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(51) Int.Cl.⁶ G01M 3/02; G01M 3/26

(19)(CA) **CANADIAN PATENT** (12)

(54) Continuous Containment Monitoring with Containment
Pressure Fluctuation

(72) Dick, Jerry Edward , Canada

(73) Her Majesty in right of Canada as represented by the
ATOMIC ENERGY CANADA LIMITED/L`ENERGIE ATOMIQUE DU
CANADA LIMITÉE , Canada

(57) 4 Claims

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ABSTRACT

A method of determining the rate of air leakage from or
into a containment is described. The internal pressure of the
containment is maintained at a positive or negative value with
reference to ambient air pressure and the air mass changes are
continuously monitored through measurements of pressure,
temperature, relative humidity and free volume. Air leakage is
measured through a mass balance equation and a regression analysis
carried out to yield constants which characterize the various
features of the leakage flow and give an indication of the
accuracy of the results.

This invention relates to the monitoring of the integrity of containments particularly but not exclusively for nuclear plants.

In Canada, nuclear reactor containments may be single unit designs in which individual reactors are housed by their own independent containment, or multi-unit designs in which the containment provisions or portions thereof are shared by a number of reactors on the same site. While this application is primarily concerned with containment monitoring in the context of the single

10   unit design, it is expected that the concepts presented will be universally applicable to any containment design, including containments for non-nuclear applications such as biological laboratories.

Most containments are equipped with ventilation systems and other auxiliary systems which penetrate the containment boundary. In the event of an accident, isolation valves on all of the major lines will automatically close to isolate the containment atmosphere from the outside environment. The isolation valves are built to rigid standards and tested

20   frequently to ensure that closure speeds and leakage characteristics will preclude radionuclide releases in excess of allowable levels. Hence, known breaches are dealt with as a part of normal containment design.

However, impairments or inadvertent breaches of the containment envelope, such as seal failures or valves left in improper states, can occur during the life of the plant. These breaches are easily identified in integrated leakage rate tests, but as such tests involve reactor shutdown, containment isolation,

and subsequent pressurization or depressurization to non-atmospheric levels, they are normally performed on an infrequent (years) basis. Hence, inadvertent breaches can remain undetected for significant periods of time.

The nuclear industry has long been interested in a means of monitoring containment integrity on a continuous basis, that is, while the reactor is operating normally. However, absolute success has been thwarted, in part, by the need to reliably distinguish inadvertent breaches from the legitimate breaches

10   represented by system penetrations (such as the ventilation system). Consideration has been given to schemes such as natural resonance of the containment atmosphere, tracer decay approaches, and close monitoring of the containment pressure response signature to selected periodic pressure forcing functions.

From these investigations, the most promising approach appears to be to employ sensors and systems which automatically measure changes in the mass of air in containment, time-integrate any known air mass flow rates across containment boundaries and perform a mass balance to obtain the air mass leaked. However, as

20   fluctuations in such measurements are typically too large to enable leakage to be calculated to the desired precision, filtering and statistical techniques must be employed to filter out random and time-dependent fluctuations. Current approaches cannot easily deal with non-random or systematic fluctuations in the measurements, such as pressure changes within the containment. As a result, sampling periods must be kept short or data measured during periods of varying containment conditions must be discarded.

Continuous monitoring of the mass in containment involves first determining the free volume of the containment and then continuously measuring the pressure, temperature and humidity throughout the containment, as well as the outside atmosphere. The presence of additional gas, if any, would require measurement also. The above parameters are sufficient to determine the air mass leakage across the containment boundary by a simple mass balance.

Trans-boundary flows present no problem in principle as long as they can be measured with sufficient precision to be included in the mass balance without obscuring the true leakage rate. The problem is that the leakage for nuclear containments is so small relative to the contained air mass and the integrated trans-boundary flows that instrument noise and drift as well as random and systematic fluctuations in the measured variables tend to mask the estimated leakage. To separate the random variations from the data, it is thus common practice to employ statistical techniques.

There are a number of methods for dealing with continuous mass measurements but only the so-called "mass point" method will be herein considered. Firstly, the governing mass balance equation (see LaFortune (1)) may be written as

$$y = (\dot{m}_{in} - \dot{m}_{out})t + M_{acc} = (LR)t$$

where,

$\dot{m}_{in}$ = known air mass flow rate into containment (kg/hr)

$\dot{m}_{out}$ = known air mass flow rate out of containment (kg/hr)

M_{acc} = air mass change in containment (kg)

LR = air leakage rate (kg/hr)

t   = time (hr)

The "mass point" method consists of a linear regression of the contained mass over time and use of the slope of the regression line as the leak rate and the intercept as the initial contained mass. Reference 2 (Keogh) recommends this approach as the only method to be used. However, the weakness in this technique is an implicit assumption that the leakage rate is independent of pressure.

Reference 3 (Zakaib) also discusses this method and indicates that, in practice, some of the basic assumptions for linear regression are often violated, for example the assumption of normally distributed and independent random errors. Systematic errors due to actual physical variations in containment conditions (common during on-power testing) are thus incompatible with this approach and must be limited in magnitude.

It is an object of this invention to provide a technique for measuring the magnitude of containment leakage which is not invalidated by systematic variations in the measured variables, for example pressure and/or temperature.

It is a more specific object to establish the nature of the leakage (laminar, turbulent or a combination) and identify the presence of systematic errors in parameters other than pressure.

Broadly, the invention provides a method of determining the leakage characteristics of the boundaries of an essentially hermetic volume comprising; maintaining the internal pressure of the volume at a value different from the ambient air pressure; continuously monitoring air mass changes within the volume preferably through measurements of pressure, temperature, relative

humidity, and free volume; and reducing the error due to random variations in the measured variables for whatever cause by statistical regression on two or more variables or dimensions.

According to a more specific aspect of the invention the acquisition steps similar to those effected by Lafortune are carried out but the mass balance equation used by LaFortune, namely

$$y = (\dot{m}_{in} - \dot{m}_{out})t + \dot{M}_{acc} = (LR)t \qquad (1)$$

10   is re-written

$$y = (\dot{m}_{in} - \dot{m}_{out} + \dot{M}_{acc})t = k(\Delta P)^{a_1}t^{a_2} \qquad (2)$$

where

ΔP = pressure differential across the containment envelope

k = leakage rate constant

a_1 and a_2 are constants.

Thereafter, a regression analysis, preferably a linear multiple logarithmic regression analysis, is performed on equation (2) to yield constants k, a_1 and a_2 which

20   characterize the various features of the leakage flow. A standard error of estimate for the regression plane can also be computed.

Brief Description of the Drawings

For a fuller understanding of the invention, reference should be had to the following detailed description of the preferred embodiment of the invention, taken in conjunction with the accompanying drawings, in which:

Figure 1 shows schematically how the leakage

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monitoring is performed; and

Figure 2 illustrates a regression plane for a particular containment.

The proposed leakage monitoring is based on an air mass balance performed continuously while the container building is kept within its operating pressure range (normally negative but possible positive) by removing the air through suitably engineered exhaust flow.

Values for $\dot{m}_{in}$, $\dot{m}_{out}$ and $\dot{M}_{acc}$ have to be established for the containment and substituted into equation (2) after which a regression analysis on the independent variables ΔP and t is carried out.

The values for $\dot{m}_{in}$, $\dot{m}_{out}$ and $\dot{M}_{acc}$ are established by continuously measuring parameters such as pressure, temperature, relative humidity and transboundary flows using a network of monitors and converting these parameters using known equations to values for $\dot{m}_{in}$, $\dot{m}_{out}$ and $\dot{M}_{acc}$. American National Standard ANSI/ANS-56.8-1987 establishes how these various parameters should be measured and reference 12, although not directed to <u>continuous</u> testing, provides further detailed information on how the data may be gathered.

It should be pointed out that temperature and relative humidity must be measured at a large enough number of locations to obtain an extremely accurate representation of the air mass.

Typically, measurements are made every 30 seconds and fed to a computer which stores the data and performs the statistical analyses required. After about 12 hours of data a

leakage rate estimate can be obtained.

As indicated above the actual manner of obtaining the data and deriving values for $\dot{m}_{in}$, $\dot{m}_{out}$ and $\dot{M}_{acc}$ has been suggested in the art and does not per se constitute the present invention: By way of example, however, the value $\dot{M}_{acc}$ can be derived from measurements of pressure, temperature and relative humidity at a number of points in time. Firstly, using the ideal gas law, the mass M of air in the containment is measured using

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$$M = \frac{(P - P_v)V}{RT_{air}} , \text{ kg}$$

where

P   = absolute containment pressure, kPa

P_v = water vapour partial pressure, kPa

V   = net free volume of containment M^3

R   = gas constant for air = 0.2871 kPa M^3/kg(air)k

T_{air} = average temperature, k.

The mass flow rates $\dot{m}_{in}$ and $\dot{m}_{out}$ across containment

20   boundaries can be monitored by direct flow measurement with a suitable correction for measured vapour content.

The value of $\dot{M}_{acc}$ may be obtained in several ways. The simplest way would be to subtract the computed value of M at one point in time from the computed value at the previous time and dividing the difference by the time interval separating the two measurements. A more accurate way would be to perform a non-linear regression on a series of computed values for M to obtain an equation which would represent the variation of M with time. This equation would be

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differentiated and $\dot{M}_{acc}$ would be the value of the derivative at the time corresponding to the time of measurement for $\dot{m}_{in}$ and $\dot{m}_{out}$. The resulting set of values for $\dot{m}_{in}$, $\dot{m}_{out}$ and $\dot{M}_{acc}$ are to be used in the planar regression which will now be described.

The first step in the regression analysis is to linearize equation 2 according to the procedure of Reference 4, Table 13.1, reproduced below.

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TABLE 13.1

Linearized forms of some nonlinear equations				
		Linearized variables		
Nonlinear equation	Linearized equation	Y	X	Z
1. $y = 1 - e^{a_0 x}$	$\ln \dfrac{1}{1-y} = a_0 x$	$\ln \dfrac{1}{1-y}$	x	
2. $y = a_0 + a_1 \sqrt{x}$ (Square root)	$y = a_0 + a_1 X$	y	$\sqrt{x}$	
3. $y = 1 - \exp\left[-\left(\dfrac{x - x_0}{\theta - x_0}\right)^b\right]$ (Weibull)	$\ln\ln \dfrac{1}{1-y}$ $= -b\ln(\theta - x_0)$ $+ b\ln(x - x_0)$	$\ln\ln \dfrac{1}{1-y}$	$\ln(x - x_0)$	

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Linearized forms of some nonlinear equations				
Nonlinear equation	Linearized equation	Linearized variables		
		Y	X	Z
4. $y = ax^b$ (Logarithmic)	$\ln y = \ln a + b \ln x$	$\ln y$	$\ln x$	
5. $y = a + \dfrac{b}{x}$ (Inverse)	$y = a + bx$	y	$\dfrac{1}{x}$	
6. $y = e^{(a+bx)}$	$\ln y = a + bx$	$\ln y$	x	
7. $e^y = a_0 x^{a_1}$	$y = \ln a_0 + a_1 \ln x$	y	$\ln x$	
8. $y = a_0(x)^{a_1}(z)^{a_2}$	$\ln y = \ln a_0 + a_1 \ln x + a_2 \ln z$	$\ln y$	$\ln x$	$\ln z$

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Linearized forms of some nonlinear equations				
Nonlinear equation	Linearized equation	Linearized variables		
		Y	X	Z
9. $y = a_0 + a_1 x + a_2 \sqrt{z}$	$y = a_0 + a_1 x + a_2 Z$	y	x	$\sqrt{z}$
10. $y = a_0 e^{(a_1 z + a_2 z)}$	$\ln y = \ln a_0 + a_1 x + a_2 z$	$\ln y$	x	z

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This gives:

$$\ln y = \ln k + a_1 \ln (\Delta P) + a_2 \ln t$$

Linear regression of the y vs P, t data produces a least squares plane. The equations are,

$$a_0 = \ln K$$

$$a_1 = \frac{(\Sigma XY)(\Sigma Z^2) - (\Sigma XZ)(\Sigma YZ)}{\Sigma X^2 \Sigma Z^2 - (\Sigma XZ)^2}$$

$$a_2 = \frac{(\Sigma X^2)(\Sigma YZ) - (\Sigma YX)(\Sigma XZ)}{\Sigma X^2 \Sigma Z^2 - (\Sigma XZ)^2}$$

$$a_0 = \bar{y} - a_1 \bar{x} - a_2 \bar{z}$$

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} \ln y_i$$

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{n} \ln \Delta P_i$$

$$\bar{z} = \frac{1}{n} \sum_{i=1}^{n} \ln t_i$$

$$Y = \ln y_i - y$$

$$X = \ln \Delta P_i - x$$

$$Z = \ln t_i - z$$

The standard error of estimate from Reference 4 is,

$$S_{y.xz} = \left[\sum_{i=1}^{n} \ln y_i - a_0 \sum_{i=1}^{n} \ln y_i - a_1 \sum_{i=1}^{n} (\ln x_i + \ln y_i) - \right.$$

$$\left. a_2 \sum_{i=1}^{n} (\ln z_i + \ln y_i) \right]/n - 3$$

This is the variance of the data relative to the regression plane. (An equation for the distribution of the residuals with respect to the regression plane (needed for confidence estimates) is not given in Reference 4, but can always be calculated from the data.)

The resulting values for a_0, a_1 and a_2 characterize the various features of the leakage flow.

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The leakage rate constant,

$$k = e^{a_0}$$

is directly proportional to the effective area of the leakage path. A sudden breach producing, say, a doubling of the leakage rate will double the measured k value.

The leakage rate law constant, a_1, will show whether the leakage flow is laminar ($a_1 = 1$), turbulent ($a_1 = 0.5$) or a combination of both ($0.5 < a_1 < 1$). Also, it is expected that the absorption/release of air by walls accompanying

10   pressure changes is a laminar-like process. Thus the value of a_1 should exhibit temporary reductions for both positive and negative pressure jumps.

The time linearity constant, a_2, will usually be unity unless there is a systematic error in one of the measurements. For example, a drift in the measurement of $\dot{m}_{in}$ or $\dot{m}_{out}$ would introduce a false time dependence. The resulting non-linearity would be reflected in the value of a_2. Hence, a_2, provides a means of judging whether the test is good, and thus the reliability of a_0.

20   The technique described is a process which can be used to monitor containment integrity on a continuous basis and involves no restrictions on variations in containment pressure. It thus allows for much longer sampling periods under conditions of fluctuating containment pressure and eliminates the invalidation of data when the containment pressure fluctuation is non-random. As a result, it should yield a much more precise value for the containment leakage characteristic. The technique also promises to be able to

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distinguish the presence of systematic errors unrelated to

systematic pressure changes and to establish whether the

containment leakage characteristic is laminar or turbulent.

While the mechanics of the calculation can be

performed in several ways a linear multiple logarithmic

regression approach is recommended.

Although the invention has been described in

relation to pressure variations, the statistical regression

technique can also be applied in relation to temperature.

10   More specifically the mass balance equation would contain T

instead of P and the regression analysis would be done on the

independent variables T and t.

ILLUSTRATIVE EXAMPLE

Figure 2 illustrates the regression plane for a

containment having the regression equation,

$$y = [1.47 \text{ kg}/(\text{hr-kPa}^{0.5}] \Delta P^{0.5} t^{1.0} \qquad [3]$$

where the units are as follows,

y   in kilograms (kg)

ΔP in kilopascals (kPa)

20   t   in hours (hrs)

The Figure depicts how measured data would yield a

regression plane which, when extrapolated to the vertical

intercept (the imaginary point where ΔP and t are both unity),

identifies the leakage rate constant. It also shows the

slopes of the plane in the ΔP and t directions, which are the

exponents of ΔP and t in Equation 3.

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THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE
PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1.   A method of determining the leakage characteristics
of the boundaries of an essentially hermetic volume
comprising; maintaining the internal pressure of the volume at
a value different from the ambient air pressure; continuously
monitoring air mass changes within the volume preferably
through measurements of pressure, temperature, relative
humidity, and free volume; and reducing the error due to
random variations in the measured variables for whatever cause
by statistical regression on two or more variables or
dimensions.

2.   A method, as claimed in claim 1, wherein the
boundaries of the volume are also traversed by well defined
pathways permitting continuous measurement of the ingress and
egress of air mass so that a mass balance of the net air mass
flow across the boundary with the air mass changes within the
volume yields the leakage characteristics sought.

3.   A method of determining the rate of air leakage from
or into a containment comprising carrying out measurements to
determine $\dot{m}_{in}$, the air mass flow rate into the containment,
$\dot{m}_{out}$, the air mass flow rate out of the containment and $\dot{M}_{acc}$,
the rate of air mass change in the containment, applying the
determined values of $\dot{m}_{in}$, $\dot{m}_{out}$ and $\dot{M}_{acc}$ to the equation

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$$y = (\dot{m}_{in} - \dot{m}_{out} + \dot{M}_{acc})t = k(\Delta P)^{a_1}t^{a_2}$$

where

k = leakage rate constant

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ΔP = pressure differential across the containment
envelope

t = time

a_1 and a_2 are constants

and performing a regression analysis on the independent variables
ΔP and t to obtain values for k, a_1 and a_2, determining that the
leakage flow is laminar when $a_1 = 1$ or turbulent when $a_1 = 0.5$ or
a combination when $0.5 < a_1 < 1$ and determining that there is a
systematic error in one of the measurements if a_2 is other than

10   unity.

4.   A method according to claim 3 wherein the regression
analysis carried out is a linear multiple logarithmic regression
analysis.

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Measurements for
Continuous Air Mass
Monitoring

Unknown
Leakage

Pressure
Temperature
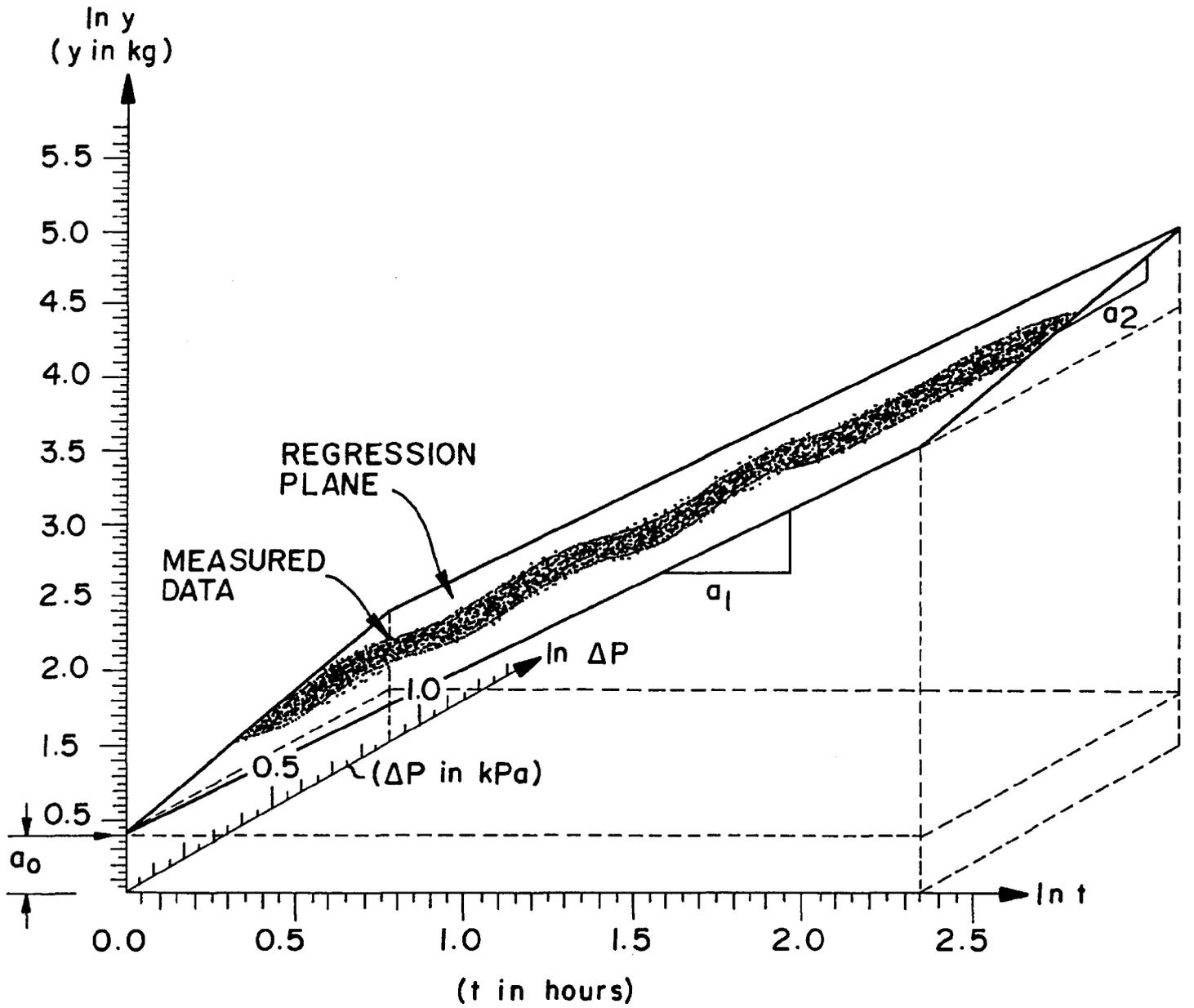Relative Humidity

Pressure
Temperature
Relative Humidity

Volumetric
Flow Rate In

Volumetric
Flow Rate Out
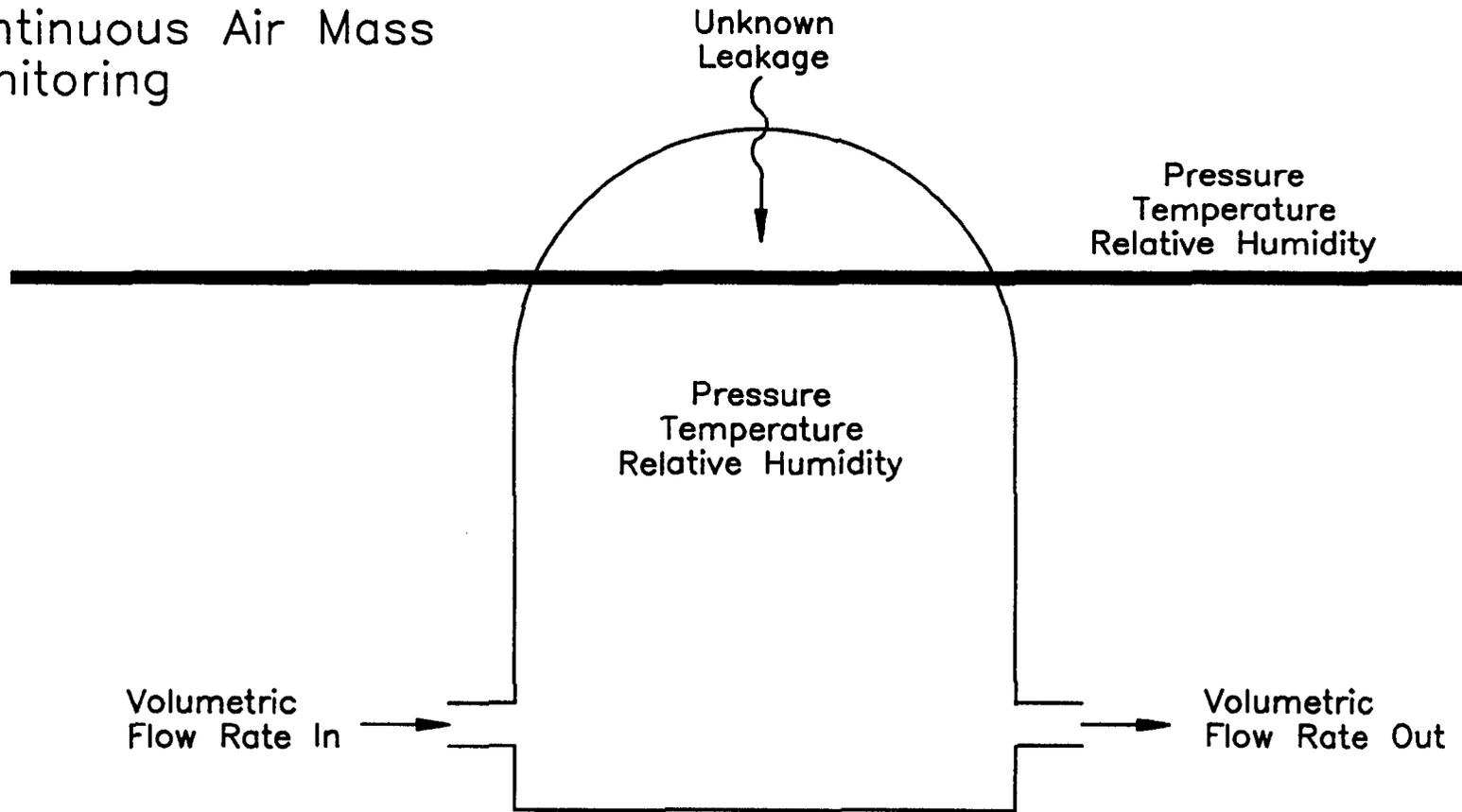
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Patent Agents
Smart & Biggar

FIG. I

FIG. 2