

## Detecting Very Small Casing Leaks Using the Water-Brine Interface Method

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### ABSTRACT

The U.S. EPA requires that all injection wells be tested every five years to determine if there are significant leaks in the casing. The traditional way to test is to set a temporary plug at the bottom of the casing and conduct a pressure test. Unfortunately, there are problems that complicate doing this for solution mining wells, such as difficulty in tightly seating the packer against scale that has built-up in the casing and the need to depressure the cavity, which disrupts production.

The members of the Salt Institute have developed a method whereby brine in a well is displaced by water to the bottom 50 feet of the well and the pressure measured. If there is a leak, the water-brine interface moves up the casing, and brine flows from the cavern into the bottom of the casing. The higher specific gravity of the additional brine causes the wellhead pressure to drop.

A simple measure of wellhead pressure will not discriminate between a casing leak and a change in cavern pressure; this is usually significant because cavern pressure is rarely constant. The problem is overcome by using a second well (or the tubing of a single well cavern) to monitor changes in cavern pressure.

By taking pressure measurements over an eight hour period and by using measuring devices with a sensitivity of at least 0.1 psi (such as traditional deadweight gauges), leaks as small as one gallon per hour can be reliably detected. The problem of seating a packer is avoided and production disruption is minimized by not having to depressure the cavern. In a gallery with at least two other connections to the cavern it is possible to operate the other wells while the test is being conducted.

The paper describes both the theory and practical application of the test method and the results of over 50 tests.

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### INTRODUCTION

It is very important that brine-wells be operated so that they do not contaminate underground sources of drinking water. According to the Chemical Manufacturers Assoc. (Chemecology, 1991) 97% of the earth's water is saltwater and 2% is glacier ice that is far removed from the people who need it. This leaves only 1% for mankind. Of the 1% for mankind, 3% is surface water and the rest is ground water that could be contaminated by leaking wells. In the United States more than half the population is dependent on ground water, including 90% of the rural population.

The U.S. Congress has enacted legislation, known as the Safe Drinking Water Act (42 U.S.C. 300h et seq.), to protect underground sources of drinking water from contamination by underground injection. To implement the legislation, the U.S. Environmen-

tal Protection Agency (U.S. EPA) has developed rules, commonly known as the Underground Injection Control Program (U.S. Code of Federal Regulations, 40 CFR 144). One of the cornerstones of the Underground Injection Control Program is the assurance that the mechanical integrity of the wells is maintained. Mechanical integrity is defined as the absence of significant leaks in the casing, tubing or packer and the absence of significant fluid movement into an underground source of drinking water through vertical channels adjacent to the injection well-bore. The rules require that mechanical integrity be demonstrated at least every five years.

This paper describes the water-brine interface method for testing for significant leaks in the casing. The method has recently been approved by the U.S. EPA (See the Federal Register at 57 FR 1109, No. 7 of January 10, 1992).

## THE TRADITIONAL TUBING AND PACKER METHOD FOR TESTING FOR CASING LEAKS

As background, the traditional method for demonstrating mechanical integrity is to depressure the cavern, run in a packer on tubing and use it to form a plug at the bottom of the well. Fluid is then injected to raise the pressure at the wellhead to normal operating pressure (or in some instances, the maximum permitted operating pressure), the wellhead is then shut-in and the pressure monitored. Each regulatory agency has its own pass/fail criterion based on the local geology and hydrology. However, a typical criterion is for pressure to drop less than 5% in 15 minutes. A leak of 1.22 gallons per hour will cause a 5% pressure drop in 15 minutes for a well 3000 ft (914.4 m) deep, with 7 inch (17.8 cm) diameter casing and a starting test pressure of 300 psi (21.09 kg/cm<sup>2</sup>). The leakage rate can be easily calculated using formula (1).

$$L = Kc \times (P1 - P2) \times Cv \times D / T \quad (1)$$

where: L = leakage rate (gallons per hour); Kc = coefficient of compressibility for brine  $3.4 \times 10^{-6}$  (decrease in unit volume per unit volume per psi); P1 = wellhead pressure at start of test (psi); P2 = wellhead pressure at end of test (psi); Cv = capacity of casing, excluding tubing (gallons/foot); D = depth from wellhead to plug (feet); T = duration of test (hours). The formula has been validated in field tests.

Although the traditional tubing and packer method has excellent sensitivity, there are several problems with its use. Frequently scale deposits in an irregular pattern on the casing wall, making it difficult to set a packer so that it does not leak. If there is a significant pressure drop, additional tests must be run to determine if there really is a casing leak or simply a packer leak.

If the well contains tubing, it must be removed to install the packer and then reinstalled when the test is complete. If the bottom of the tubing is initially buried in a rubble pile, it is virtually impossible to reinsert it into the rubble pile when the test is completed, losing the tubing's value as a "deep straw" to draw the saturated brine off the bottom.

Because most caverns operate under enough pressure at the production wellhead to cause the brine to flow to the processing plant, the entire cavern must be depressured while running in and removing the tubing and packer. This means that not only must the well being tested be taken out of service, but also all other wells in the gallery must be taken out of service. Taking all the wells in the gallery out of

service may result in significant production disruption.

Finally, testing for mechanical integrity using the tubing and packer method is costly.

Because of these concerns, the Salt Institute sponsored the development of an alternative method, known as the water-brine interface method. This paper discusses the underlying theory of the method, its practical application and the results of having used it on more than 50 wells.

## THE WATER-BRINE INTERFACE METHOD

### Underlying principle

The underlying principle is very simple. Consider the following example. A two-well gallery consists of wells T and R, well T is the well to be tested and well R is a reference well (the use of the reference well will be explained). For this example, water is normally injected down well R and brine is produced up well T. To start the test, well T is shut in and injection through well R continues for a short time to build up the pressure in the cavern. Injection is then stopped and well R is back-flowed to fill the casing with fluid of the same specific gravity as the fluid in the cavern; this is indicated by repeat samples at the wellhead having the same specific gravity. Well R is then shut in and water is injected down well T in just the right quantity to fill all but the bottom 50 feet. The fluid in the cavern compresses slightly, the cavern expands slightly and the cavern pressure increases. The amount of cavern pressure increase depends on the amount of water that is injected, the volume of the cavern, and the flexibility of the rock that surrounds the cavern, all site specific factors. The wellhead pressure at well R increases by the same amount as the cavern pressure increases. The wellhead pressure at well T increases due to the cavern pressure increasing and due to replacing the brine in the casing with the lower specific gravity water. The increase in wellhead pressure at well T can be calculated from formula (2).

$$PT2 - PT1 = [K \times (SPGR1 - SPGR2) \times (D2 - D1)] + (PR2 - PR1) \quad (2)$$

where: PT2 = wellhead pressure at well T after injecting the water (psi); PT1 = wellhead pressure at well T before injecting the water (psi); K = 0.4331 (psi/ft), a conversion constant which is the pressure gradient for fresh water; SPGR1 = the specific gravity of the fluid below the interface; SPGR2 = the specific gravity of the fluid above the interface; D2 = depth from the wellhead to the final depth of the interface (ft); D1 = depth from the wellhead to the initial depth of the interface (ft). (When injecting water to establish the interface, the interface is ini-

tially at the wellhead and  $D1 = 0$ );  $PR2$  = wellhead pressure at well R after injecting the water (psi);  $PR1$  = wellhead pressure at the well R before injecting the water (psi).

Continuing the example, if there is a leak in well T and some of the water is lost, brine from the cavity will flow into the bottom of the well. The cavern pressure will drop and this will be reflected by a drop in the wellhead pressure of well R.

The wellhead pressure of well T will also drop, in part because the fluid in the casing has a higher specific gravity and in part because of the drop in cavern pressure. The wellhead pressure at well R will drop only because of the drop in cavern pressure.

Formula (2) can be rearranged so that if the wellhead pressures at the start and end of a test are known, then the amount of interface movement can be calculated. If the amount of interface movement is multiplied by the capacity of casing (e.g., gallons/foot) and divided by the duration of the test, then the leakage rate can be easily calculated, formula (3).

$$L = \frac{C_v \times [(PT2 - PT1) - (PR2 - PR1)]}{T \times K \times (SPGR1 - SPGR2)} \quad (3)$$

All terms are as defined for formulas (1) and (2).

Formula (3) represents the underlying principle of the water-brine interface method. It is quite simple and small casing leaks can be easily detected if the method is properly applied.

Figures 1, 2 and 3 illustrate the underlying principle. Figure 1 shows a cavern after the wells are shut in and the casing of well R is filled with fluid of the same specific gravity as the cavern fluid at the bottom of the well but before water is injected in well T. Figure 2 shows the cavern just after the water is injected in well T. Figure 3 shows the cavern after eight hours with a leak of 0.5 gallons per hour. The wellhead pressures for the three conditions are tabulated and compared in Table 1. A leak of 0.5 gallons per hour for eight hours caused a change in the difference of the wellhead pressures of  $-0.21$  psi ( $0.0148$  kg/cm<sup>2</sup>) or  $-0.026$  psi ( $0.00183$  kg/cm<sup>2</sup>) per hour.

The sensitivity of the test depends on the precision in measuring the pressures, the difference in the specific gravities of the fluids above and below the interface and the duration of the test. Dead-weight pressure gauges are advertised to have a sensitivity of  $0.10$  psi ( $0.00703$  kg/cm<sup>2</sup>) but in practice they have been found to have a sensitivity of  $0.02$  psi ( $0.00141$  kg/cm<sup>2</sup>). An electronic pressure gauge with a sensitivity of  $0.01$  psi ( $0.000703$  kg/cm<sup>2</sup>) is available.

The practical application of the method is described in the next section.

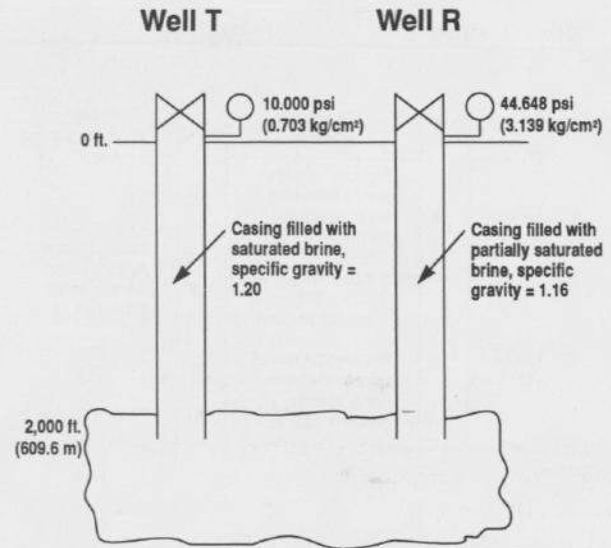


Fig. 1. Cavern with wells shut in, before injecting water in well T.

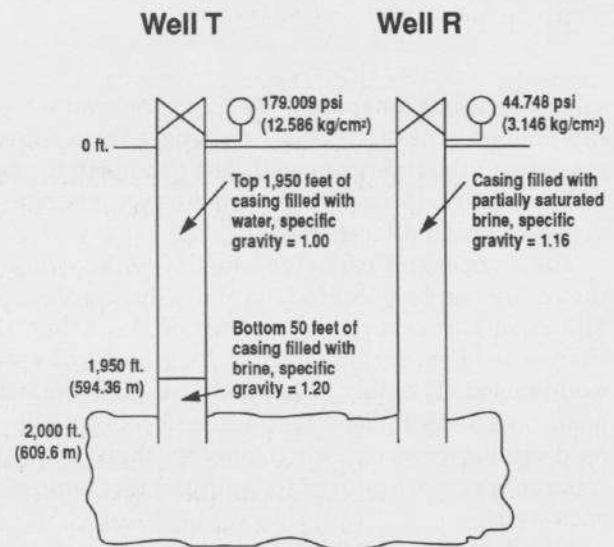


Fig. 2. Cavern with wells shut in. Water has been injected in well T to fill top 1950 ft (594.4 m). Assume injecting water raises cavern pressure  $0.100$  psi ( $0.007$  kg/cm<sup>2</sup>).

### Practical application

The test is eminently practical, provided attention is paid to the following details:

(1) Always use a reference well (in a single well cavern the annulus is what is tested and the tubing is the reference well). Injecting the water will raise the cavern pressure, and a leak will reduce it. If the cavern contains undersaturated brine, and it probably will if the cavern has recently been used for solution mining, dissolving will take place in the cavern which will cause the cavern pressure to drop. As indicated previously, the problem is easily re-

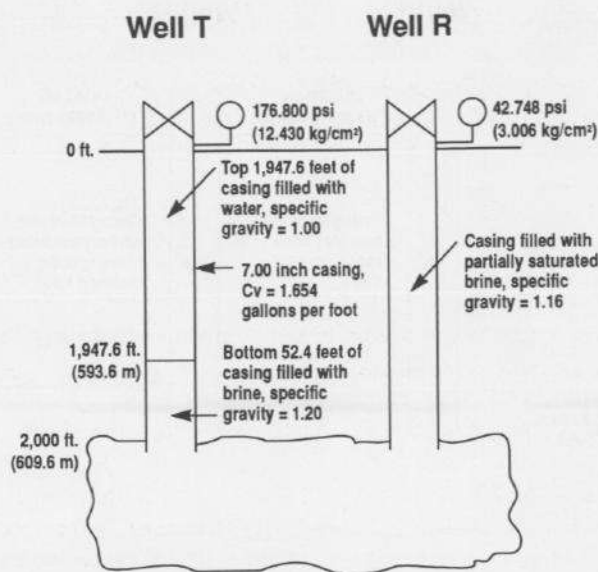


Fig. 3. Cavern with wells shut in eight hours after injecting water in well T. Due to dissolving, assume cavern pressure drops 2,000 psi (0.1406 kg/cm<sup>2</sup>). Well T has a leak of 0.5 gallons (1.89 l) per hour.

solved by using a separate well as a reference well. Any change in cavern pressure changes the wellhead pressure of the reference well. The change in the test well pressure is then adjusted for the change in pressure of the reference well.

There is a significant side benefit — other wells in the cavity can be operated normally during the test. The cavern pressure may go up or down but the change is of no significance as long as a reference well is used. The only requirement is that the wellhead pressures for the test and reference wells be read simultaneously, which means there must be separate pressure gauges for both the test and reference wells.

(2) Fill the reference well with cavern fluid. If the reference well is filled with water but has a leak, brine will flow into the reference well and the wellhead pressure will drop. This in turn could mask a leak in the test well. The problem is avoided by filling the reference well with fluid from the cavity before starting the test. If there is a leak, the fluid that is lost is replaced with fluid of the same specific gravity and therefore, the leak is of no significance to the test. (The leak is detected when the reference well becomes the test well at a later time.)

(3) Remove any salt that has crystallized in the casing of the test well before starting the test. If the salt in the casing of the test well goes into solution during the test, the specific gravity of the fluid in the test well increases and the wellhead pressure will drop, possibly resulting in a false negative report. To

TABLE 1

Wellhead pressures (psi) for the example in Figs. 1–3

	Well T	Well R	Difference	Change in difference
Before injecting water	10.000	44.648	-34.648	
After injecting water	179.009	44.748	134.261	-168.909
Eight hours later with a leak of 0.5 gallons/hour	176.800	42.748	134.052	-0.209

avoid this, the test well must be washed with water or undersaturated brine in advance of the test. Note that this is required for testing a production well but not for testing an injection well as there will not be crystallized salt in the casing of an injection well.

(4) Allow 36 hours for the liquids in both wells to come to temperature equilibrium. For example, cold water might be injected in the test well, which in turn is heated by the formation. Warmer water has a lower density and expansion will move the interface down. A 25°F (13.9°C) temperature increase in a 2000 ft (609.6 m) well will cause the interface to move down by 12.5 ft (3.66 m), enough to mask a leak, causing a false positive result. In a field test, temperature logs were run every 12 hours after injecting the water and there was no significant temperature change after 36 hours.

(5) If there is a leak in the casing and the interface moves up to it during the temperature equilibrium period, the leak may not show up during the actual test. Check that the difference in wellhead pressures between the test and reference wells is essentially the same before and after the 36 hour temperature equilibrium period.

(6) Inject the water at a rate to cause the interface to move down less than 20 ft (6.1 m) per minute. In a field test at an injection rate of 20 ft per minute, it was found that the salinity changed from 15% saturated to 85% saturated over a 37 ft (11.3 m) range. This means that for a distance approximately 20 ft (6.1 m) above the nominal depth of the interface, the test is somewhat less sensitive.

(7) Dissipation of the interface due to diffusion of the brine is not a problem because it happens so slowly. This is evidenced by experiments with solar heating ponds (shallow ponds partially filled with brine and then water floated on top). There are reports of the brine staying on the bottom for weeks at a time while being heated by solar power to 98°C,

TABLE 2  
Wellhead pressures for a 19 hour test

Elapsed time (h)	Test well pressure (psi)	Reference well pressure (psi)	Pressure difference (psi)	Change from pressure difference at start (psi)
Start	381.37	336.62	44.75	
2	381.07	336.31	44.76	+0.01
5	380.70	335.98	44.72	-0.03
19	379.22	334.47	44.75	0.00

at the same time the temperature of the water at the surface remained close to ambient temperature (Bertram, 1991). Inasmuch as diffusion is not a problem in solar ponds, it is not of concern in a brine-well where the temperatures are much lower and the duration is for only a few days.

(8) The interface should not be placed below the bottom of the casing. There is a small chance that a pool of water will remain below the bottom of the casing and it will flow into the casing instead of the cavern fluid in the event of a leak. This potential problem can be avoided by placing the interface 50 ft (15.24 m) above the bottom of the casing. While this results in the bottom 50 ft of the well not being tested, it usually is of no significance.

(9) Changes in atmospheric pressure and lunar tides have no affect. This is because the change affects the test well and reference well identically.

(10) If the sensitivity is low due to a small difference in the specific gravities, fill the test well with oil rather than water.

(11) Use pressure readings and formula (2) to determine the amount of water to inject. The proper amount of water to inject is not known directly because of scale inside the casing. In using formula (2), D1 will equal 0 and D2 the target depth for the interface. Measure the two wellhead pressures before injection starts and then periodically as water is injected. The interface can be easily placed within a few feet of the target depth.

(12) If not otherwise known, use formula (2) to determine the depth to the bottom of the casing. Measure the wellhead pressures before injecting water and then inject water until PT2 is essentially constant, which will happen when the casing is filled with water. Formula (2) may then be solved for D2, which will be the depth to the bottom of the casing.

(13) Install blanks at the wellhead rather than relying on valves. The valves will almost certainly leak and it is a waste of time to run a test without first installing blanks.

(14) Do not change the elevation of the pressure gauges. If the two fluids have a specific gravity difference of 0.2, a one-foot drop in elevation of a pressure gauge will change the pressure differences by the same amount as the interface moving up by 5 ft; this may be enough to fail the test.

(15) Rather than just taking measurements at the start and end of the test period (typically eight hours), take readings every two hours. The change in pressure difference should be essentially the same for each two hour period. If it is not, there is probably at least one erroneous reading.

**Results from using the water-brine interface method**

In June 1989, a well was tested for 19 hours with the results shown in Table 2. The test and reference wells were in a cavity in which other wells were being used for injection and brine production at a rate of several hundred gallons per minute. Note that during the 19-hour period the reference well pressure dropped by over 2 psi but the test well pressure dropped an identical amount and the pressure difference remained at 44.75 psi, indicating that the well did not have a casing leak.

At the end of the 19-hour period, 10 gallons of water was drawn from the test well to demonstrate the validity of the test. The capacity of the casing was 2.56 gallons (9.69 l) per foot so removing 10 gallons (37.8 l) of water moved the interface up 3.9 ft (1.19 m). The wellhead pressure difference between the test and reference wells should have changed by 0.34 psi (0.024 kg/cm<sup>2</sup>), calculated as follows:

$$(1.200 - 1.000) \times 3.9 \text{ ft} \times 0.4331 \text{ psi/ft} = 0.34 \text{ psi} \\ (0.024 \text{ kg/cm}^2)$$

Wellhead pressures were measured before and after withdrawing 10 gallons of water and they are shown in Table 3. The measured change in pressure

TABLE 3  
Wellhead pressures for simulating a ten gallon leak

	Test well pressure (psi)	Reference well pressure (psi)	Pressure difference (psi)	Change from pressure difference at start (psi)
Before removing 10 gallons of water	379.22	334.47	44.75	
After removing 10 gallons of water	378.84	334.42	44.42	-0.33

difference of 0.33 psi (0.023 kg/cm<sup>2</sup>) is essentially identical to the calculated change of 0.34 psi (0.024 kg/cm<sup>2</sup>), validating the test method. On other occasions the method was similarly validated.

Between 1988 and 1990, over fifty wells were tested to provide data to evaluate the efficacy of the test and refine the methodology. The results of the testing were incorporated in the U.S. EPA final approval and the preceding discussion.

Of all the wells tested, one had a leak which allowed gas to flow into the casing. No significant fluid leaks from the casing to the formation were discovered.

## CONCLUSIONS

The water-brine interface method has the same sensitivity as the traditional tubing and packer method, but none of the disadvantages: The problem of packer leaks is avoided, tubing does not need to be removed and reinstalled, only the test well and reference well must be taken out of service (other wells in the gallery may continue to operate), and the cost of the water-brine interface method is substantially less than the cost of the tubing and packer method.

## ACKNOWLEDGEMENTS

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## APPENDIX: Calculations for Figs. 1-3.

### Figure 1

1. Assume wellhead pressure at well T is 10.00 psi (0.703 kg/cm<sup>2</sup>)
2. Pressure at bottom of well T: 10 psi + (1.20 × 0.4331 psi/ft × 2000 ft) = 1049.440 psi (73.7861 kg/cm<sup>2</sup>)
3. Pressure of bottom of well R = pressure at bottom of well T
4. Wellhead pressure of well R: 1049.440 psi - (1.16 × 0.4331 psi/ft × 2000 ft) = 44.648 psi (3.1392 kg/cm<sup>2</sup>)

5. The difference in well head pressures: 10.000 psi - 44.648 psi = -34.648 psi (2.4361 kg/cm<sup>2</sup>)

### Figure 2

1. Assume that injecting water to fill the top 1950 ft (594.36 m) of well T raises the pressure at the bottom of well T by 0.100 psi (0.00703 kg/cm<sup>2</sup>)
2. Pressure at bottom of well R: 1049.440 + 0.100 = 1049.540 psi (73.7932 kg/cm<sup>2</sup>)
3. Pressure at bottom of well T = pressure at bottom of well R
4. Wellhead pressure of well T: 1049.540 psi - 0.4331 psi/ft [(1.200 × 50 ft) + (1.000 × 1950 ft)] = 179.009 psi (12.58612 kg/cm<sup>2</sup>)
5. Wellhead pressure of well R: 1049.540 psi - (1.16 × 0.4331 psi/ft × 2000 ft) = 44.748 psi (3.1462 kg/cm<sup>2</sup>)
6. The difference in wellhead pressures: 179.009 psi - 44.748 psi = 134.261 psi (9.4399 kg/cm<sup>2</sup>)
7. The change in difference between wellhead pressures in Fig. 1 and Fig. 2: 134.261 psi - (-34.648 psi) = 168.909 psi (11.876 kg/cm<sup>2</sup>)

### Figure 3

1. A leak of 0.5 gallons/hour (1.893 l/h) occurs in well T for 8 h, for a total loss of 4.000 gallons (15.142 l).
2. Assume the casing of well T has a capacity of 1.654 gallons/ft (1.908 l/m).
3. The distance the interface moves up: 4.000 gallons/1.654 gallons/ft = 2.4 ft (0.73 m)
4. Assume that due to dissolving caused by previously injected fluid, cavern pressure drops during the 8 h period by 2.000 psi (0.141 kg/cm<sup>2</sup>)
5. Pressure at bottom of well R: 1049.540 - 2.000 = 1047.540 psi (73.653 kg/cm<sup>2</sup>)
6. Pressure at bottom of well T = pressure at bottom of well R: = 1047.540 psi (73.653 kg/cm<sup>2</sup>)
7. Wellhead pressure of well T: 1047.540 psi - 0.4331 psi/ft × [(1.200 × 52.418 ft) + (1.000 × 1947.583 ft)] = 176.800 psi (12.431 kg/cm<sup>2</sup>)
8. Wellhead pressure of well R: 1047.540 psi - (1.16 × 0.4331 psi/ft × 2000 ft) = 42.748 psi (3.006 kg/cm<sup>2</sup>)
9. The difference in wellhead pressure: 176.800 psi - 42.748 psi = 134.052 psi (9.425 kg/cm<sup>2</sup>)
10. The change in difference between wellhead pressures in Figs. 2 and 3: 134.052 psi - 134.261 psi = -0.209 psi (-0.0147 kg/cm<sup>2</sup>)
11. As a check, the change in difference between wellhead pressures is a function of the distance the interface moved and the specific gravity difference: (1.20 - 1.00) × (-2.418 ft) × 0.4331 psi/ft = -0.209 psi (-0.0147 kg/cm<sup>2</sup>)