \Sigma t_i^2 / n, \quad (15)$$

where t_i is the time at which sample i is taken.

The theoretical standard error of estimate can finally be written as

$$S_{yt}^2 = (\sigma_{in}^2 + \sigma_{out}^2)\Sigma t_i^2 / n + 2M_{acc}^2[(\sigma_P / P^2) + (\sigma_T / T^2)]. \quad (16)$$

The expression is similar for the tracer gas method, as long as the concentration is maintained approximately constant. In that case, flows are those of tracer gas and the pressure and temperature terms of equation 17 are replaced by σ_c^2, where c is the concentration of tracer gas in the reactor building.

Assumptions

Since the results of the test at reduced pressure cannot be known in advance, it is necessary to accept some assumptions in order to predict the error.

As discussed previously, the error on the operational correction terms is unpredictable. Therefore, for the theoretical analysis, instruments are considered to be the only source of error.

Furthermore, in order to calculate the error, one must know the leak rate at any given pressure. For that purpose, and in light of the many correlations mentioned in a previous section, it is assumed that leak rates vary linearly with pressure.

Similarly, leak rates at negative and positive pressures are assumed to be identical. This is not entirely true; however, it is considered to be satisfactory for the purpose of error prediction.

Range of Test Parameters

Three main parameters are considered to affect the theoretical error prediction: the test pressure, duration, and the actual leak rate being measured. Our study includes test pressures of up to ±20 kPag, and durations of up to five days. Target leak rates of 0.5% to 24% per contained volume per day are used; they range from single-unit to multi-unit containment design leak rates.

The instrument air-flow rate used in this study is 150 m^3 per hour, and is matched by the exhaust flow rate. This represents an average of the values reported in Boyd, 1986.

Results

Results of the theoretical error analysis are reported in Figures 3 to 8. In Figures 3 to 7, the error is shown as a function of test duration for various test pressures. It should be noted that, for the absolute mass method, pressures indicated can be taken as negative as well as positive. In Figure 8, the sensitivity of the absolute mass method is shown as a function of pressure, for various durations. The minimum detectable leak rate is taken to be the one for which a 50% error at 95% confidence is obtained. All errors shown were calculated assuming that one data point was taken every 15 minutes.

As it can be seen in Figures 3 to 7, the error of a given test decreases with time and pressure. For a given pressure, the minimum error is reached at very long test durations. This error constitutes a limit for a test carried out at that pressure. This is mostly true for low pressures (≤3 kPag) and small leak rates. In all cases, the major contributor of inaccuracy is the flow measurements. They account for up to 95% of the total error, and they are most important for small leaks. For this reason, continuous on-line monitoring at normal operating conditions is impractical. Because of the very small pressure differential across the containment

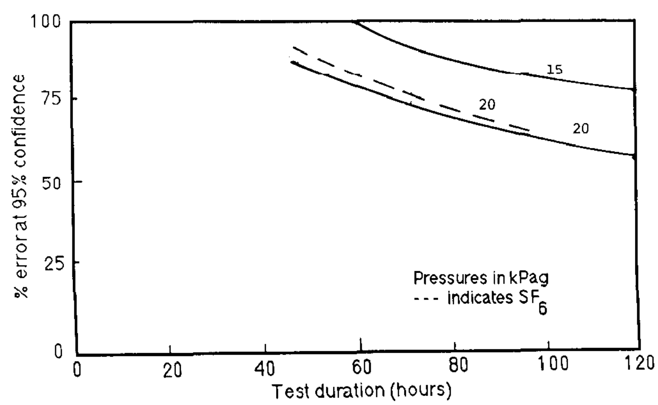

Figure 3 Test error for a target leak rate of 0.5% per day.

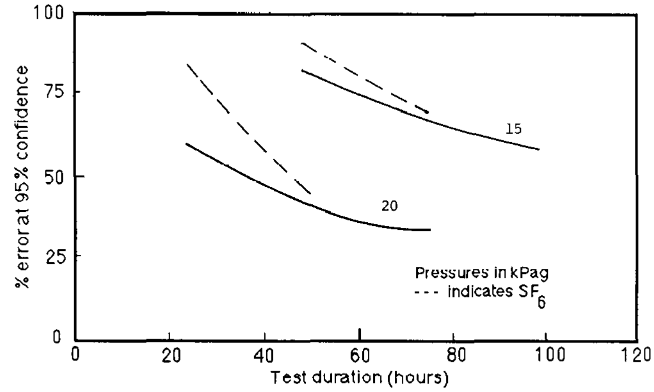

Figure 4 Test error for a target leak rate of 1% per day.

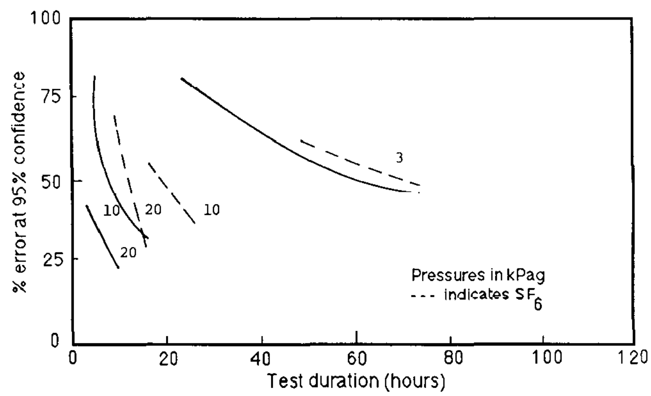

Figure 5 Test error for a target leak rate of 5% per day.

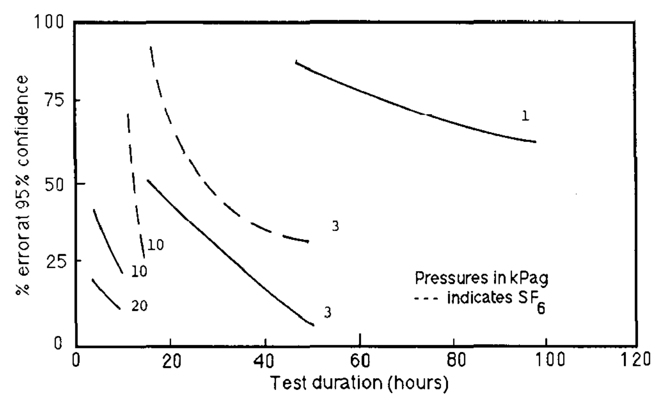

Figure 6 Test error for a target leak rate of 10% per day.

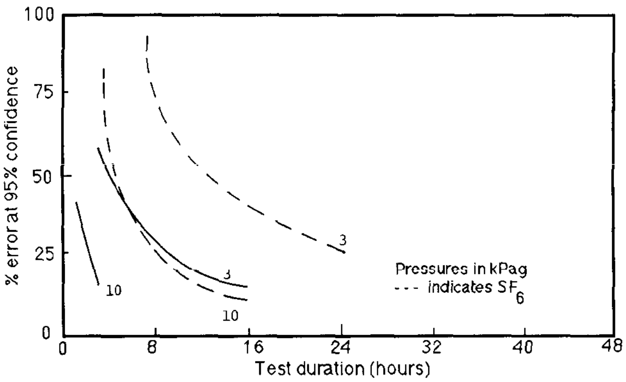

Figure 7 Test error for a target leak rate of 24% per day.

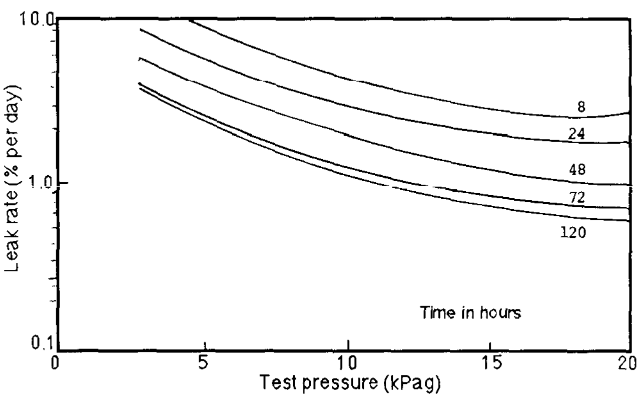

Figure 8 Minimum detectable leak rate at 50% error.

boundary, the actual leakage is too small to be detected at the desired accuracy.

The tracer gas method was originally proposed to eliminate the need for measurement of the instrument air flow rate, and the error associated with this measurement. Since there would be no tracer gas in this air, the flow rate would not be needed for a tracer gas mass balance. However, errors with the tracer gas method are generally worse than those with the absolute mass method.

Figure 8 yields additional information on the sensitivity of the test. Only the absolute mass method results are shown, since the tracer gas method would yield similar data. From this representation, it appears possible to classify the test parameters into three categories according to their ability to detect leak rates within a certain range. This result is summarized in Table 3. A leak rate of 0.5% per contained volume per day can be detected, but only after a long test of over 5 days. However, slightly higher leak rates can be detected within three days by carrying out a test at high pressure (±15–20 kPag). A rough evaluation of the containment integrity may be obtained in less than a day, but leak rates of less than approximately 5% per day would not be adequately detected.

Table 3: Classification of Test Parameters

Sensitivity (at 50%)	*Test duration*
high (~0.5% per day)	>5 days
medium (~1.0% per day)	2–3 days
low (~5.0% per day)	<1 day

Discussion

Reliability of the Error Analysis

Operational Factors

The error analysis carried out in the last section is meant to give an indication of the real experimental error which would be obtained should the test be done. However, certain assumptions had to be made in order to predict the error. Some operational factors which were not considered may affect the predictions. Moreover, the errors were calculated from theoretical instrument accuracies and may not be absolutely representative of the actual experimental standard deviation.

The main operational factors which were not considered in the calculations, but which directly affect the mass balance equation, are the air locks, the fuelling machine and the instrument air (through accumulation in the storage tanks, inside the building).

If the equipment airlock is opened at least once every shift (eight hours), the air transferred via that route corresponds to approximately 0.23% of the contained air per day if the building is pressurized to 10 kPag.

The mass transfer due to the operation of the fuelling machine and its temporary connection to the spent fuel discharge bay is more difficult to evaluate; with a 10 kPa pressure differential between the reactor building and the discharge bay, the flow through a 0.635-cm orifice would be equivalent to 0.02% of the contained air for every hour during which the fuelling machine is connected.

Obviously, a test which is done with no refuelling and with no access to the reactor building would eliminate the above two operational errors. This would be the best circumstance. However if this is not feasible for a given utility, the corrections must be calculated and incorporated in the mass balance.

The instrument air pressure variation also introduces an error which can, however, be controlled by installing a pressure regulator on the instrument air line, or by modifying the instrument air system so that air is drawn directly from within the building. The pressure fluctuations in the storage tanks are otherwise 875 to 910 kPa. Given the total volume of these tanks to be 25.5 m^3, the possible error corresponds to approximately 0.02% of the contained air in the containment building. Assuming that the equivalent design leak rate at 10 kPag is linearly related to the 0.5% of the contained air per day, at full pressure, the possible air mass accumulation provided by the storage tanks is at least ten times greater than the mass of air leaked. This would seriously affect the leakage calculation if it were neglected.

There are other factors which may affect the error analysis. They have been mentioned in the section on operational considerations. The D_2O recovery system may leak; however, assuming the leaks to be consistent from test to test, this factor may be considered as a systematic error. Perfect mixing of the air was assumed in the calculations, as temperature, humidity, and pressure data were assumed to be unique. The multiplication of instrumentation measurements to obtain one single datum (the contained mass) will also certainly affect the error, and so will the local averaging.

The hysteresis effect is another important aspect; absorption by the concrete may lead to false readings. Results obtained after raising the pressure higher than the pressure test prior to the test will be different than if the test had commenced as soon as the test pressure was reached [Toossi, 1981]. However, because of air ingestion into the concrete and subsequent release as the pressure is reduced, American National Standard recommends that the pressure be held at 85% (or lower) of the test pressure, in order to insure conservative estimates [Koegh, 1985]. Because of the lack of data in the latter case, there is no consensus about which procedure should be followed. The alternative would be to maintain the pressure prior to the test in order to saturate the concrete and open as many pathways as possible.

Finally, variations in weather conditions and daily cycles were not considered in the calculations, but may significantly affect the measurements. Typical daily pressure fluctuations of 1 to 2 kPa [Dick, 1984] would lead to an additional error in the determination of the leak rate of 5 to 33% for test pressures of 20 and 3 kPag, assuming that pressure inside the building is unaffected by atmospheric pressure. However, it can be shown that inside pressure follows to some extent outside variations [Dick, 1984], thereby reducing these errors. Therefore, for reasons of consistency, it may be important to repeat the test over similar conditions. It is possible to eliminate the error due to daily fluctuations by performing a test over several days. However, in that case, weather stability and seasonal changes become important, though less significant because of the increased total leakage.

Pressure Correlations

Since the test is to be performed at reduced pressure, the leak rate measured will not be directly related to the leak rate at full pressure. This can affect the predicted error in three ways:

1. The theoretical error depends on the leak rate, and the estimated leak rate used in the error analysis assumed a linear pressure relationship; should this relationship be different, the actual measured leak rate at low pressure for a given leak rate at full pressure will not be that used.
2. For a given measured leak rate at low pressure, the extrapolation to a higher pressure will introduce an error.
3. Leak rates at negative and positive pressures are not identical, but they were assumed to be the same in the analysis.

Since it appears that pressure correlations are system-dependent, the error due to pressure extrapolation may be reduced by establishing a 'custom-made' correlation for the particular reactor building under investigation.

Comparison with the Previous Test

In order to compare errors predicted to the actual experimental errors, the parameters from the commissioning test [Harvey, 1982] were used in the error model. The calculated relative error was found to be 2.6%. The relative error given in Harvey is 0.8%.

This discrepancy does not discredit the theoretical analysis, but introduces the consideration of reproducibility. In practice, the standard deviation of the data collected may be more related to the reproducibility of the instrument, rather than to its accuracy, which is a deviation from a calibrated measurement. As long as the instrument calibration remains stable, and if the reproducibility does not vary with the scale, this comparison with the actual data from the commissioning test indicates that the error analysis results are conservative. However, one must be careful in interpreting this result, since operational factors did not interfere with the commissioning test.

Test Selection

Although the results thus far are not completely sufficient to allow a final choice of the most suitable method, enough information is available to provide some clue as to which methods may or may not be favorable.

The Tracer Gas Method

Injection of a tracer gas such as SF6 in the reactor building, and monitoring of its concentration in various relevant locations, appears to be a very attractive solution to test containment integrity. Calculated errors are found to be acceptable, if slightly higher than those obtained using the other method. The fact that the contained mass of SF6 can be obtained from one single measurement, the concentration, certainly favors this method.

However, there are some serious unknowns which may have an important impact on the validity of this technique. It is not known what the effect of small quantities of SF6 would have on the equipment and the structures. It is also difficult to predict the possible

Table 4: Test Options

Test	*Parameters*	*Sensitivity*	*Comments*
Tracer gas			Single measurement Simple procedure Unknown behavior
Absolute mass	≥5 days 20 kPag	0.5% / day	Low instrument error Chance of large operational error High theoretical sensitivity
	2–3 days 20 kPag	1% / day	Low instrument error Low operational error Moderate sensitivity
	≤1 day 10–20 kPag	≥5% / day	Minimum operational error Low sensitivity
1/2 Design pressure test	5 hours 62 kPag	0.5% / day	Performed at shutdown Instrument air off
Modified instrument air intake	12 hours 20 kPag	0.5% / day	Instrument air intake within reactor building

absorption of the tracer gas by concrete, or its behaviour in the D_2O recovery system. Furthermore, the tracer gas method restricts the possible test pressures to positive differentials.

The Absolute Mass Method

As was observed in the results from the error analysis, the absolute mass method can be used with a wide range of test parameters. As determined, three options are available for this test (see Table 4). Each option imposes different constraints on the operating system, and each focuses on a particular range of detectable leak rates. However, the technical feasibility of the test is also affected by two factors: time and pressure.

The major error source (flow measurements) cannot be eliminated for an on-line test, unless the instrument air intake is temporarily or permanently installed within the building. If this is done, it is conceivable that the overall errors reported in the error analysis could be reduced by up to 95%. This would make a leak rate of 0.5% of the contained air per day detectable in 12 hours at 20 kPag (with a 50% error at 95% confidence). Otherwise, optimization of the test parameters is restricted to the other factors.

A test which could be completed in less than eight hours would eliminate the need to apply any correction to the mass balance equation, since the air locks and the fuelling machine can easily be kept inoperative over such a short period. This leads to a minimum operational error, but because of the instrument accuracy, this test would be limited to detecting leak rates in excess of 5% of the contained volume per day.

A longer test (over five days) would theoretically allow the detection of the target leak rate of 0.5% per day. However, the reactor may have to be refuelled, and operation of the fuelling machine introduces the most important operational error. A solution might be to cease refuelling operations over an extended length of time. In that case, cost penalties due to perturbed fuel management may have to be considered.

Another important consideration with long tests is the buildup of tritium in the reactor building. Although it is difficult to estimate this quantity, it is hoped that the continued operation of the D_2O recovery system will help maintain it at an acceptable concentration.

Since short tests appear to have a low sensitivity, and since long ones (over a period in which refuelling is required) introduce large errors due to the refuelling operation, the compromise is a test of moderate duration, during which there is no refuelling (at no burn-up penalty). With such a test, it should be possible to detect a leak rate as low as 1% of the contained volume per day. Although this is twice the current design target, it could be considered as a reasonable compromise for an on-line test.

The other factor which may affect the feasibility of a given test is test pressure. Ideally, higher pressures should be used, because they yield higher leak rates and potentially lower errors. However, there are two major problems with raising the pressure differential: the equipment and the trip set points. Similarly, higher pressures take longer to reach, and require further adjustment of the reactor trip set points. Above +14 kPag, the dousing system set point would have to be adjusted. This increases the time necessary for the preparation of the test, and it introduces safety concerns.

There is a third option, along with the tracer gas and absolute mass methods, which may have some attractive features: an annual test, at shutdown, done at half pressure. Such a test would yield an acceptable estimate of a leak rate of the order of the design target in a matter of 5 hours (with a 50% error at 95% confidence), and would eliminate most of the problems associated with operational errors. Because the reactor would then be shut down, the test pressure could be reached without any concern for the trip set points. The whole test, including preparation, could be done in less than half a day, provided that the instrumentation was prepared before shut-down. This avenue has not been seriously considered, for a cost comparison would be required to assess its merits. However, it remains a possible solution.

A summary of the test options is given in Table 4.

Reliability of the Test Results

One of the main questions when performing an on-line test at reduced pressure will be: how far can the results be trusted? In fact, this is a very serious concern, since a wrong decision could financially penalize the utility.

The answer depends on many factors. The first one is the error expected, or predicted, for a 95% confidence interval. This should determine the interval of acceptability of the measured leak rate. However, this is not sufficient. Adequate control of the operating and the test conditions, along with good instrument calibration and reproducibility from test to test, is absolutely crucial to the reliability of the result. The accuracy of the pressure and temperature correlation is also important in order to account for slightly different conditions at the time of the test. Finally, the ability of the data acquisition system to detect transients such as those resulting from a change in the system is instrumental in the adequate and reliable determination of leak rates.

Reliability concerns introduce the concept of a criterion for test failures. Obviously, a test should fail if the measured value is above the 95% confidence interval. However, in such a case, it may be wise to repeat the test and to verify that no sporadic event occurred which led to an unaccounted mass transfer.

Conclusions

Based on the requirements for an on-line measurement technique, a test procedure is proposed. It is based on a mass balance over the reactor building. Integrated air flows and mass changes are measured, while data acquisition keeps track of the air locks and fuelling machine operation, in order to apply a calculated correction term to the mass balance equation.

An error analysis is used to determine the suitability of the test procedures and parameters. It was shown that it is possible to reduce the instrument error by performing a long test, but that short ones eliminate the need to apply operational corrections. Moreover, the overall test accuracy is increased by increasing test pressure differentials.

Finally, it was shown that the target leak rate of 0.5% per day could be measured at 50% error with 95% confidence in 12 hours at 20 kPag if the instrument air intake can be installed inside the reactor building.

While the most attractive test conditions seem to be moderate pressures (10–20 kPag) and a moderately long test (3 days) with no refuelling, the test parameters for a utility are best determined by site management and the appropriate regulatory agency. They will depend on the exact objective of the test, which may vary between accurate determination of the leak rate to monitoring of status changes and detection of gross leaks.

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