Ambient Pressure Monitoring

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Contents:

I. BACKGROUND

Ambient pressure monitoring within geological reservoirs used for industrial waste disposal through injection wells (Class I) is required by 40 CFR Part 146. The extent of the monitoring program at any site will be determined by the susceptibility for fluid movement at that site, but there is a minimum requirement that a pressure falloff test be conducted each year. Fracturing, whether intentional or accidental, can be identified and changes in fracture half length may be determined through pressure fall-off testing. If reservoir boundaries exist within a radius of investigation determined by the length of the test and magnitude of pressure change, they can be identified. Significant loss of liquid from the injection interval due either to transmissive fracturing or leaking containment strata may also be identified. For wells which have been subject to the no-migration petition demonstration for exemption from the land disposal restrictions under 40 CFR Part 148, this testing can provide confirmation that the pressure increase within the injection interval is less than that predicted and assure that the modeled parameters represent actual conditions. Formation damage can be assessed and remedial action planned or evaluated. This information will enhance the protection of underground sources of drinking water.

II. PURPOSE OF GUIDANCE

According to 40 CFR &sect 146.13(e) and &sect 146.68(e), "Based on a site specific assessment of the potential for fluid movement from the well or injection zone, and on the potential value of monitoring wells to detect such movement, the Director shall require the owner or operator to develop a monitoring program. At a minimum, the Director shall require monitoring of the pressure buildup in the injection zone annually, including, at a minimum, a shut down of the well for a time sufficient to conduct a valid observation of the pressure falloff curve".

This guidance has been developed by the USEPA in Region V to assist operators in planning, conducting, and analyzing the results of a basic ambient pressure monitoring program using only the injection well(s). It outlines a comprehensive program of reservoir evaluation which we believe is warranted in many cases. We recognize that what is appropriate at one site may not be appropriate at other sites. This guidance should not be regarded as immutable. However, any ambient testing program will be judged inadequate if it does not adequately address the concerns which are outlined below.

The purpose of the minimum requirement is to identify conditions in the injection zone which might indicate failure, or potential failure, of the containment system, that is, either the geological strata overlying the injection interval or the well construction. This can be done by comparing the increase of pressure in the zone with that predicted by the simulation performed during the petition process and/or by comparing annual determinations of reservoir characteristics. This will help identify an initiation of fracturing or an increase in the length of fractures, changes in the skin factor which might signal a need for well stimulation to allow injection at a lower pressure, or a decrease in the skin factor which might be indicative of significant dissolution of carbonate material around the well bore due to the injection of acidic wastes.

In order for the data gathered through the observation of the pressure falloff to be useful, certain preparatory steps must be taken and the test must be carried out in such a manner that the pressure response is reflective of the conditions within the injection reservoir. This guidance has been prepared to offer operators general recommendations in planning a basic ambient pressure monitoring program which will provide the information necessary to establish an annual record which accurately indicates changing conditions within the injection reservoir. The suggestions presented here are expected to lead to the development of data which will permit valid estimations of reservoir properties to be made. However, since the planning of tests must take geology, past operations, and on-site facilities into account, it remains the responsibility of the operator to develop testing methods which will provide adequate data for a meaningful analysis of reservoir conditions at each disposal facility. The requirement that a valid observation of the pressure falloff curve be made each year implies that the testing requirement is not satisfied until valid data are produced.

III. GENERAL PRINCIPLES

The pressure within an injection interval can be monitored in two ways. Observation wells which can be used for continuous or very frequent monitoring may be drilled or, periodically, the injection well itself can be used as a monitoring well. In addition to a determination of the average reservoir pressure within the radius of investigation of the tested well, a number of other important pieces of information about the reservoir can be determined from the data produced during the pressure falloff test. This information is needed because it will reflect changing conditions within the reservoir. In some cases, it may confirm that the basis upon which the exemption from the land disposal restrictions was granted is, or remains, valid.

The relationship of the pressure differential between the well bore and the aquifer being tested is the basis of falloff testing, which is only one of a number of reservoir testing methods based on the analysis of pressure transients. In such tests, measurable pressure responses of the reservoir to known flow rates are used to learn something about the physical characteris- tics of the reservoir. The tests are carried out in situ and, when properly designed and interpreted, give the best representation of reservoir characteristics available. Unfortunately, geological, hydrological, and even mechanical conditions can have complicating effects on the data upon which interpretation must be based. At the Director's discretion, ambient pressure monitoring may include pressure transient testing methods other than falloff testing.

The pressure falloff test is the simplest pressure transient test applicable to injection wells. Other tests include injectivity test, two-rate falloff test, step rate test (SRT), pulse test, and interference test. Each test has particular features which might make it more appropriate than other tests in specific situations. These features will be discussed along with planning and operation of each test.

It is expected that at least estimates of the most important reservoir properties, such as porosity and permeability, have been made. These estimates, and knowledge of the injectate viscosity, injection rate, and the compressibility of the rock-fluid system, allow estimation of adequate test duration and choice of range and sensitivity of the gauge. Because of the possibility of detecting boundary conditions during late times, the tests should not be terminated as soon as data necessary for determination of the rock properties near the well bore have been gathered. Rather, the test should be continued until observed pressure changes approach the limitations of the measuring device.

Variations from predicted results may occur because of mechanical effects due to the arrangement of the injection system and the changes in the reservoir parameters in the vicinity of the well due to the injection operations. Nevertheless, these predictions are valuable because they allow equipment and test procedures to be chosen which will best define the responses of the formation to a stimulus. If an appropriate testing program is designed, analysis will usually be straightforward; however some cases are more complex and certain data may not be reliably analyzed. The effects of wellbore storage, partial penetration, hydraulic fracturing, and slanted holes must be taken into consideration when analyzing well test data. Otherwise, estimates of formation permeabilities and skin factors may be inaccurate.

IV. CHOOSING THE PROPER TEST

Because the falloff test is the simplest test to run and is capable of determining the same information as the other tests of single wells, it is normally the test of choice. However, there are circumstances in which the standard falloff test may not produce usable data. The falloff test with no unusual modifications can be used if it is expected that a positive pressure will exist at the wellhead throughout the test procedure. If the well is expected to "go on a vacuum" after injection ceases, well bore storage may be so great that the necessary straight line portion of the pressure-time plot which reflects hydrologic properties of the aquifer cannot be reached. In this case, a two-rate falloff test (Earlougher, 1977) or a multi-well test is appropriate in order to eliminate changing wellbore storage effects.

Generally, an injectivity test can be combined with the falloff test because little additional time is required and, if the falloff test fails to develop the necessary information, the injectivity test may prevent the necessity of designing and executing a new testing program. Injectivity tests are particularly useful when very permeable zones have suffered significant amounts of damage and when high well bore storage obscures data during falloff testing.

In the event that two or more wells injecting into the same aquifer are available, the Director requires that multi-well tests (interference or pulse tests) be conducted as early as possible. These tests require at least one active (injecting) well and at least one pressure observation well. In multi-well testing, the flow rate at an active well is varied while reservoir response is measured at the observation well(s). These tests allow an opportunity to determine average properties through the body of reservoir rock between the wells involved in the test, the values of parameters which cannot be investigated using the falloff test, and largely eliminate the effects of skin and wellbore storage. In Region V, interference tests have been run at most facilities where more than one well exist during the course of the development of no-migration demonstrations. These tests serve to meet the requirement for multi-well testing if the data developed and submitted are adequate for full analysis.

In an interference test, a long duration modification of flow rate in one well creates a pressure disturbance in an observation well which can be analyzed to estimate reservoir properties. A pulse test provides equivalent data by using shorter pulses (with smaller pressure changes), but the analysis technique is more complicated. When a multi-well test is required, the interference test is preferred. Reasons for choosing to conduct a pulse test include; 1) less disruption of injection activities because the active well injects intermittently, 2) use of the cyclic pattern to recognize pressure transient arrival at the observation well if the amplitude is so small that the pressure change might be lost amidst background "noise", and 3) reservoir complexities which have been shown to render interference tests uninterpretable.

While the spatial relations of the wells involved in tests are limited to those of existing wells, every effort should be made to determine directional variations in reservoir properties. To do this, various combinations of injection and observation wells can be used. All the required multi-well tests need not be conducted in a single year if operational requirements make such testing impractical. Multi-well tests will not be an annual requirement. Subsequent to submission of interpretations of acceptable multi-well test data, additional multi-well testing might not be required at that site. Annual pressure falloff or injectivity tests should thereafter provide adequate data to monitor reservoir conditions.

If the relationship of flow rate to the injection pressure differential at the formation face is not linear, then a SRT must be run to determine the formation parting pressure. This test should be run in addition to, and should follow, other testing. SRTs may be required at any time at the Director's discretion.

V. PLANNING THE TEST PROCEDURE

The general relationship between injection rate, reservoir parameters, and fluid parameters to pressure response is well known. This relationship can be used in designing test procedures so that the range and sensitivity of pressure measuring devices and the length of testing periods can be chosen.

When planning multi-well tests it is very important to determine an injection rate which will produce a pressure change which is measurable at the observation well. In some cases, it may be necessary to use positive displacement pumps capable of injecting at higher pressures than the equipment normally used in order to generate the necessary injection rate. The requirement that multi-well tests be run at sites having more than one well will be waived only if the calculated pressure change will necessitate injection at a pressure or rate which exceeds permit limitations. If a waiver is desired, the basis for the request, with the limiting factors quantitatively described, must be presented.

Operational requirements may not allow the flexibility necessary to plan an effective multi-well test and the USEPA does not wish to interfere with production if it is possible to avoid such interference. Therefore, a plan for multi-well testing should be prepared. If circumstances become such that a multi-well test can be run, for example, a plant shut down may allow the disposal operations to be curtailed, then a multi-well test must be run.

The costs of testing can be reduced through careful planning. If there is a large amount of uncertainty in aquifer parameters and, hence, in expected performance, it may be most economical to use surface reading pressure gauges (SRPGs) located down hole because the reservoir responses can be monitored constantly. However, electronic memory recorders (EMRs) can provide comparable data quality at a fraction of the cost if there is little uncertainty involved in the operation. In addition to the electronic gauges, mechanical gauges of the Bourdon tube type are available. Each type has advantages. However, the use of electronic gauges with quartz crystal sensing elements is strongly recommended because of the superior long-term stability of the quartz gauges and the precision possible when these gauges are properly used. Difficulties in accurately reading pressures from the charts used in some mechanical gauges at short intervals during early time as well as inherently lower accuracy make the use of mechanical gauges undesirable.

In many cases, a short pilot test is useful to determine appropriate injection rates, data collection intervals, and other criteria. In such a test, the injection rate is lower than in the full scale test and the potential radius of investigation is limited. The test is capable of determining reservoir properties which will influence the early portions of the full-scale test and so that test design can accommodate well-specific conditions. This sort of test is recommended when there is considerable uncertainty concerning the reservoir parameters.

VI. EXECUTING THE TEST

At the start of any test, the reservoir pressure must be relatively stable. If the test to be run is a pressure falloff test, this is accomplished by maintaining injection at a constant rate for a period of time. For an injectivity test, the test does not begin until the reservoir pressure stabilizes. To ensure that the pressure is stable, the downhole pressure measuring device should be put in place to monitor the stabilization process for at least eight hours prior to beginning the pressure transient test. The stabilization process can be improved if the injection rate can be held constant for some time before the test process actually begins. The longer the period through which a constant rate is maintained preceding the test, the better the data quality is likely to be.

Either the normal injectate or fresh water may be used for testing. Fresh water is preferred if there is a possibility that inconsistencies in the density of the injectate might cause the pressure at the injection interval to vary significantly. The injection rate should vary by no more than five percent and, if the pump(s) normally used to inject cannot maintain a constant rate at the pressure found to be necessary to conduct the test successfully, then positive displacement pumps must be acquired for the test. Whenever injection rates are changed, including starting and cessation, the change should be made as quickly as possible. Valves or other regulators should be chosen with this capability in mind.

Since wellbore storage can be a major problem in interpreting test results, it may be necessary that the test be run using tubing and packer and/or other equipment or methods which will minimize this problem. If analysis shows that wellbore storage obscured the necessary data, the well must be retested using safeguards to eliminate the problem.

It is anticipated that SRPGs or EMRs placed down hole will normally be used in order to provide sensitivity and avoid errors due to the necessity of extrapolating pressures measured at the surface during injection phases of testing to the reservoir depth. Use of wellhead pressure gauges (face gauges) is discouraged although they may be used in some cases, such as for pressure measurements at the well used for injection during an interference test or during a falloff test when a positive pressure is maintained at the well head throughout the test. Any gauge used to measure wellhead pressure must be sensitive to pressure changes equal to one half of one percent (.005) of the range of the expected pressure change through the test. That is, if the pressure range is 300 psi, then the gauge must be sensitive to changes of 1.5 psi. Similarly, it must be possible to read the gauges with no loss in precision. These are minimum sensitivity requirements and the use of minimally suited equipment will not be adequate reason for failure to deliver useful data.

The preference for measurements using electronic measuring devices is to provide accuracy and sensitivity to allow for use of derivative curves to enhance the ability to characterize reservoir parameters and to detect change in reservoir responses. The SRPG or EMR should be located at the top of the perforated or open hole portion of the well if measurements during injection phases are to be used. When a wellhead measurement is used, the surface pressure should be extrapolated to this elevation (top of the open interval).

During most testing operations, the injection rate should be the maximum rate which can be held constant under the conditions at the site without exceeding the maximum injection pressure limitation. This will maximize pressure changes. There are a number of reasons why this is desirable: 1) The radius of investigation is increased when pressure changes are increased. 2) There is a certain amount of pressure "noise" within any reservoir due to stray transients. Greater pressure changes are less likely to be obscured by the background noise. 3) In the case of interference tests, a larger, more easily detected pressure change will be generated.

The injection pressure should not cause fracture opening. This will allow investigation of matrix properties which may be only slightly affected by the secondary permeability system. Testing at a higher injection rate may be required to identify changes in the secondary permeability system.

When SRPGs are available, it is strongly recommended that the capability to produce the plots needed to analyze the test be available at the well site. This will help ensure that good data are generated and false testing runs can be identified and aborted, saving both time and money. Similarly, when EMRs are used, plots produced at the well site can show whether the data gathered are usable and, if not, the well can be retested immediately.

In general, it is wise to record data as frequently as possible and then filter those which are unnecessary for analysis. The need for taking frequent readings at short duration is critical, particularly if permeabilities are high (fractures, caverns, etc.) and the pressure response at the observation well is almost instantaneous. The time interval at which readings must be recorded for submission may be varied as the test proceeds. During the early part of falloff and injectivity tests when the pressure is changing rapidly and wellbore effects may be dominant, the interval must be short. Readings should be made at intervals no longer than five seconds for the first ten minutes. For the next 20 minutes, pressure should be recorded at intervals no longer than 30 seconds. Pressure readings beyond this point can be taken at intervals based on the rate of pressure change and the total pressure change expected. An appropriate, maximum interval is the time required for the pressure to change by one percent. However, in no case should the intervals between measurements exceed 15 minutes. New determinations of interval length can be made hourly or at longer intervals.

In interference testing, the pressure measuring device should be placed into the observation well at least 12 hours prior to the initiation of the pressure transient which is to be measured in order to determine background effects. The interval at which data are recorded through the time period when the pressure transient is expected to reach the observation well should be no greater than one tenth of one percent (.001) of the length of time calculated for the pressure transient to reach the observation well. So, if the estimated travel time is 12 hours, then a 1.5 minute interval (24 hrs. x 60 mins./hr. x .001 = 1.44 mins.) is minimally appropriate.

VII. FALLOFF TEST PROCEDURE - AN EXAMPLE

The following is a suggested procedure for conducting an initial test of an injection well:

1. Stabilize injection into all nearby wells near their planned test rate(s) for at least 72 hours. (It is preferable that all injection be shut down but this is often not possible.) The injection rates, pressures, and specific gravities of injectate at all wells during this period should be recorded.
2. If a downhole pressure measuring device is to be used, run the pressure measuring device into the hole and position it while injecting. Monitor pressure until stable. If actual monitoring is not possible, a calculated stabilization time with an allowance for error can be used.
3. Shut in well at wing valve or by using a downhole shut-in tool. Begin pressure monitoring at short time intervals just before shut in.
4. Monitor reservoir pressure until stable. If actual monitoring is not possible because surface readout is not available, a calculated shut-in time with an allowance for error can be used.
5. After completing the falloff portion, begin the injectivity test at a single rate. This test should last the lesser of 24 hours or until the injection pressure stabilizes.
6. If a valid SRT has never been conducted, conduct a SRT. All SRTs must be run using down-hole pressure measurements. Select injec-tion rate steps so that at least three will have been completed before the pressure at the formation face reaches the lowest probable parting pressure (0.6 psi/ft x depth in feet). The time intervals should be equal and at least an hour in length unless the previous testing has indicated that pressure stabiliz-ation will occur in a lesser time. The SRT should be continued for at least two steps beyond the formation parting pressure. Following injection, measurements should continue until the closure pressure can be determined or measured pressure is relatively stable.
7. Remove the test tools from the well bore and return the well to regular service.

VIII. INTERPRETING THE TEST RESULTS

It is expected that the test will be evaluated by a person who is knowledgeable in the methods of pressure transient test analysis. A full, written report must be submitted. This report should include details of the operational and interpretational methods used, intermediate results, all necessary graphs, and the testing log kept by the engineer at the site. The graphs must include plots of the log of pressure change versus the log of time change with the log of the pressure derivative with respect to time as described in Bourdet et al., 1983, Pirard et al., 1986, and Bourdet et al., 1989, in order to confirm that the data used in the calculations are valid. These plots should be prepared and submitted along with, or on the same graph as, the type curves for comparison. In addition to the above described plots, graphs on Cartesian axes should be prepared to clearly show time and pressure relationships. The scales used should be appropriate for the range of significant change. When appropriate, supplementary graphs at expanded scales should be submitted. Adequate data must be submitted to allow construction of plots for independent analysis of all tests

If an iterative, matching process is used to find the best combination of reservoir parameter values to simulate the observed pressure responses, a graph, either log-log or semilog, of the observed data and the simulated data along with the pressure-derivative data should also be presented as confirmation that a valid match has been achieved. Other plots described below need not be presented unless specifically required.

At a minimum, the Horner method should be used to determine the permeability-thickness product. If appropriate, the test should be analyzed as a multiple rate test. Values of permeability, skin factor, pressure drop due to skin, effective well bore radius, and the condition ratio should be determined. When interference tests are run, reservoir storativity, porosity, and permeability and thickness should also be determined. The analysis should take into account viscosity differences between the native brine and injectate and the effect of temperature. It may be possible, particularly if data from an interference test are analyzed, to determine the approximate position of the waste front. Any boundary conditions or extraordinary reservoir conditions which can be inferred from the data should be noted and described to the extent possible. In the case of SRTs, analyses should be made at each flow rate as described by Felsenthal, 1974, and Singh et al., 1987. This allows unambiguous definition of the parting pressure and the effect of increased injection pressure.

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