(51) International Patent Classification 6:
G01M 3/28

(11) International Publication Number: WO 95/16901

(43) International Publication Date: 22 June 1995 (22.06.95)

(21) International Application Number: PCT/US94/14465

(22) International Filing Date: 16 December 1994 (16.12.94)

(30) Priority Data:
08/170,092 17 December 1993 (17.12.93) US

(71) Applicant: VISTA RESEARCH, INC. (US/US); 100 View Street, Mountain View, CA 94042 (US).


(74) Agent: JAFFER, David, H.; Rosenblum, Parish & Isaacs, 15th floor, 160 W. Santa Clara Street, San Jose, CA 95113 (US).

(54) Title: SIMPLIFIED APPARATUS FOR DETECTION OF LEAKS IN PRESSURIZED PIPELINES

(57) Abstract

An apparatus for detection of leaks in pressurized pipelines which utilizes a large pressure vessel (610) and a smaller measurement vessel (612). The measurement vessel (612) magnifies level changes during leak detection tests. The apparatus is connected to a pipeline through the measurement vessel (612). The entire system can be filled with liquid from the pipeline by opening a valve (V2) between the measurement (612) and pressure (610) vessels. Leak detection tests are conducted by measuring changes in volume with the measurement vessel (612) over time while the pressure over the liquid in the pressure vessel (610) and measurement vessel (612) is maintained approximately constant. During tests, liquid communication between the measurement vessel (612) and pressure vessel (610) is prevented by closing the valve (V2) between them, but vapor communication between the vessels is permitted.
FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AT</td>
<td>Austria</td>
<td>BB</td>
<td>Barbados</td>
<td>BE</td>
<td>Belgium</td>
</tr>
<tr>
<td>AU</td>
<td>Australia</td>
<td>BU</td>
<td>Burkina Faso</td>
<td>BF</td>
<td>Bulgaria</td>
</tr>
<tr>
<td>BJ</td>
<td>Benin</td>
<td>BR</td>
<td>Brazil</td>
<td>BY</td>
<td>Belarus</td>
</tr>
<tr>
<td>CA</td>
<td>Canada</td>
<td>CG</td>
<td>Congo</td>
<td>CH</td>
<td>Switzerland</td>
</tr>
<tr>
<td>CI</td>
<td>Côte d’Ivoire</td>
<td>CM</td>
<td>Cameroon</td>
<td>CN</td>
<td>China</td>
</tr>
<tr>
<td>CS</td>
<td>Czechoslovakia</td>
<td>CZ</td>
<td>Czech Republic</td>
<td>DE</td>
<td>Germany</td>
</tr>
<tr>
<td>DK</td>
<td>Denmark</td>
<td>ES</td>
<td>Spain</td>
<td>FI</td>
<td>Finland</td>
</tr>
<tr>
<td>FR</td>
<td>France</td>
<td>GA</td>
<td>Gabon</td>
<td>GB</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>GE</td>
<td>Georgia</td>
<td>GN</td>
<td>Guinea</td>
<td>GR</td>
<td>Greece</td>
</tr>
<tr>
<td>HU</td>
<td>Hungary</td>
<td>IE</td>
<td>Ireland</td>
<td>IT</td>
<td>Italy</td>
</tr>
<tr>
<td>JP</td>
<td>Japan</td>
<td>KE</td>
<td>Kenya</td>
<td>KG</td>
<td>Kyrgyzstan</td>
</tr>
<tr>
<td>KP</td>
<td>Democratic People’s Republic of Korea</td>
<td>KR</td>
<td>Republic of Korea</td>
<td>KZ</td>
<td>Kazakhstan</td>
</tr>
<tr>
<td>LI</td>
<td>Liechtenstein</td>
<td>LK</td>
<td>Sri Lanka</td>
<td>LU</td>
<td>Luxembourg</td>
</tr>
<tr>
<td>LV</td>
<td>Latvia</td>
<td>MC</td>
<td>Monaco</td>
<td>MD</td>
<td>Republic of Moldova</td>
</tr>
<tr>
<td>MG</td>
<td>Madagascar</td>
<td>ML</td>
<td>Mali</td>
<td>MN</td>
<td>Mongolia</td>
</tr>
<tr>
<td>MR</td>
<td>Mauritania</td>
<td>MW</td>
<td>Malawi</td>
<td>NE</td>
<td>Niger</td>
</tr>
<tr>
<td>NL</td>
<td>Netherlands</td>
<td>NO</td>
<td>Norway</td>
<td>NZ</td>
<td>New Zealand</td>
</tr>
<tr>
<td>PL</td>
<td>Poland</td>
<td>PT</td>
<td>Portugal</td>
<td>RO</td>
<td>Romania</td>
</tr>
<tr>
<td>RU</td>
<td>Russian Federation</td>
<td>SD</td>
<td>Sudan</td>
<td>SE</td>
<td>Sweden</td>
</tr>
<tr>
<td>SI</td>
<td>Slovenia</td>
<td>SK</td>
<td>Slovakia</td>
<td>SN</td>
<td>Senegal</td>
</tr>
<tr>
<td>TD</td>
<td>Chad</td>
<td>TG</td>
<td>Togo</td>
<td>TJ</td>
<td>Tajikistan</td>
</tr>
<tr>
<td>TT</td>
<td>Trinidad and Tobago</td>
<td>UA</td>
<td>Ukraine</td>
<td>US</td>
<td>United States of America</td>
</tr>
<tr>
<td>UZ</td>
<td>Uzbekistan</td>
<td>VN</td>
<td>Viet Nam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Specification

Simplified apparatus for detection of leaks in pressurized pipelines

Background of the invention

Field of the invention
The present invention relates generally to a method and an apparatus for the reliable detection and quantification of the flow rate produced by a leak from pressurized pipeline systems containing petroleum, solvent, or other chemical liquids.

Brief discussion of the prior art
There are a wide variety of pressurized pipeline systems carrying petroleum, solvents, and other chemical products that may contaminate or seriously damage the surrounding environment in the event of a leak. In underground or underwater pipelines, where visual inspection is not possible, a leak can be a significant problem. Small leaks in these pipeline systems (e.g., several tenths of a gallon per hour) can go undetected for long periods of time and result in a large cumulative release of product into the soil or groundwater, or into fresh or ocean water.

The need for leak detection capability in pressurized pipelines associated with underground storage tanks containing petroleum products has recently been identified. This need is an important one because the number of tanks involved is very large, and so is the volume of product dispensed through the pipelines associated with these tanks. The pipeline systems in question are most commonly made of steel or fiberglass; they are typically 2 inches in diameter, 50 to 200 feet long, buried 1.5 to 3 feet below grade, and are pressurized at 20 to 40 psi while product is being dispensed. In September 1989, the United States Environmental Protection Agency (EPA) issued technical standards for the detection of leaks in underground storage tanks.
containing petroleum or other hazardous chemicals and solvents. This regulation established the minimum performance standards that must be met by any leak detection system designed for testing the integrity of underground tanks and/or the pressurized pipelines associated with these tanks.

The EPA requires that underground storage tank (UST) pipeline systems that contain petroleum products be tested for leaks either on a monthly or an annual basis. To satisfy the criterion for monthly testing, a system must have the capability to detect leaks as small as 0.20 gal/h with a probability of detection \( P_D \) of 0.95 and a probability of false alarm \( P_{FA} \) of 0.05. To satisfy the criterion for annual testing, a system must be capable of detecting leaks as small as 0.10 gal/h with the same \( P_D \) and \( P_{FA} \) required of the monthly test.

There have been a number of approaches to leak detection in pipeline systems. Some leak detection systems are designed to operate while product is being moved through the line; others require that the flow of product be stopped for the duration of a test. Leak detection systems generally use one of three methods: they measure the drop in pressure in the pipeline over a period of time, they measure the difference in pressure or flow rate at two or more points along the pipeline, or they measure the change in the volume of the product over a period of time. Detecting small leaks is difficult because there are many physical phenomena present in pressurized pipeline systems that produce pressure, volume, and flow-rate fluctuations that are as large as or larger than those produced by a leak. These normally occurring fluctuations degrade the performance of the leak detection system and result in false alarms or missed detections. As a consequence, a number of compensation schemes have been proposed to reduce them.

**Pipeline Leak Detectors That Measure Pressure:**

The most common approach to the detection of leaks in a pressurized underground pipeline containing an
incompressible fluid at rest is to relate the pressure
drop in the line to the flow rate of the leak. A leak in
the line is declared if the pressure drops by a specified
amount over a given period. If this specified amount, or
threshold, is not exceeded, the line is declared tight.
Pressure tests are very difficult to interpret because
the pressure drops are coupled with the properties of the
pipeline itself. Thus, a similar pressure drop in two
different pipeline systems should not necessarily be
interpreted in the same way. Experimental measurements
with controlled leaks indicate that (1) the pressure
decreases exponentially with time as product is released
from a line, (2) the volume released from a line
decreases linearly with pressure when no vapor is trapped
in the line, and (3) the leak rate decreases
exponentially with pressure. The relationships between
pressure and (1) volume, (2) leak rate, and (3) time are
controlled by the elasticity of the pipeline system. The
properties of the line are usually measured in terms of
the bulk modulus, which is the inverse of the elasticity
constant. As the elasticity of the line increases, the
time required for the pressure to decay from the
operating pressure of the line to zero (or to any other
pressure below the operating pressure) increases. In one
line it might take 15 minutes for the pressure to drop 10
psi when there is a leak of 0.1 gal/h (defined at the
operating pressure of the line), while in another line it
might take 60 minutes. If the length of the test is
defined as 15 minutes, the test protocol will prevent the
sensor from detecting a 0.1-gal/h leak in some of the
lines that are tested.

Some of the pressure changes that occur in
pressurized pipelines are not associated with a leak.
The most important are those associated with the thermal
expansion or contraction of the liquid, the trapped
vapor, and the pipe material itself. Experimental
measurements in underground pipeline systems containing
petroleum indicate that the pressure changes are directly
proportional to the temperature changes and the bulk
1 modulus of the pipeline system. These temperature-
2 induced pressure changes occur frequently in both leaking
3 and nonleaking pipelines. When the pressure changes in a
4 leaking pipeline are no greater than these normally
5 occurring temperature-induced changes, it is difficult to
6 detect a leak by monitoring the line for drops in
7 pressure.
8 Accurate detection of a leak demands (1) that both
9 the instrumentation and protocol have sufficient
10 sensitivity to detect the smallest leaks of interest, (2)
11 that the temperature changes in the line be measured and
12 compensated for, and (3) that the pressure changes be
13 related to the flow rate of the leak. All three require
14 that the range of the elasticity properties of the
15 pipelines that will be tested be known. The second
16 requires that the temperature of the product be measured.
17 The third requires that the pressure-volume relationship
18 be measured each time for each line being tested.
19
20 **Bulk Modulus:**
21 The bulk modulus of a pipeline is defined by the
22 relationship between pressure and volume within that
23 line. The bulk modulus of both the line and the product
24 must be known before one can convert the pressure and
25 temperature changes to volume changes or before one can
26 interpret the meaning of a pressure drop. One can
27 estimate the bulk modulus by simultaneously measuring the
28 pressure of the line and the volume of product released
29 through a valve in the line. Errors in determining this
30 relationship occur if the line is leaking, if the
31 temperature of the product in the line is changing, or if
32 vapor or air is trapped in the line. Accurate
33 calibration is difficult because the integrity of the
34 line is unknown, as are the temperature of the product in
35 the line and the volume of trapped vapor. Furthermore,
36 the bulk modulus of the pipeline system changes over time
37 as the volume of trapped vapor and air changes, and as
38 the elasticity of the flexible hosing, the mechanical
39 leak detector, and the pipe material changes.
1 Thermally Induced Pressure Changes:
2 Thermally induced fluctuations in pressure are the major source of error in detecting a liquid leak with a pressure detection system. The magnitude of the error depends on the magnitude of the coefficient of thermal expansion and the bulk modulus of the liquid and the line material. For gasoline motor fuels, whose coefficient of thermal expansion is 6 to 7 times larger than that of water, even small temperature changes have been shown to produce large pressure changes. (E.g., a 0.1°C fluctuation in temperature can cause the pressure to change by 10 psi.) Furthermore, both theoretical and experimental analysis demonstrate that the rate of change of temperature in an underground pipeline system can be high and complicated.

From the standpoint of petroleum-dispensing operations, it is difficult to distinguish temperature-induced pressure changes from those that are leak-induced, because the rate of change of pressure varies exponentially both with the volume of product released through a hole in the line and with the change in the temperature of the product. The temperature of the product varies exponentially when product from the tank is brought into the line, because the temperature of this product differs from the temperature of the backfill and soil around the pipeline. This temperature difference, which can be many degrees, results in an exponential change as the product in the line attempts to come into equilibrium with its surroundings. In lines that are 100 to 200 feet long and 2 inches in diameter, it may be 6 to 12 hours before the rate of change of temperature is low enough to permit accurate testing.

The traditional methods of compensating for temperature effects, which require the measurement of the rate of change of temperature of the liquid and the pipeline, are impractical because (1) the temperature distribution of the product in the line is spatially inhomogeneous, and a large number of temperature sensors would have to be retrofitted along the line in order to
measure it; and (2) installing, maintaining, and
calibrating a large number of sensors would be difficult.
The best method of compensating for the effects of
temperature fluctuations is to wait until these fluctua-
tions are small enough to be negligible. For accurate
pressure tests, this waiting period should be between 6
and 12 hours.

Summary:

Detecting small leaks in a pressurized pipeline by
monitoring the pressure changes in the line is very
difficult. High performance requires (1) that the test
be long enough to allow the pressure to drop by a
specified amount, suitable for detecting the smallest
leaks of interest over the full range of pipeline systems
to be tested, and (2) that the waiting period between the
last dispensing of product and the beginning of the test
be long enough for the temperature changes in the line to
become negligibly small. To obtain accurate results in
the case of the 2-inch-diameter lines found at a typical
retail service station, dispensing operations might have
to be terminated up to 12 hours before beginning the
test. Thus, the total time required to conduct a test
becomes quite long.

Pipeline Leak Detectors That Attempt to Compensate for
Thermal Changes:

In U.S. Patent 4,608,857, Mertens describes a
method for detecting leaks as small as 1 L/h in a
pressurized pipeline without waiting for fluctuations in
the temperature of the product to subside. (As we have
seen, such fluctuations induce pressure changes that can
be mistaken for a leak.) Mertens establishes three
measurement periods of equal length. Initial line
pressure is the same during the first and third periods
but is lower during the middle period. Pressure changes
are measured during all three periods. The middle
measurement is then subtracted from the average of the
first and third. The difference is compared to a
threshold, and in this way the existence of a leak is
determined. Mertens indicates that the volume of product
in the line must be small for the method to work
properly. Furthermore, according to Mertens, the method
accurately compensates for temperature providing that
"the sum of the consecutive measurement periods is very
small compared to the half value period of a temperature
equalization process."

Analysis of this method shows that, when a leak is
present in the line, the average pressure change that
occurs during either the first or third periods will
always be greater than that during the middle period.
Furthermore, depending on the bulk modulus of the
pipeline system, the actual volume change that occurs
during these measurement periods will vary from one
leaking line to another, even when these lines have the
same initial starting pressures and identical leaks.
Mertens's method does not require that the bulk modulus
be measured and does not attempt to interpret the test
results in terms of the actual leak rate. Mertens's
method declares a leak in the pipeline if the difference
between the high- and low-pressure measurements exceeds a
predetermined threshold value. However, a wide range of
volume changes could produce this same pressure change,
and therefore, the accuracy of his method will vary from
line to line.

**Pipeline Leak Detectors That Attempt to Detect Leaks
While There Is Flow in the Line**

The method described by Mullen in U.S. Patent
3,702,074 detects leaks in pressurized pipelines while
product is flowing through the line. Mullen measures
flow rate at two different points along the line (either
the inlet and the outlet or any other two points
sufficiently distant from one another) and at two
different pressures, one high and one low. The
difference in flow rate between the two measurements made
at the lower pressure is subtracted from the difference
between the same measurements made at the higher
pressure. The result is then compared to a threshold
leak rate, which, if exceeded, is the basis for declaring
a leak in the pipeline. Mullen contends that because his
measurements are closely spaced in time, he prevents
long-term dynamic trends, such as those produced by the
thermal expansion and contraction of the product, from
affecting the results. However, while the temperature
changes, the rate of change remains the same. For
example, if measurements are made one minute apart the
temperature change is much less than if they are made one
hour apart; however, the rate of change is the same over
any interval, whether it is a minute or an hour.
Mullen's approach does not work because it confuses the
rate of change with the actual change, which has no
bearing on the results. Mullen's method will effectively
compensate for temperature changes only if they happen to
be the same during the high- and low-pressure
measurements. This is unlikely to be the case, however,
because, as stated above, the change in temperature in a
pipeline is generally not constant (i.e., it tends to be
exponential with time). Furthermore, the fact that
Mullen does not account for inventory changes also
affects the accuracy of his method. Mullen minimizes
short-term transient effects, such as those due to
pressure, by taking several readings at each pressure and
averaging them. By isolating different sections of line
and by repeating the test at each segment of the line, he
can locate the leak. He eliminates false alarms due to
faulty equipment by comparing the test results for each
segment of pipe tested; if the equipment is faulty, the
flow-rate threshold will be exceeded in all of the
segments tested.

SUMMARY OF THE INVENTION

It is an object of this invention to provide a
method, and a device, for the reliable detection of small
leaks in pressurized pipelines containing liquids,
including water, petroleum, solvents, and other chemical
products.
Another object of this invention is to provide a method of and a device for quantitatively estimating the volume change and the flow rate of a leak in a pipeline at any pressure in the line.

Yet another object of this invention is to provide a method of and a device for compensating for the thermal expansion and contraction of the product in the pipeline and of the pipeline itself.

A further object of this invention is to provide a method of and a device for quantitatively estimating the thermally induced volume change and flow rate of the product in a pipeline at any pressure in the line.

The invention is designed to detect small leaks in pipelines that contain any type of incompressible liquid and that are either pressurized or can be placed under pressure for the duration of a test. The invention is particularly useful in underground or underwater pipeline systems, but can also be used on pipeline systems located above ground, such as those found in buildings or placed in specialized containment systems. The major application of this invention is for the detection and quantification of the flow rate produced by a leak in UST pipeline systems containing petroleum and other chemical products.

The invention requires that a leak detection test of the line be performed when the fluid in the line is at rest. Because the device will compensate for thermally induced changes in the pressure or volume of the product during a test, it is particularly useful for liquids that have a high coefficient of thermal expansion compared to water.

All references to the pressure of the pipeline system or pressure vessel made in this specification refer to gauge pressure. When the gauge pressure of the pipeline system is zero, the absolute pressure of the pipeline system is equal to atmospheric pressure. The claims made in this patent are based on absolute pressure. Thus, when the pressure is atmospheric, the gauge pressure of the pipeline system is zero.
Briefly, the preferred embodiment of the present invention is a simplified apparatus for detection of leaks in pressurized pipelines which utilizes a large pressure vessel and a small measurement vessel. The measurement vessel magnifies level changes during leak detection tests. The apparatus is connected to a pipeline through the measurement vessel. The entire system can be filled with liquid from the pipeline by opening a valve between the measurement and pressure vessels. Leak detection tests are conducted by measuring changes in volume with the measurement vessel over time while the pressure over the liquid in the pressure vessel and measurement vessel is maintained approximately constant. During tests, liquid communication between the measurement vessel and pressure vessel is prevented by closing the valve between them, but vapor communication between the vessels is permitted.

**BRIEF DESCRIPTION OF THE DRAWINGS**

Fig. 1 illustrates the preferred embodiment of the present invention, in which an acoustic sensor system located inside a pressure vessel measures product-level changes and in which the vapor space above the product is used to maintain constant pressure during a leak detection test;

Figs. 2(a) and 2(b) show side and top views of the preferred embodiment of the acoustic sensor system;

Figs. 3(a) and 3(b) show side and top views of an alternative embodiment of the acoustic sensor system;

Figs. 4(a) and 4(b) show four possible shapes for the cross-section of the bar-shaped fiducial, the preferred triangular shape and three alternatives (rectangular, half-circular and circular);

Figs. 5(a) and 5(b) show side and top views of a second alternative embodiment of the acoustic sensor system;

Fig. 6 shows an alternative embodiment of the pipeline leak detection system in which the acoustic sensor system housed inside the pressure vessel shown in
Fig. 1 has been replaced by an electromagnetic sensor system attached to a float that rests on the product surface;

Figs. 7(a) and 7(b) show side and top views of an alternative placement of the electromagnetic sensor, in this case outside and along the neck of the pressure vessel;

Fig. 8 shows a second alternative embodiment of the pipeline leak detection system in which a pressure regulator and a container of inert gas are used to keep the pressure constant in the vessel that contains the acoustic sensor system;

Fig. 9 shows a third alternative embodiment of the pipeline leak detect system in which the acoustic sensor system shown in Fig. 8 has been replaced by an electromagnetic sensor system;

Fig. 10 shows a fourth alternative embodiment of the pipeline leak detection system in which the pressure vessel and pressure regulator in Figs. 8 and 9 have been replaced by a pressure sensor and a positive displacement pump that is used to pump liquid into or out of the pipeline as a means of keeping the pressure constant;

Fig. 11 shows a fifth alternative embodiment of the pipeline leak detection system in which the positive displacement pump in Fig. 10 has been replaced by a piston that is used to displace a volume of liquid in the pipeline as a means of keeping the pressure constant;

Fig. 12 shows a simplified version of the preferred embodiment of the present invention;

Fig. 13 shows an alternative embodiment of the simplified apparatus shown in Fig. 12;

Fig. 14 illustrates a typical leak detection test sequence, with four 5-minute level measurement segments separated by 2-minute intervals;

Fig. 15 illustrates the simplified apparatus implemented with an electronic sensor for measuring level changes; and
Fig. 16 illustrates the simplified apparatus implemented with capability for both manual and electronic level measurements.

DESCRIPTION OF THE PREFERRED EMBODIMENT

In order to measure the volume change that is due to a leak (i.e., the flow rate), it is necessary to compensate for the temperature-induced volume changes. The present invention compensates for the thermal expansion or contraction of the product in the line without having to measure the temperature of that product. The time it takes to test a line is less than an hour. Unlike most of the methods currently in operation, this new technology is not based on measuring pressure changes in the pipeline system. Instead, it calls for a measurement of the change in the volume of product in the pipeline system. At least two consecutive measurements are made, one at the operating pressure of the line, and the other at zero pressure; for accurate temperature compensation, the pressure must be constant or nearly constant during the measurement. The invention compensates for temperature changes by differencing the volume changes noted during each of these measurements. A high degree of temperature compensation is achieved if the thermally induced volume changes are nearly the same during measurements at each pressure. Since this may or may not be the case, and since there is no way to verify it, a third measurement is made at the same pressure as the first measurement; it is then averaged with the first measurement before the volume changes obtained at zero pressure are subtracted.

The methodology used to measure the temperature-compensated volume rate due to a leak takes advantage of the fact that the flow rate (volume change) due to a leak is not linear with pressure, but the flow rate (volume change) due to temperature fluctuation is. The preferred approach is to make one volume measurement when the line pressure is near zero and a second measurement at a higher pressure, preferably in the vicinity of the
operating pressure of the line. At zero pressure, the
flow rate due to a leak is zero; thus, the only volume
change that occurs is due to thermal expansion and
contraction of the product, vapor, or pipeline. The
difference between the zero-pressure and the nonzero-
pressure measurements represents the thermally
compensated flow rate due to a leak at the nonzero pres-
sure.

In general, to determine whether a pipeline system
is leaking, the mass flow rate should be estimated from
the change in mass of the liquid product in the pipeline
system measured over the duration of the leak detection
test. For detection of leaks in underground storage
tanks and pipelines, it is the industry practice to
measure and report the volumetric flow rate estimated
from the change in volume of the product in the tank or
pipeline system over the duration of the test. For the
accuracy required for tests on underground storage tank
pipeline systems, the mass flow rate and the volumetric
flow rate can be assumed to be approximately equal. The
difference between the mass flow rate and the volume flow
rate is small, because the liquid product is
incompressible at the pressures that an underground
storage tank pipeline system is operated and the
temperature of the product during a leak detection test
does not change sufficiently to change the density of the
product. The volumetric flow rate can also be accurately
estimated from measurements of the change in the level of
the liquid product in a pressure vessel, which is
attached to and in communication with the pipeline system
and contains both liquid product and trapped gas, during
a leak detection test, because level changes can be
easily converted to volume changes using a calibration
factor. This specification measures and reports
volumetric flow rate. There is a wide range of devices
that can be used to implement the temperature
compensation approach described above. Each device
requires a sensing system to measure the change in volume
of the product in the line. These devices can use any
type of mass, volumetric, level, or density sensing
system to measure and report volumetric flow rate. The
sensing systems described in this specification measure
either volume or level, but mass or density measurement
systems could be used interchangeably.

In the preferred embodiment of the present
invention, a test is conducted at the operating pressure
of the line and at a pressure near zero. The basic
measurement scheme is to divide the test into three
segments of equal length, and to make measurements at one
pressure during the first and third segments and
measurements at the other pressure during the middle
segment. The operating-pressure measurement can be made
during the first and third segments and the zero-pressure
measurement during the middle segment, or vice versa.
The averaging of the two operating-pressure measurements,
which bracket the lower or zero-pressure measurement,
minimizes any nonlinear changes in the temperature field
during the total test period. It is acceptable to use
more than three test segments providing the three-segment
data collection and data analysis procedures are
followed; doing so actually improves the accuracy of the
system, and for this reason there is no upper bound on
the number of tests. Mathematically, there are a number
of equivalent ways to process the multiple-segment data.

This three-segment approach assumes that the
product temperature changes determined from averaging the
temperature changes during the first and third segments
is approximately equal to the temperature changes that
occur during the middle segment. This assumption is
valid for underground pipelines because the temperature
changes in the line tend to increase or decrease exponen-
tially over time when there is a temperature difference
between the product in the pipeline and the surrounding
ground.

The accuracy of a single test of the line will
depend upon (1) the precision of the instrumentation used
to measure the volume or volume-related changes in the
line, (2) how constant the pressure can be kept during
the measurements, (3) the duration of each measurement,
(4) the number of data samples used to compute the volume
change at each pressure, and (5) the temperature changes
that occur in the liquid over the duration of the test.

To improve performance, a multiple-test strategy is
used. This minimizes false alarms and missed detections.
Three tests are conducted, although the waiting period
described below is applied only to the first test. A
temperature-compensated volume change is estimated from
each three-segment test, or from an average of two or
more three-segment tests. Providing that no product has
been dispensed between the first and last test sequences,
the rate of change of temperature should be decreasing
over time, and the volume rate measurement should
approach a constant value.

Accuracy can be somewhat degraded if the test is
conducted immediately after new product has been brought
into the pipeline and if the temperature of this new
product is significantly different from that of the
surrounding ground. The initial exponential change in
temperature that occurs immediately after product is
brought into the line is highly nonlinear. Even though a
test conducted during this period can still meet the EPA
release detection standards, a short waiting period
(approximately 15 minutes) can minimize this nonlinearity
and improve performance dramatically. For UST pipeline
systems, the waiting period starts immediately after
dispensing has ceased.

There are four approaches that can be used to
implement this method. The approach taken will depend on
the size of the pipeline, the maximum allowable size of
the detector, the accuracy of the test, and the cost
tradeoffs. These approaches are:
(a) **Level sensor and reservoir (Passive Method).** A
reservoir, in this case a closed pressure vessel,
is filled with fluid from the pipeline until the
pressure in the vapor space of this container is
equal to the line pressure of interest. A sensor
is then used to measure changes in the level of the
liquid in the vessel. The vessel is designed so that the level changes, and therefore the pressure changes, remain small during the measurement. Measuring the level changes in the vessel requires a high-precision sensor.

(b) Level sensor and reservoir (Active Method). As in the Passive Method, a closed container is partially filled with fluid from the pipeline. The remaining space is filled with a gas and maintained at a constant pressure equal to the line pressure of interest. Again, a sensor is used to measure the changes in the level of the liquid in the container.

c) Piston-displacement device. An object of known volume is inserted into or removed from the liquid in the pipeline to maintain a constant pressure in the line.

d) Pump and reservoir. A small, two-way pump is used to move fluid back and forth between the line and a reservoir or container to maintain a constant pressure in the line. The volume changes are measured directly by the pump.

The first two devices measure level changes and convert these to volume changes. If there is no vapor in the line, one can calculate these changes from the geometry of the container; otherwise, one can generate a calibration curve by draining the container and measuring the volume of the liquid taken out of the container. The size of the container used to add or remove liquid from the line should be proportional to the size of the line, the amount of thermally induced volume change, the elasticity properties of the pipeline system, the volume of vapor in the line, and the size of the leak (although the leak is generally responsible for only a fraction of the volume changes contributed by all the other factors listed here). Conversion from level to volume changes is done most easily if the cross section of the container does not change with level. A vertical cylinder is an
example of such a container. The reason for keeping the
pressure constant during a test is that the pressure
changes in the vapor space are small when the level
changes are small. The pressure changes in the container
can be calculated from the perfect gas law. The vapor
acts as a highly elastic spring. Any sensor that can
measure liquid level independently of pressure with
sufficient precision and accuracy to detect the smallest
leak rates of interest will suffice (for example, an
acoustic, optical, electromagnetic, or capacitance
sensor). For reliable detection of leaks as small as
0.05 gal/h, these level sensors need to have a precision
of approximately 0.002 inches or better.

An automatic pipeline leak detection system (PLDS)
is illustrated in Fig. 1 as it would be used in an
underground storage tank 220 in accordance with the
preferred embodiment of the present invention. The PLDS
has three main components: The probe assembly 122, a
transducer controller 112, and a system controller 100.
The transducer controller 112, which is mounted adjacent
to the probe assembly 122 within an explosion-proof
housing, controls the acoustic transducer 30. The system
controller 100 is mounted to an above-ground support and
is in electrical communication with the transducer
controller 112 through a cable 90. The cable 90 carries
power and command data from the system controller 100 to
the transducer controller 112, and acoustic data from the
transducer controller 112 back to the system controller
100.

The transducer controller 112 contains the pulse
waveform shaping, transmitting and receiving, and digital
preprocessing electronics for the PLDS system. The
system controller 100 contains the remainder of the
hardware and software necessary to control the desired
operational modes from the transducer controller 112,
acquire the acoustic data, process the data in terms of
product level, product-level changes, and leak rate, and
display the results. The system controller 100 can also
be equipped to control other sensor systems, such as
those that provide overfill protection and alert, an
automatic tank gauging system, detection of leaks in the
annular space of a double-wall tank, detection of
petroleum floating on the groundwater outside the tank,
and detection of vapors in the soil and backfill outside
the tank.

The transducer 30 is in electrical communication
with the transducer controller 112 by means of a
conductor 92. With reference to Fig. 2(a), the
transducer 30 receives command data from the transducer
controller 112 and transmits a series of accurately timed
acoustic pulses up the probe, through the product, and to
the various fiducials (acoustically reflective targets).
Fiducials 24 and 22 comprise the bottom circumference of
two concentric thin-walled nylon tubes (the "sleeve")
separated in the vertical by a known distance; the nylon
sleeve fits into a cylindrical tube, preferably a 1.5-
inch-diameter plastic tube, that holds the probe
assembly. The lower fiducial 24, F₁, is preferably
positioned at a height, h₁, about 2 inches above the
transducer 30, while the upper fiducial 22, F₂, is
preferably positioned at a height, h₂, about 4 inches
above the transducer. In operation, acoustic pulses
emitted by the transducer 30 are reflected from the
fiducials 24 and 22 and from the interface between the
product and the vapor, whether the product level is high
40 or low 50.

Referring to Figs. 1 and 2(a), the probe assembly
122 consists of a cylindrical pressurized vessel 10, the
acoustic sensor 31 (which includes the transducer 30
mounted on a base 32, a tube 20 with a hole 26 located
near the bottom of the tube, and two fiducials 22 and 24
separated by a known distance and mounted on a sleeve
comprised of two concentric nylon tubes 28 and 34), and a
series of valves, pipes, and cables linking it to the
tank, pipeline and controllers. A valve 62 connects a
pipe 60 from the pressure vessel to a pipe 70 attached to
the pipeline 200; this valve 62 is the means by which
product from the pipeline enters the pressure vessel.
Another valve 64 connects the pipe 60 from the pressure vessel to a pipe 80 that drains into the tank 220 or another holding container; this valve 64 is the means by which product is removed from the pressure vessel during a test. The trapped vapor 33 in the pressure vessel is used to maintain a constant or nearly constant pressure during the measurements at each product level in the pressure vessel. An electric cable 92 connects the transducer to its controller unit 112. Because the fluid in the pipeline must be at rest during a leak detection test, the pipeline 200 has a flow switch 120 to monitor whether product from the tank enters the line during a test. It also has a high-performance check valve so that pressure in the line can be maintained during a test. Valves 66 and 68 are used in the calibration of the sensor.

The acoustic sensor 31 (Fig. 2), which measures level changes within the pressure vessel, is housed in a tube 20 that supports both the transducer 30 and the two reference fiducials 22 and 24. The transducer is located at the bottom of the tube, and the fiducials are mounted at a known distance from the transducer on a sleeve (comprised of nylon tubes 28 and 34) that is inserted in the tube above the transducer. A hole 26 near the bottom of the tube allows product from the pressure vessel to enter or leave.

Figs. 3(a) and 3(b) show another alternative embodiment of the acoustic sensor 31. The fiducials 322 and 324, which are affixed to the tube, are thin bars positioned such that their long axes are perpendicular to the transducer. Four of many acceptable cross-sectional shapes 330, 332, 334, and 336 for the fiducials 322 and 324 are shown in Fig. 4(a). The triangular bar 330 has the preferred cross-section, because (1) the bottom edge of the bar is flat and perpendicular to the transducer so that the acoustic energy reflected from the fiducial is maximized, and (2) the top edges of the bar are not perpendicular to either the transducer or surface, so
that the acoustic energy reflected from the top of the bar is minimized.

In yet another alternate configuration of the acoustic sensor system (Fig. 5), the transducer and fiducials are not housed in a tube; the transducer 30 is mounted on the bottom of the pressure vessel 10 and the fiducials 342 and 344 are mounted on a rod 340 suspended vertically from the top of the pressure vessel. Some acceptable cross-sectional shapes for the fiducials 342 and 344 are shown in Fig. 4(a).

It is convenient but not absolutely necessary for the pressurized vessel 10 to have a cross-sectional area that does not change with height. A cylinder is preferred, because the height-to-volume conversion factor is then the same regardless of the level of product within the vessel. If the cross-sectional area changes from top to bottom, such as in a spherical vessel, the height-to-volume conversion factors is a function of the level of the product, and a table of conversions is required.

Referring to Fig. 2(a), three measurements are made with the acoustic sensor subsystem 31. First, an estimate of the speed of sound through the product between the transducer and the liquid surface is made; when the speed of sound is known, an acoustic pulse can be used to measure the height of the product in the pressure vessel and to measure the rate of change of level. The pulse travels from the transducer to the fiducial closest to the product surface. The lower fiducial 24 is used to measure sound speed when the product surface is at the lower level 50, and the upper fiducial 22 is used when the product surface is at the higher level 40. The speed of sound with one fiducial can be measured by

\[ U_1 = \frac{h_i}{2t_i}, \]  

where
$U_i =$ the speed of sound in inches/second between
the transducer and either the upper fiducial
22 or the lower fiducial 24

$h_i =$ the known distance in inches between the
transducer and the upper fiducial 22 or the
lower fiducial 24

t$_i =$ the round-trip travel time in seconds between
the transducer and the upper fiducial 22 or
the lower fiducial 24

i = either 1, which represents measurements made
between the transducer and the lower fiducial
24, or 2, which represents measurements made
between the transducer and the upper fiducial
22

If the product surface is above the upper fiducial
22, both fiducials can be used, with the following
algorithm, to estimate the speed of sound $U_{1-2}$:

$$U_{[1-2]} = \frac{(h_2 - h_1)}{2(t_2 - t_1)} \quad (2)$$

Second, an estimate of the surface level of the
product in the pressure vessel is made; this ensures that
the product is at the correct level, either the higher
level 40 for measurements made at the operating pressure
of the pipeline or the lower level 50 for measurements
made at zero pressure. The liquid level in the pressure
vessel changes because of the contraction or expansion of
the vapor in the pressure vessel as the pressure in the
pipeline system increases or decreases, respectively.
This estimate is repeated for each segment of a leak
detection test. The height of the surface above the
transducer in inches, $h_s$, is then calculated from

$$h_s = U_s (t_s) / 2, \quad (3)$$

where

$h_s =$ the measured distance, in inches, between the
transducer and the product surface 40 or 50
\( t_s = \) the round-trip travel time in seconds between the transducer and the product surface 40 or 50

\( U_s = \) the speed of sound in inches/second between the transducer and the product surface; \( U_s \) is estimated from either \( U_i \) (the speed of sound in inches/second between the transducer and the fiducial 22 or 24 that is closest to the product surface) or \( U_{1-2} \) (the speed of sound in inches/second between fiducials 22 and 24)

The speed of sound through the product varies as the density of the product changes. For a product of uniform chemical composition, the change in density is dependent on the change in the temperature of the product. As a consequence, the speed of sound through a given product can be accurately determined from the average temperature of the product over the propagation path of the acoustic signal. For the liquids of interest, changes in the speed of sound vary linearly over the range of ambient temperatures that will be encountered during underground pipeline tests and can be determined from

\[
U = mT + b, \quad (4)
\]

where
\[
U = \text{speed of sound speed in meters/second}
\]
\[
T = \text{temperature in degrees Centigrade}
\]
\[
m = \frac{dU}{dT} \text{ in meters/second/degrees Centigrade}
\]
\[
b = \text{sound speed in meters/second at } T = 0 \text{ degrees Centigrade}
\]

Third, the change in the level of the product is determined from

\[
\delta h_s = 39.37 \left( \frac{U_s}{2} \right) [\delta t_s - \delta t_i],
\]

where
\[
U_s = U_i = \text{speed of sound in meters/second between the transducer and the surface; the fiducial}
\]
closest to the product surface (either
fiducial 22 or 24) is used in estimating the
speed of sound
\[ \delta t_s = \] the change over time in the round-trip travel
time in seconds between the transducer and the
surface
\[ \delta t_i = \] the change over time in the round-trip travel
time in seconds between the transducer and the
fiducial closest to the product surface
(either fiducial 22 or 24)
The first term in the square brackets in Equation
(5), \( \delta t_s \), is a measurement of the product-level changes,
and the second term, \( \delta t_i \), is used to correct the level
changes for errors due to sound speed changes. The
product in the pressure vessel is subject to thermal
expansion and contraction. In general, however, no
correction is made for this phenomenon because the error
associated with it is usually smaller than the precision
required of the sensor for measuring level changes. If
the pressure vessel were large or if the temperature
changes of the product in the vessel were great, the
height changes would be estimated with the following
equation, which compensates for the thermal expansion and
contraction of the product in the pressure vessel:
\[ \delta h_s = 39.37 \left( \frac{\delta t_s}{2} \right) \left[ \delta t_s - \delta t_i - \left( \frac{V}{A} \right) C_e t_s \Delta T \right] \]
where
\[ V \] = volume, in cubic inches, of the product in the
pressure vessel at a surface height of \( h \)
\[ h \] = height, in inches, of the liquid surface in
the pressure vessel above the transducer
\[ A \] = cross-sectional area, in square inches, of the
surface of the product in the pressure vessel
at a height of \( h \) above the transducer
\[ C_e \] = coefficient of thermal expansion of the liquid
in the pressure vessel
\[ \Delta T \] = change in the average weighted temperature
between the transducer and the fiducial that
is located closest to the product surface during the measurement
An estimate of the average temperature change is made from
\[ \Delta T = -\frac{\frac{\delta t_i}{t_i}}{\frac{\delta t_i}{t_i}} \left[ \frac{1}{U_s d \Delta T} \right]^{-1} \]
where \( t_i \) is the round-trip travel time between the transducer and either fiducial 22 or 24. The third term in Equation (6), involving \( \Delta T \), is the one that compensates for the thermal expansion and contraction of the product in the pressure vessel.
An alternative yet similar equation that can be used to estimate the temperature-compensated level changes in the pressure vessel is
\[ \delta h_s = \frac{U_s}{2} \left[ \delta t_s - t_s \frac{\delta t_i}{t_i} - \frac{V}{A} C_e t_s \Delta T \right] \]
The only difference between Equations (6) and (8) is the term that is used to correct the level changes for sound speed. Once the speed of sound through the layer of product between the transducer and the fiducial 22 or 24 has been estimated, the quantity \( \frac{t_s}{t_i} \) in Equation (8) is used to extrapolate that estimate to the layer of product between this fiducial 22 or 24 and the surface.
Another method of estimating \( \delta h \) is to use the speed of sound through the layer of product between the two fiducials 22 and 24 when the product is at the higher level 40 and above the higher fiducial 22 to estimate the sound speed changes in the layer above this upper fiducial 22. This method uses
\[ \delta h_s = \frac{U_s}{2} \left[ \delta t_s - \frac{V}{A} C_e t_s \Delta T \right] - \frac{\delta t_i}{2 t_s} \left[ t_i U_s + (t_s - t_i) U_{1-2} \right] \]
where \( U_{1-2} \) = speed of sound between fiducials 22 and 24.
The protocol for conducting a pipeline leak detection test with the preferred embodiment of the invention shown in Figs. 1 and 2 is as follows:
1. During the installation of the leak detection system, it is determined what the height of the liquid in the pressure vessel 10 will be (1) when the pressure is zero and (2) when the pressure is at another, higher level that will be used during a test. This is done as follows. The first step is to establish the height of the product when the pressure is zero (i.e., atmospheric). All valves 62, 64, 66 and 68 are closed except for the one 62 that allows product to enter the pressure vessel from the pipeline 200 via connecting lines 70 and 60. Valve 62 is then closed and valve 66 is opened, allowing the vessel to come to atmospheric pressure. The valve 64 at the juncture of the connecting lines 60 and 80 is then opened, allowing product to drain from the pressure vessel into the tank or other appropriate holding container until the level of the product in the vessel falls to a point as close as possible to, but still above, fiducial 24. Valve 64 is closed. Next valve 62 is opened and a submersible pump 240 is turned on and allowed to pressurize the pipeline 200. The pressurized product from the pipeline flows into the pressure vessel via connecting line 70 and rises to the upper level 40 (pipeline pressure greater than zero). If the pressure vessel and the fiducials have been properly designed, the level should rise above the upper fiducial 22 until it is approximately the same distance from this fiducial as it was from the lower fiducial 24 when the pressure was zero. Once the levels have been checked by means of Equation (3), a calibration can be performed to establish the height-to-volume conversion factor for the system.

2. The height-to-volume conversion factor, which relates the level of the product in the vessel to a corresponding volume, is then determined. When the pressure in the vessel 10 is zero, valve 68 is opened and a known quantity of product is removed
from the container. The change in level resulting from this change in volume is measured with the acoustic transducer 30. The height-to-volume conversion factor is obtained by dividing the volume change by the level change.

3. A leak detection test is initiated from the system controller 100. The system controller instructs the submersible pump 240 via cable 110 to pressurize the pipeline 200. However, no product is dispensed from the line. The system controller then opens valve 62 via cable 102 to allow product from the pipeline to enter the pressure vessel until it reaches the upper level 40 and the pressure in the vapor space 33 is the same as that in the pipeline. The pump is then turned off via a command from the system controller 100 via cable 110. The height of the product in the pressure vessel is then checked. It should be above the upper fiducial 22 at the upper level 40.

4. The system controller 100 then instructs the transducer controller 112 to collect data on level changes over a specified period of time, nominally 5 minutes. The rate of change of the level is calculated by fitting a least-squares line to the data. The slope of the line, when multiplied by the height-to-volume conversion factor, is the rate of change of volume at the higher pressure.

5. The system controller 100 then lets the pressure in both the pipeline 200 and the pressure vessel drop to zero by opening valve 64 via cable 104. When zero pressure has been reached, another check on the height of the product is made. It should now be above fiducial 24 at the lower level 50.

6. The system controller 100 then instructs the transducer controller 112 to collect data on level changes over a period of time identical to the one used in step 4 (for the high-level measurements). The rate of change of the level is calculated by fitting a least-squares line to the data. The
slope of the line, when multiplied by the height-
to-volume conversion factor, is the rate of change
of volume at the zero pressure.

7. The system controller then closes valve 64 via
cable 104, opens valve 62 via cable 102, and
instructs the submersible pump 240, via cable 110,
to pressurize the pipeline system. Again, the
level of product in the pressure vessel rises until
the pressure in the vessel is the same as that in
the pipeline. The height of the product in the
pressure vessel is again checked. Then the system
controller 100, via cable 110, turns off the
submersible pump and instructs the acoustic
transducer controller 112 to collect data on level
changes over a specified period of time. The rate
of change of the level is calculated by fitting a
least-squares line to the data. The slope of the
line, when multiplied by the height-to-volume
conversion factor, is the rate of change of volume
at the higher pressure (being measured now for the
second time).

8. Via cable 108, the system controller 100 checks the
flow switch 120 continuously throughout the test to
determine whether any product is being dispensed.
If there has been no flow, data analysis can
proceed. If there has been flow, the test is
terminated.

9. Thermal fluctuations in the rate of change of
volume must be compensated for. The temperature-
compensated volume rate is calculated as follows.
The average of the two measurements of the rate of
change of volume obtained when product is under
pressure and at the upper level 40 is subtracted
from the rate obtained when the pressure is zero
and the product is at the lower level 50.

10. If the temperature-compensated volume rate exceeds
a predetermined threshold, the pipeline may be
leaking.
11. If in the first test, the threshold is exceeded,
   two more tests identical to the one described above
   are conducted. It is determined on the basis of
   the last two tests whether the line should be
   declared leaking. In this way the possibility of
   false alarms is reduced.
   The test procedure is identical for the alternative
   embodiments, shown in Figs. 3 through 5, that use an
   acoustic sensor, and for the alternative embodiments
   shown in Figs. 6 and 7 in which the level changes are
   measured with a linear variable-differential transformer
   (LVDT) and LVDT controller 312, rather than with an
   acoustic system.
   The primary function of the acoustic sensor 31 is
   to measure the level of the product in the pressure
   vessel and to detect and measure any changes in this
   level. Any level-measurement sensor system can be used
   providing it has sufficient accuracy, precision and
   resolution to meet the performance standard for measuring
   level and changes in level. The acoustic sensor 31 shown
   in Figs. 1 through 5 has been replaced in Fig. 6 by a
   system 380 that uses an electromagnetic float 360 to
   track the surface. The float 360 is attached to a
   vertical rod 370 that in turn is attached to a cylinder
   386 with a ferromagnetic core; the cylinder moves up and
   down inside a linear variable-differential transformer
   (LVDT) 382, a commercially available device. The LVDT
   measures the change in the magnetic field as the cylinder
   386 moves up and down. Level changes of better than
   0.001 inches can be measured. The length of the LVDT
   depends on the difference in the levels 40 and 50 to be
   measured. The LVDT can be completely contained within
   the pressure vessel as shown in Fig. 6, located on top of
   the pressure vessel as shown in Fig. 7, or placed in any
   position in between. The LVDT measures only level
   changes, so in order to measure absolute height, the
   changes in level must be continuously summed by the
   system controller 100. Although the shape of the float
   does not affect the performance of the measurement
system, the vertical dimension of the pressure vessel can
be minimized if the shape of the float matches the shape
of the vessel. To minimize evaporation and condensation
effects, the float should have a cross-sectional area
nearly as wide as that of the pressure vessel.

The present invention quantitatively estimates the
flow rate from a leak at the operating pressure of the
pipeline; compensates for thermal expansion and
contraction of both the product and the pipeline without
the need for measuring temperature directly; can conduct
a leak detection test in a short time (approximately 15
minutes); is self-calibrating, because it measures volume
directly, or measures level changes, which can easily be
converted to volume changes from the height-to-volume
calibration measurements or from the cross-sectional area
of the pressure vessel; only requires level or volume
measurement sensors in order for the invention to measure
volume changes; and increases its performance when a
multiple-test strategy is used.

DESCRIPTION OF ALTERNATIVE EMBODIMENTS

Four alternative embodiments of the present
invention are shown in Figs. 8 through 11. Each of these
embodiments measures the volume changes at zero pressure
and at the operating pressure of the line, keeping the
pressure constant during these measurements. The three-
segment procedure is then used to compute the
temperature-compensated volume rate. The devices shown
in Figs. 8 and 9 measure level changes in a pressure
vessel, while those in Figs. 10 and 11 measure volume
changes directly. The devices shown in Figs. 8 and 9 are
nearly identical to the ones shown in Figs. 1 and 6,
except that a pressure-regulating subsystem 414 is used
to raise and lower the pressure within the vapor space
and to maintain a constant pressure within the vessel.
The devices shown in Figs. 1 and 6 maintain constant
pressure without any additional devices, while the ones
in Figs. 8 and 9 include a device intended for this
purpose. The pressure-regulating subsystem 414 consists
of a pipe 420 connecting the gas in the pressure vessel
to either a high- or low-pressure regulator. When the
valve 410 is opened, an inert gas enters the pressure
vessel 350. This gas is used to establish and maintain
constant pressure at the higher level. If the pressure
in the vessel drops below this level, a regulator 430
raises it; if the pressure rises, another regulator 432
lowers it appropriately. When the valve 412 is opened,
the inert gas is allowed to escape; thus, the gas is also
used to establish and maintain a pressure of zero in the
vessel 350. If the pressure in the vessel drops below
zero, a regulator 440 raises it back to zero; conversely,
if the pressure rises above zero, a regulator 442 lowers
it back to zero. The acoustic sensor subsystem in Fig. 8
requires only one fiducial 462, which is located as close
as possible to the underside of the surface of the
product 390 in the pressure vessel. The device in Fig. 9
is identical to the one in Fig. 8 except that the
acoustic transducer measurement system has been replaced
by an electromagnetic float system like the one described
in Fig. 6.

The test procedure for the alternative embodiments
shown in Figs. 8 and 9 is very similar to that for the
embodiments shown in Figs. 1 and 6, except that the
pressure in the pipeline 200 and the vapor space 33 in
the pressure vessel is controlled with a pressure-
regulating subsystem 414. The higher pressure is
maintained constant during both measurements (Steps 4 and
7) by the high 430 and low 432 regulators, and the zero
pressure (Step 6) is maintained by two additional high
and low regulators 440 and 442.

Figs. 10 and 11 show a measurement system that
maintains a constant pressure by adding or removing a
known volume of product from the pipeline, and that then
sums the volume changes. In Fig. 10, the sensor 122
(shown in Fig. 1) is replaced by a positive-displacement
pump 500, a motor 510, and a pressure sensor 520.
Product is added to the pipeline 200 through a pipe 82 or
removed from the pipeline through a drain line 80. The
valve 501 is used to calibrate the positive-displacement pump 500 and motor 510. The pressure sensor 520, which is connected to the pipeline via a pipe 528, is used to maintain the proper pressure conditions during a test. The controller 100, which is connected electrically to the pressure sensor via a cable 522 and to the motor 510 and positive-displacement pump 500 via cables 524 and 526, establishes both the high pressure and the zero pressure and maintains pressure by reading the pressure sensor and turning the displacement pump’s motor on or off. When the pump removes product from the pipeline 200, the pressure in the line drops. When the pump adds product to the pipeline, the pressure rises. The volume change in the line at the higher pressure or at zero pressure is measured directly by the pump 500.

The device in Fig. 11 is substantially the same as the one in Fig. 10, except that the motor 510 and positive-displacement pump 500 have been replaced by a displacement piston device 530 and a linear actuator 540. The linear actuator is connected to the system controller 100 via a cable 542 and to the displacement piston 530 via another cable 544. The motor and positive-displacement pump have been replaced by a displacement device 530 that uses a piston 532 to displace a known volume of fluid in the containment volume 534. The volume changes are determined directly from the movement of the piston 532.

The alternative embodiment of the invention shown in Fig. 10 measures volume changes directly. The protocol for conducting a pipeline leak detection test with this embodiment is as follows:

1. The motor 510 and positive-displacement pump 500 in Fig. 10 are calibrated over the range of volume measurements expected during a test. This is done by withdrawing known amounts of liquid from the line 82 via valve 501 and measuring the resulting change in volume. An alternative location of the valve 501 is in the line 80 connecting the pump 500 to the container or tank 220. A calibration curve
is then generated by fitting a least-squares line to the data that identify the measured volume and the actual volume withdrawn from the line.

2. A leak detection test is initiated from the system controller 100. The system controller instructs the submersible pump 240 via cable 110 to pressurize the pipeline 200. Once the test pressure is reached ("test pressure" meaning the one higher than zero), a command from the system controller turns off the submersible pump via cable 110.

3. The system controller 100 then instructs the positive displacement pump controller 512 to record data on the change in volume over a specified period of time, nominally 5 minutes. The pressure in the pipeline is measured via the pressure sensor 520, and the system controller maintains a constant pressure in the pipeline by providing instructions to the motor 510 and positive-displacement pump 500 to add or remove product to maintain this pressure at a constant level during the test. The rate of change of volume is calculated by fitting a least-squares line to the data. The slope of the line is the rate of change of volume at the higher pressure.

4. The positive-displacement pump 500 removes product via the drain line 80 until the pressure in the pipeline 200 drops to zero. This is confirmed by the pressure sensor.

5. The system controller 100 then instructs the positive displacement pump controller 512 to record data on the change in volume over a period of time identical to the one used in Step 3 (for the high-pressure measurements). The rate of change of volume is calculated by fitting a least-squares line to the data. The slope of the line is the rate of change of volume at the higher pressure.

6. The system controller 100 then pressurizes the pipeline 200. Via cable 110 it instructs the
submersible pump 240 to add product to the pipeline until the desired pressure has been reached. The system controller then turns off the submersible pump and activates the motor 510 and the positive-displacement pump 500, which adds or removes product from the pipeline 200 over the specified period of time so that the pressure remains constant during this measurement, as verified by the sensor 520. The rate of change of level is calculated by fitting a least-squares line to the data. The slope of the line is the rate of change of volume at the higher pressure (being measured now for the second time).

7. Via cable 108 the system controller 100 checks the flow switch 120 continuously throughout the test to determine whether any product is being dispensed. If there has been no flow, data analysis can proceed. If there has been flow, the test is terminated.

8. Thermal fluctuations in the rate of change of volume must be compensated for. The temperature-compensated volume rate is calculated as follows. The average of the two measurements of the rate of change of volume obtained when the line is pressurized is subtracted from the rate obtained when the pressure is zero.

9. If the temperature-compensated volume rate exceeds a predetermined threshold, the pipeline may be leaking.

10. If, in the first test, the threshold is exceeded, two more tests identical to the one described above are conducted. It is determined on the basis of the last two tests whether the line should be declared leaking. In this way the possibility of false alarms is reduced.

The alternative embodiment of the invention shown in Fig. 11 also measures volume changes directly. The protocol for conducting a pipeline leak detection test
with this embodiment is similar to the embodiment shown
in Fig. 10 and is as follows:

1. The displacement piston device 530 and linear
actuator 540 in Fig. 11 are calibrated over the
range of volume measurements expected during a
test. This is done by withdrawing known amounts of
liquid from the line 82 via valve 501 and measuring
the resulting change in volume. A calibration
curve is then generated by fitting a least-squares
line to the data that identify the measured volume
and the actual volume withdrawn from the line.

2. A leak detection test is initiated from the system
controller 100. The system controller instructs
the submersible pump 240 via cable 110 to
pressurize the pipeline 200. Once the test
pressure is reached ("test pressure" meaning the
one higher than zero), a command from the system
controller turns off the submersible pump via cable
110.

3. The system controller 100 then instructs the
displacement piston device and linear actuator
controller 552 to record data on the change in
volume over a specified period of time, nominally 5
minutes. The pressure in the pipeline is measured
via the pressure sensor 520, and the system con-
troller maintains a constant pressure in the
pipeline by providing instructions to the dis-
placement piston device 530 and linear actuator 540
to add or remove product to maintain this pressure
at a constant level during the test. The rate of
change of volume is calculated by fitting at least-
squares line to the data. The slope of the line is
the rate of change of volume at the higher
pressure.

4. The displacement piston device 530 removes
product from the pipeline via the line 82
until the pressure in the pipeline 200 drops
to zero. This is confirmed by the pressure
sensor.
The system controller 100 then instructs the displacement piston device and linear actuator controller 552 to record data on the change in volume over a period of time identical to the one used in Step 3 (for the high-pressure measurements). The rate of change of volume is calculated by fitting a least-squares line to the data. The slope of the line is the rate of change of volume at the higher pressure.

The system controller 100 then pressurizes the pipeline 200. Via cable 110 it instructs the submersible pump 240 to add product to the pipeline until the desired pressure has been reached. The system controller then turns off the submersible pump and activates the displacement piston device 530 and linear actuator 540, which adds or removes product from the pipeline 200 over the specified period of time so that the pressure remains constant during this measurement, as verified by the sensor 520. The rate of change of level is calculated by fitting a least-squares line to the data. The slope of the line is the rate of change of volume at the higher pressure (being measured now for the second time).

The remaining steps necessary to complete a test are the same as steps 7 through 10 described above for the motor 510 and displacement pump 500 in Fig. 10.

ALTERNATIVES FOR COLLECTING AND ANALYZING VOLUMETRIC DATA:

There are many alternative embodiments of the basic method of collecting and analyzing volumetric data for the conduct of a pipeline leak detection test. It is required that the volumetric data be collected at two or more different pressures and during two or more measurement periods (i.e. segments) that are contiguous.
or nearly contiguous and have the same or nearly the same
duration. For a high level of performance, data should
be collected at two pressures using three measurement
segments in which the pressure separation is maximized.
A two-pressure leak detection test with only two segments
can be conducted, but in order to achieve a high level of
temperature compensation, and therefore a high level of
performance, the rate of change of temperature must be
uniform or nearly uniform. The accuracy of the two-
segment approach, which can be effective under some
pipeline temperature conditions (especially if one
observes a waiting period before conducting a test), is
controlled by the ambient rate of change of the
temperature of the product at the time of the test. If
the rate of change of product temperature is not constant
during a test, the results will be in error. When a
third measurement segment is added, accurate temperature
compensation can be achieved even when pipeline
temperature conditions during a test are not uniform,
provided that the rate of change of temperature during
data collection is monotonic (i.e. that it only increases
or only decreases during a test). Such temperature
conditions are typically encountered in underground
pipelines, especially those associated with storage tanks
at petroleum fuel storage facilities; thus, the two-
pressure, three-segment volumetric data collection and
analysis method will have wide application.

The two-pressure, three-segment approach works well
because the rate of change of temperature of the product
in the pipeline does not change with pressure but the
flow rate due to a leak does. The flow rate due to a
leak, which is usually defined at a specific line
pressure, can be determined directly by testing first at
some operationally useful test pressure and then at
atmospheric pressure (i.e. zero gauge pressure). The
value chosen for the test pressure, which can be either
below or above atmospheric pressure, is usually the same
as the operating pressure of the pipeline, or it is some
pressure specified in an environmental regulation or
professional society testing standard. The flow rate due
to a leak at a specific test pressure can be determined
even if neither of the two pressures is atmospheric,
provided the relationship between leak rate and pressure
is known or can be estimated empirically. For flow under
pressure through an orifice or hole, the relationship
between leak rate and pressure is well known; it is
proportional to the square root of pressure for liquids
with viscosities near water and is linear for more
viscous liquids.

Since it takes a finite time to change the nominal
pressure in the line, the two (or three) measurement seg-
ments will not be absolutely contiguous. For a variety
of reasons, the time interval between measurement
segments may need to be longer than the time required to
change the pressure. For example, the added time may be
needed to allow any pressure transients and instabilities
produced by the pressure change to subside before a
volume measurement is made, which is particularly
important when testing long or complicated lines.
Additional time might also be required to insure equal
intervals between measurement segments when the pressure
changes are done manually. For best performance, the
segments should be of equal duration, as should the time
interval(s) between them. If they are not, it does not
mean that a leak detection test can not be conducted, but
it will produce an error in the final test result. The
magnitude of the error is dependent primarily on the rate
of change of temperature of the product in the line.

It is important to note that more than three
measurement segments may be used. When the three-segment
pattern is repeated, multiple estimates of temperature-
compensated volume rate can be made and averaged, a
 technique that increases the accuracy of the final test
result. It is also important to note that the nominal
pressure can be different during each measurement seg-
ment, regardless of the number of segments. If this is
the case, however, more stringent precision requirements
of the sensor used to measure volume may be needed, and
the magnitudes of any errors in the final test result
will also be larger than a test conducted when the
pressures of the first and third measurement segments are
the same and equal to the highest (or lowest) pressure of
a three-pressure test and the pressure of the second
measurement segment is equal to the lowest (or highest)
pressure of a three-pressure test. Whether this error is
significant depends on what performance must be achieved
by the leak detection system.

The two-pressure, three-segment volumetric
measurement method described above can be modified either
for other applications or to accommodate some important
operational constraints that may be placed on a test.
One especially useful application, in which pressure is
maintained at the same level during any two consecutive
measurement segments in a three-segment test, has
operational advantages for several scenarios: (1) when
pressure transients occur each time the pressure is
changed, as is the case when testing large pipelines; (2)
when the storage, handling, or disposal of product, which
might occur when pressure is changed, is difficult; and
(3) for simplification of the test protocol when a manual
or semi-automatic implementation of the test methodology
is used. The pressure sequence may be high-low-low, low-
high-high, high-high-low, or low-low-high, which hereafter
will be referred to as the 'high-low-low' protocol.
In the implementation previously described, the pressure
is kept constant or nearly constant in the first and
third measurement segments, but is changed during the
second, or middle, segment. The pressure sequence can be
either high-low-high or low-high-low. The same algorithm
for computing the magnitude of the temperature-
compensated flow rate for the "high-low-high" imple-
mentation is applied for the "high-low-low"
implementation, i.e. averaging the volumetric flow rate
estimated during the first and third measurement segments
and subtracting the volumetric flow rate computed during
the second segment. If one of the pressures is
atmospheric, the absolute value of the magnitude of the
temperature-compensated volume rate computed according to
the "high-low-low" protocol is equal to one-half the flow
rate due to a leak. The absolute value of the magnitude
of the temperature-compensated volume rate computed
according to the "high-low-low" protocol is equal to one-
half the flow rate computed with the "high-low-high"
protocol if both test sequences are conducted using the
same pressures. If both pressures are non-zero (non-
atmospheric), the temperature-compensated flow rate is
equal to one-half the difference in the flow rates that
are estimated at both pressures. If a leak is present,
the flow rate is due to the leak and any errors in the
test; if the line is not leaking, then any nonzero flow
rate is due to these errors. Again, the pressures can be
positive or negative or a combination of both.

A manual or a semi-automatic implementation of the
two-pressure, three-segment test using the "high-low-low"
protocol is attractive for underground pipelines
associated with underground storage tank (UST) and
aboveground storage tank (AST) facilities that dispense
petroleum with a pump, where in order to change pressure
in the line one must normally have control of the
dispensing pump. For convenience, the leak testing
apparatus can be attached to the line at a valve
connection located at or near the fuel dispensing pump.
When this pump is turned on, which can be done manually,
the line is pressurized. For example, this is easily
done using the pump handle on a dispenser at a retail
motor fuel service stations. A high-low-low test can be
initiated once the pump is turned off. The decreasing
pressure levels required for the second and third
segments can be attained by removing product from the
line or pressure vessel or by releasing the vapor trapped
in the pressure vessels of three of the four test
apparatuses described above. If possible, sufficient
product (or vapor) should be removed so that the pressure
drops to atmospheric level (i.e. zero gauge pressure).
This can be done automatically or manually by an
operator. Once this has been accomplished, the test can
be completed without any further pressure changes. No further access to the fuel dispensing pump is required, a factor that has cost, safety, and operational benefits. This approach is particularly amenable to portable and/or battery operated implementations.

The difference in flow rate (also called the temperature-compensated volume rate, or TCVR) between the average pressure of the first and third segments and the second segment is obtained by averaging the rate of change in the volume of product as measured during the first and third segments and subtracting this average from the rate of change computed for the second segment. The TCVR obtained in this manner is

\[
TCVR(P_1, P_2, P_3) = \left(\frac{(VR_1(P_1) + VR_3(P_3))}{2}\right) - VR_2(P_2)
\]  

(10)

where \(P_1\), \(P_2\), and \(P_3\) are the line pressures that are maintained constant or nearly constant during each measurement segment and \(VR_1(P_1)\), \(VR_2(P_2)\), and \(VR_3(P_3)\) are the volumetric flow rates determined for each measurement segment at pressures \(P_1\), \(P_2\), and \(P_3\), respectively.

Assuming that the volume changes due to the thermal expansion or contraction of the product in the line are perfectly compensated for by the analysis algorithm, then Eq. (10) reduces to

\[
TCVR(P_1, P_2, P_3) = \left(\frac{(LR_1(P_1) + LR_3(P_3))}{2}\right) - LR_2(P_2)
\]  

(11)

where \(LR_1(P_1)\), \(LR_2(P_2)\), and \(LR_3(P_3)\) are the volumetric leak rates determined for each measurement segment at the designated pressures. If \(P_1\), \(P_2\), or \(P_3\) is equal to atmospheric pressure, then \(LR_1\), \(LR_2\), or \(LR_3\), respectively, would be zero.

In practice, there will be some type of error due to residual compensation errors, as well as sensor noise and other sources of noise not compensated for by this technique. For best performance, the difference between the lowest and highest pressures should be as great as possible, and the precision (i.e. volumetric sensor
noise) should be smaller than the error in estimating the
TCVR that is determined in Eq. (10) and that is due to
the leak rate of interest. In all of the implementations
described above, whether they are based on two pressures
and three segments or on three pressures and three
segments, the flow rate can be derived from Eq. (10).
The error in compensating for the thermal expansion
or contraction of the liquid product in the pipeline can
be estimated as part of the test procedure if there is
time to permit the addition of one or more measurement
segments to the leak detection test. The approach is to
use the same analysis algorithm, but to apply it to three
segments in which the pressure is the same or nearly the
same. Since the flow rate due to a leak would be the
same in each segment, any non-zero estimate of flow rate
would be due mainly to the error in compensation. This
calculation would also quantify other errors (e.g. sensor
errors). There are many ways to incorporate this error
calculation into the test procedure. For example, if a
low-high segment is added to the end of a high-low-high
two-pressure, three-segment test, then the first, third,
and fifth segments can be used to estimate the error in
temperature compensation and the first three, middle
three, last three, or an average of any of these three
segments can be used as the basis for the leak detection
test. If the error is substantial, especially in
comparison to the estimated TCVR, the test should be
considered invalid and should be repeated. Another
example is to add a low-pressure segment at the end of a
high-low-low sequence. The first three segments are then
used as the basis for the leak detection test, and the
last three to estimate the error in temperature
compensation. The estimate is less meaningful this way,
because the data used as the basis for the test have been
collected over a somewhat different period in time than
those used to estimate the temperature compensation
error.

Another method for obtaining an error estimate uses
the difference between two temperature-compensated volume
change or flow rate tests. If two tests are conducted
(whether or not the tests have overlapping measurement
segments), the volume of flow rate due to a leak should
be the same if the leak rate remains constant over the
period of time in which the two tests are made.
Therefore, any difference between the two test results
will provide an estimate of the error in the test
results. Comparisons of multiple test results will
provide a more accurate error estimate, but will also
take more time to obtain.

SIMPILIFIED APPARATUS FOR LEAK DETECTION:
The technology described above can be implemented
very simply if (1) the level changes that occur in the
pressure vessel shown in FIGS. 1 and 6, which are due to
volume changes in the pipeline, are magnified so that
they can be made manually with a ruler or electronically
with an inexpensive, low-precision level sensor; and (2)
the need to transfer liquid in and out of the pressure
vessel for the purpose of changing line pressure from one
measurement segment to the next can be eliminated. Both
goals can be accomplished with the embodiment shown in
FIG. 12. This device is simple and inexpensive to make
because there is no need for a high-precision level
sensor or for electronic access to the transfer pump; it
is also inherently safe to use in pipelines containing
potentially combustible liquids such as petroleum
products, because it does not use electrical power.
Furthermore, these advantages can be realized without any
sacrifice in the overall performance of the system in
detecting pipeline leaks. The leak detection system can
be permanently attached to a pipeline or it can be a
portable system attached to a line only for the purpose
of conducting a test.

The key functional features of the embodiment shown
in FIG. 12 for conducting a leak detection test are as
follows: (1) a large-diameter, cylindrical pressure
vessel (pressure cylinder 610), (2) a small-diameter,
cylindrical pressure vessel of similar height
(measurement cylinder 612), (3) a sight glass with a
ruler or tape marked in increments of approximately 1/16
inch for measuring the level of liquid in measurement
cylinder 612, and (4) three manually operated valves V1,
V2, V3. Measurement cylinder assembly 616 includes both
measurement cylinder 612 and the level gauge (i.e., sight
glass 614 with measurement tape). Pressure cylinder 610
and measurement cylinder 612, as well as connecting
piping, are preferably constructed of steel; however, any
material that can withstand the maximum expected pressure
can be used. Sight glass 614 is preferably constructed
of glass, which is clear to permit the liquid level to be
read but sufficiently robust to withstand the pressures
at which the system is used (typically 30-100 psi).

The purpose of pressure cylinder 610 in FIG. 12,
which is also the main purpose of the pressure cylinder
in the embodiments shown in FIGS. 1 and 6, is to maintain
constant pressure in the pipeline during each of the
measurement segments that comprise a leak detection test.
The purpose of measurement cylinder 614 is to magnify
those volume changes occurring in the pipeline that are
due either to a leak or to thermal influences in such a
way that small changes in volume are converted into large
changes in level that can be measured easily through
sight glass 614. For this purpose, sight glass 614 (with
its measurement tape) is attached to measurement cylinder
612. If measurement cylinder 612 is 1-5/8 inches in
diameter and sight glass 612 is 5/8 inch in diameter,
then volume changes of 3 ml occurring in the pipeline can
be measured by reading the level changes in sight glass
612 to 1/16 inch. A crucial difference between the
embodiment shown in FIG. 12 and those shown in FIGS. 1
and 6 is that during a test the liquid in the pipeline
communicates only with the liquid in measurement cylinder
612 and not with the liquid in pressure cylinder 610.
The function of measurement cylinder 612 is not to
measure level changes, but rather to magnify small
changes in volume occurring in the pipeline. In the
embodiment in FIG. 12, it is sight glass 614 and its measurement tape that are used to measure the level changes in measurement cylinder 612. It should be noted, however, that measurement cylinder 612 itself could be used for this purpose if it were made of a transparent material and a tape measure were attached to it.

Each of the three valves on the embodiment shown in FIG. 12 has a specific purpose. V1 must be open to pressurize the pipeline and leak detection system for a test and to conduct a test. When V1 is closed, the leak detection system is completely isolated from the pipeline. When open, V1 lets liquid from the pipeline into measurement cylinder 612 or from measurement cylinder 612 into the pipeline. Pressurization is accomplished by pumping liquid product into the measurement and pressure cylinders 612 and 610; V2 must also be open during the pressurization process. For best performance during the ensuing leak detection test, both cylinders should be nearly empty before the pressurization process begins; this results in the maximum volume of vapor being trapped at the test pressure, which means that the pressure can be better maintained at a constant level during each measurement segment. V2 is used to isolate level changes that occur in pressure cylinder 610 from changes in the level of liquid in measurement cylinder 612 and pipeline. This valve must be closed during each measurement segment of a leak detection test.

As noted above, when measurement cylinder 612 is isolated from pressure cylinder 610 by closing V2, very small changes in the volume of liquid in the pipeline can be accurately measured at a constant pressure. V3 is used to lower the pressure in both the pipeline and the leak detection system (i.e., the measurement and pressure cylinders 612 and 610). When V3 is opened, vapor is released from both cylinders through vapor release tube 618; if all of the vapor is released, the pressure in the pipeline returns to atmospheric level (i.e., zero gauge pressure). For safe operation, the apparatus also includes pressure relief valve 620 to prevent inadver-
tent over-pressurization of the system and liquid check
valve 622 to prevent the possibility of liquid
overflowing during a test.

The embodiment shown in FIG. 12, as well as those
in FIGS. 1 and 6, uses a pump to pressurize the pipeline.
A slight modification to the embodiment in FIG. 12 will
allow pressurization by means of bottled gas such as
nitrogen, thus eliminating the need to use the transfer
pump or another pump dedicated to this purpose. This
modified embodiment is shown in FIG. 13. One advantage
of pressurizing the line with bottled gas 624 such as
nitrogen is that the operator can conduct the entire test
without leaving the site of the leak detection system.
Another advantage is that once the pressure and
measurement cylinders 610, 612 have been filled with an
amount of liquid sufficient for conducting a test, they
do not have to be emptied and refilled again to repres-
surize the line for the conduct of a test. The bottled
gas 624 can be permanently attached to the leak detection
system or it can be a portable unit that is attached to
the system any time a test is conducted. When V5 and V3
are open and V4 is closed, the pipeline can be
pressurized. Once the line has been pressurized, V5 and
V3 are closed and V4 is opened; from then on the steps
for performing a leak detection test are identical for
the embodiments shown in FIGS. 12 and 13.

Using the bottled gas pressurization technique,
however, requires that there be sufficient product
already present in the apparatus before a leak detection
test is initiated. It should be noted that once the test
pressure is reached, the gas bottle 624 is isolated from
the pressure cylinder by means of a valve, and no further
pressurization of the pipeline is required. In contrast,
in the embodiments shown in FIGS. 8 and 9, gas is
continuously added or removed as the means of maintaining
constant pressure during each measurement segment. In
the embodiment shown in FIG. 13, the volume of vapor in
the pressure cylinder 610 (which is in direct
communication with measurement cylinder 612) is large
enough to maintain approximately constant pressure in the
pipeline without any active adjustments in pressure.

The embodiments in FIGS. 12 and 13 can be designed
for applicability to a wide range of pipelines of
different sizes and diameters. One of the most important
is the kind of large underground pipeline found at
terminals for aboveground storage tanks (ASTs) that
contain petroleum products. These lines are typically 4
to 10 inches in diameter and 100 to 500 feet in length.
Both embodiments are also applicable to the smaller lines
associated with underground storage tank (UST)
facilities, for example, the lines found at retail gas
stations. These are typically 2 inches in diameter and
50 to 200 feet in length. These embodiments can be used
to test lines larger than those found at terminals. The
main difference between the embodiments for use on
smaller lines and those for use on larger lines is in the
size of the pressure and measurement cylinders 610, 612.
Both the diameter and the height of the two cylinders
must be increased as the diameter and/or length of the
pipeline increases. The correct size of the pressure and
measurement cylinders 610, 612 for a given line can be
calculated analytically using the perfect gas law.

The diameter and height of the two cylinders should
be such that they can (1) accommodate the anticipated
changes in the volume of product in the line, regardless
of whether these changes are due to a leak or to thermal
expansion and contraction of the product, and (2) limit,
during any given measurement segment, the pressure
changes due to such volume changes while (3) still
maintaining an acceptable level of precision. The
pressure cylinder 610 must be large enough that any
pressure changes occurring within it (and resulting from
volume changes in the line) are small in relation to it.
Similarly, the measurement cylinder 612 and sight glass
614 must be large enough height-wise to handle the
product volume changes that might occur during a
measurement segment, yet small enough in diameter that
level changes can be measured precisely. If the diameter
of the measurement cylinder 612 is too large, there is a
loss of precision in the ability to measure volume
changes in the pipeline. If its diameter or length is
too small, the apparatus may not be able to accommodate
the volume changes that occur during a measurement
segment (whether due to a leak or to thermal influences).
The measurement cylinder 612 can be configured so that it
is longer than the pressure cylinder 610, extending above
and/or below it; this will permit the leak detection
system to accommodate even larger leaks and larger
thermally induced volume changes.

As indicated above, the size of the pressure and
measurement cylinders 610, 612 will depend on the
application. Several examples of typical cylinder
geometries are given below. When used to test the
larger-capacity pipelines associated with ASTs containing
petroleum products, the pressure cylinder might be
approximately 16 inches in diameter and 36 to 48 inches
high, and the measurement cylinder 2 to 2-1/2 inches in
diameter and at least the same height as the pressure
cylinder. When used to test the smaller-diameter lines
associated with most USTs containing petroleum products,
the pressure cylinder would typically be 4 to 6 inches in
diameter and 12 to 24 inches high, and the measurement
cylinder 1 to 1-1/2 inches in diameter and approximately
the same height as the pressure cylinder. Both of these
typical cylinder geometries can be shown to accommodate a
wide range of testing conditions at AST and UST
facilities.

The general approach to testing a pipeline with
either of the two embodiments of the device shown in
FIGS. 12 and 13 is, as with the other embodiments shown
in FIGS. 1 and 6, to divide a test into three or more
distinct "measurement segments". The measurement
segments are used in different combinations to obtain
both the temperature-compensated volume rate between the
average of the highest and the lowest pressures (test
result) and an estimate of the error in the test result
(test error). For example, when two of three measurement
segments are conducted at two different pressures, an estimate can be made of the difference in temperature-compensated flow rate between the two pressures; when three contiguous or three alternating measurement segments are conducted at the same nominal pressure, an estimate can be made of the error in temperature compensation volume rate. This error estimate includes the error in temperature compensation, level readings, and uniformity of leak rate. The number of segments, the level of pressure during each segment, and the sequence of high- and low-pressure segments are all application-dependent.

For a manually conducted leak detection test, a high-low-low-low data collection protocol can be used, where the higher pressure is the test pressure and the lower one is atmospheric (i.e., zero-gauge pressure). The test pressure can be established by means of either a pump or bottled gas, and the lower pressure is obtained by simply opening V3 and allowing the vapor to be released. Provided that the pressure cylinder 610 has a large enough diameter and that it contains a large enough volume of vapor, pressure in the line will not change significantly during any of the four measurement segments unless there is a very large change in the volume of liquid in the line.

When the apparatus in FIG. 12 is to be used to conduct such a high-low-low-low test, V1 and V2 are opened, V3 is closed, and the transfer pump is turned on until both the pipeline and apparatus have been pressurized. Product will enter the pressure cylinder 610 until the pressure in the vapor space of that cylinder is equal to the pressure in the line. (As stated above, if pressure cylinder 610 already contains enough liquid for the conduct of a test, it can be pressurized with a bottled gas such as nitrogen using the apparatus in FIG. 13.) Once the liquid in sight glass 614 reaches a constant level, the apparatus is fully pressurized and the test can begin. At this point, the transfer pump (or the connection to the bottled gas) is
turned off and V2 is closed. Any volume changes in the
line during the measurement segment are reflected as
level changes in the measurement cylinder assembly 616.
V3 is then opened, releasing vapor, and the pressure is
lowered to zero. Once the system has been depressurized,
V3 is closed, and V2 is opened so that the liquid in the
measurement cylinder 612 comes into equilibrium with that
in the pressure cylinder 610. V2 is then closed in
preparation for the next segment, conducted at
atmospheric (zero gauge) pressure. The process is
repeated twice more to complete a test.

FIG. 14 illustrates a typical test sequence. The
data collection portion of this leak detection test takes
26 minutes. There are four 5-minute segments during
which level measurements are made. Each 5-minute segment
is separated from the next by a 2-minute interval that
allows the test operator to depressurize the line by
opening and closing the appropriate valves. This 2-
minute interval also serves to let the level of liquid in
the measurement cylinder stabilize after the line has
been depressurized.

At the beginning and end of each level-measurement
segment, the test operator reads and records the level of
the liquid product in the sight glass 614 attached to the
measurement cylinder 612. For high performance, this
reading should be made to the nearest 1/16 inch or
better; even if the manual readings are not this
accurate, system performance may still be acceptable.
This leak detection test requires eight measurements in
all, one at the beginning and one at the end of each of
the four measurement segments. The first six (made in
this test sequence at 0, 5, 7, 12, 17, and 21 minutes
after the start of a test and shown on the time line in
FIG. 14) are used to compute the test result. The last
six (made in this test sequence at 7, 12, 17, 21, and 26
minutes) are used to compute the test error.

FIG. 15 illustrates an embodiment of the device
implemented with an electronic sensor for measuring the
level changes in the measurement cylinder. This
1 embodiment is similar to the one in FIG. 12, but can be
2 implemented using the apparatus shown in FIG. 13 as well.
3 In this electronic embodiment, a differential pressure
4 sensor 626 is used; however, any type of level sensor
5 with acceptable precision would be usable. The only
6 difference between the embodiment in FIG. 12 and that in
7 FIG. 15 is that the former use a tape and a sight glass
8 614 for measuring level changes and the latter uses an
9 electronic sensor 626. This sensor has one port 628
10 connected to the measurement cylinder below the liquid
11 level and one port 630 connected to the measurement
12 cylinder above the liquid level. The difference in
13 pressure can be used to determine changes in liquid
14 level, and the sensor need only have a precision equal to
15 that obtained by a person reading an inexpensive ruler.
16 As mentioned above, when the measurement cylinder is
17 properly sized, it makes little difference whether the
18 level readings are made manually or electronically; the
19 performance of the leak detection system will be very
20 nearly identical in either case. FIG. 16 shows an
21 embodiment with a capability for both manual and
22 electronic measurements. This embodiment allows a manual
23 test to be conducted and the level-change data to be
24 collected and archived for later data quality assurance
25 and auditing.
26 What is claimed is:
CLAIMS

1 1. An apparatus for detecting a leak in a pressurized pipeline system containing a liquid product by measuring the flow rate due to a leak while compensating for thermally-induced volume changes, comprising:
   (a) a pressure vessel for maintaining approximately constant pressure during a test measurement period;
   (b) a measurement vessel connected to the pressure vessel by liquid communication means and vapor pressure communication means, the measurement vessel sized to permit the measurement of liquid product volume changes to a pre-determined level of sensitivity;
   (c) valve means for opening and closing the liquid communication means between the pressure vessel and the measurement vessel, whereby liquid communication between the pressure vessel and the measurement vessel is prevented during a test measurement period;
   (d) pressure adjustment means for adjusting the pressure within the pressure vessel, measurement vessel, and pipeline system so that the apparatus can be operated at multiple pressures;
   (e) measurement means for determining the change in volume of liquid product in the measurement vessel due to changes in volume in the pipeline during a test measurement period; and
   (f) connection means for connecting the pressure vessel and the measurement vessel to the pipeline system, whereby liquid product from said pipeline system can enter and partially fill said pressure vessel and measurement vessel, and said measurement vessel is in liquid communication with the pipeline system during a test measurement period.

1 2. The apparatus of claim 1, wherein the pressure adjustment means comprises valve means for releasing vapor pressure from the pressure vessel and measurement vessel.
3. The apparatus of claim 1, wherein the pressure adjustment means comprises valve means for releasing liquid product from the pressure vessel and measurement vessel.

4. The apparatus of claim 1, further comprising means for pressurizing the pressure vessel, measurement vessel, and pipeline system to a desired test period measurement pressure.

5. The apparatus of claim 4, wherein the pressurization means comprises a pump pressurization system in communication with the pressure vessel and measurement vessel.

6. The apparatus of claim 4, wherein the pressurization means comprises a gas pressurization system in communication with the pressure vessel and measurement vessel.

7. The apparatus of claim 1, wherein the measurement means comprises a sensor to measure changes in the level of liquid product in the measurement vessel.

8. The apparatus of claim 7, wherein the measurement means comprises a ruled sight glass, whereby changes in the level of liquid product in the measurement vessel may be visually determined.

9. The apparatus of claim 7, wherein the cross-section of the measurement vessel is constant for different product measurement levels, thereby simplifying conversion of height to volume.

10. The apparatus of claim 1, wherein the measurement means comprises a differential pressure sensor, whereby changes in the level of liquid product in the measurement vessel are measured by sensing the pressure changes of the product within said measurement vessel with reference
6 to the pressure of the gas vapor over the measurement
7 vessel and the pressure vessel.
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) : G01M 3/28
US CL : 73/40.5R
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
U.S. : 73/40.5R, 49.2, 49.1, 149, 302, 303, 328, 332

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>US, A, 3,910,102 (McLEAN) 07 October 1975, entire document</td>
<td>1-10</td>
</tr>
<tr>
<td>A</td>
<td>US, A, 4,114,426 (McLEAN) 19 September 1978, entire document</td>
<td>1-10</td>
</tr>
<tr>
<td>A</td>
<td>US, A, 4,807,464 (JANOTTA) 28 February 1989, entire document</td>
<td>1-10</td>
</tr>
<tr>
<td>A</td>
<td>US, A, 4,893,498 (JENSEN) 16 January 1990, entire document</td>
<td>1-10</td>
</tr>
<tr>
<td>A</td>
<td>US, A, 4,918,968 (HOFFMAN) 24 April 1990, entire document</td>
<td>1-10</td>
</tr>
</tbody>
</table>

Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents:
  *A* document defining the general state of the art which is not considered to be part of particular relevance
  *E* earlier document published on or after the international filing date
  *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
  *O* document referring to an oral disclosure, use, exhibition or other means
  *P* document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"a" document member of the same patent family

Date of the actual completion of the international search: 02 FEBRUARY 1995
Date of mailing of the international search report: 03 APR 1995

Name and mailing address of the ISA/US Commissioner of Patents and Trademarks
Box PCT
Washington, D.C. 20231
Facsimile No. (703) 305-3230

Authorized officer: MICHAEL J. BROCK
Telephone No. (703) 305-4700

Form PCT/ISA/210 (second sheet)(July 1992)*