# Airlift Testing In Exploration Coreholes

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**Abstract** Hydrogeologic studies at mining exploration sites rely on airlift-pumping tests because it is a relatively fast, simple, and accurate method of obtaining hydraulic conductivity values in deep fractured aquifers. A single data set from a typical packer-isolated airlift test can include falling-and rising-head slug sequences, discharge-rate decay from the constant-head pumping, and long-term recovery data. Slug tests need not be instantaneous to be analyzed by the Hvorslev method. Recovery from constant-head pumping can be analyzed by Theis methods, however, casing-storage effects can limit the use of the Theis analysis when the discharge rate is less than about 0.13 L/s (2 gpm).

**Keywords** Testing in exploration drillholes, airlifting, Theis analysis, Hvorslev analysis

## Introduction

Mining operations, especially in the early exploration, scoping, and pre-feasibility stages, include extensive HQ (78 mm diameter) diamond-core drilling programs. As a consequence, hydrogeological investigations for these early mine development stages are to a large extent based on hydraulic testing in slim holes, and this is best done by airlift pumping. Mine-development programs also drill with reverse-circulation (RC) rigs, which also lend themselves to airlift testing.

Airlifting is a preferred method to "pump" water from small-diameter holes because it employs simple equipment often found at remote sites, and it can produce relatively high discharge rates, especially when static water is at significant depth (as much as 200 m) below surface. Airlift-pumping tests are not as clean, sophisticated, nor easily-interpretable as conventional tests with down-hole pumps. Other differences with conventional tests include:

- Airlifting approximates constant discharge, rather than constant-head pumping;
- A discharge flow meter cannot be used (air and water must be separated);
- Analyses are done on recovery data alone, and on discharge-rate trends;
- Airlift recovery data are almost always burdened with excessive casing storage; and
- Airlifting is poorly described in hydrogeological literature, and is susceptible to misinterpretation and misunderstanding by reviewers.

## Airlifting Procedures

A typical airlift test in an advancing corehole requires a diverter wellhead threaded onto the drill rods, an airline (nominal 1-in threaded PVC or steel pipe, nominal ¾-in polypropylene tubing, or PEX tubing) inserted through the wellhead and down the rods, a connection to an air compressor, and a discharge hose and measuring tank. A transducer may be installed in a packer housing, secured at the end of the airline, or lowered into the well after airlifting stops.

Airlift pumping then proceeds by injecting air at about 70 to 140 L/s (150-300 cfm) down the airline. Air bubbles rise in the water column, entraining and lifting water up the rods and out the discharge hose. Discharge water is measured by timing the flow of air/water discharge into an open-top drum or tank of known volume.

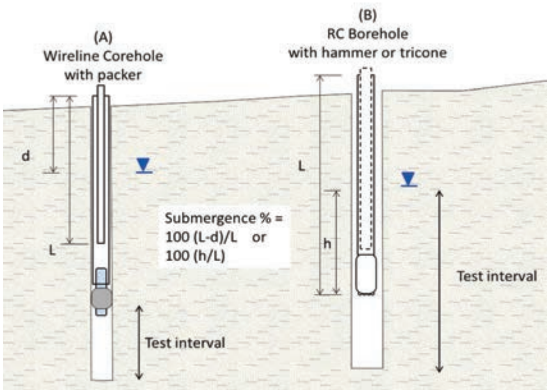


***Fig. 1*** *Airlift Submergence and Test Intervals for Tests in Coreholes and Air-Rotary Boreholes*

Dubek and Beale (1992) provide an early description of airlift testing in rotary boreholes in Nevada. When testing in air-rotary boreholes, the dual-wall pipe constitutes both the airline and the eductor pipe. Importantly, it is assumed that the rotary bit and drill rods do not fit tightly in the borehole, so that the entire saturated thickness of the borehole contributes to the pumping discharge and to the recovery (Fig. 1b). Air, generally from the rig compressor, is injected down the rods, and the discharge water is measured as it exits the cyclone. At the end of pumping the air must be turned off and vented as quickly as possible, and the drilling head broken open to allow rapid insertion of a transducer down the inner tube of the dual-wall pipe, where water-level recovery is measured. The transducer record (*t'*=0) must begin the moment the airlift stops, even though the first water level recorded in this way may be as much as 5 minutes into the recovery.

## Time and Discharge Rate

Where rig time is at a premium, airlift pumping continues for periods of time typically between one and three hours while the discharge rate is periodically measured; recovery of the groundwater is monitored for approximately equal periods of time. Longer-term pumping tests, of as much as 2 to 5 days, can be conducted in completed wells.

The rate of airlift discharge depends directly upon the dynamic submergence of the airline. Fig. 1 illustrates static submergence; dynamic submergence is always less than static submergence due to drawdown in the casing. In low-transmissivity test intervals where the formation cannot quickly replace the water blown from the casing, dynamic submergence, and the resultant discharge rate, can be quite low. Expected discharge rates from HQ rods using an 860 kPa (125 psi) compressor, and assuming that the airpipe is inserted to the maximum unloading depth, range from 0.1 L/s (1.5 gpm) where static water level is about 140 m btoc, to 2 L/s (31 gpm) where static water is less than 30 m btoc. A larger compressor, *e.g.* 1,700 kPa, will yield similar discharge rates, but over a greater depth range. Rates are lower in NQ pipe and 51mm (2-in) wells; in 102 mm wells and PQ pipe, discharges can be up to 9.5 L/s (150 gpm).

## Well and Aquifer Responses

Fig. 2A shows a complete hydrograph from a transducer housed at the bottom of a water-inflated packer (IPI SWPS® system) during a packer-isolated airlift test in a moderately deep (228 to 259 m) bedrock interval with a moderately high hydraulic conductivity (0.3 m/d). The hydrograph shows multiple data sequences that can be analyzed to provide estimates of hydraulic conductivity in the test interval. These include:

- The equivalent of an instantaneous falling-head slug test (#3 in Fig. 2A);
- An "instantaneous" rising-head slug test (#5 in Fig. 2A);
- A constant-head pumping test (#6), the discharge values for which must be collected periodically during the airlift; and
- Relatively long-term recovery data (#8 in Fig. 2A).

The nearly flat drawdown curve in Fig. 2A illustrates the constant-head flow characteristic of airlift tests, while the recovery curves of

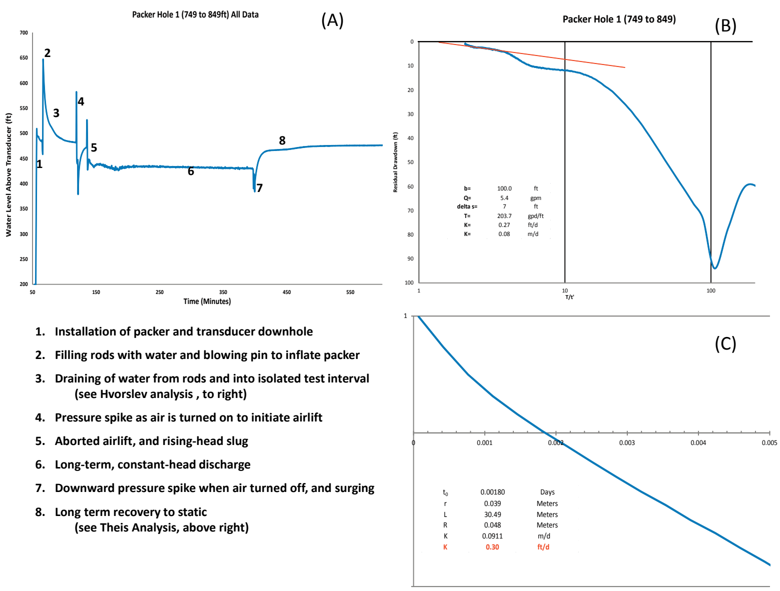


***Figure 2*** *Hydrograph (A) and Hvorslev (C) and Theis (B) Analyses of a Typical Packer-Isolated Airlift-Recovery Test in a Deep Corehole.*

nearly 100 ft show the large casing-storage effects inherent in the method. Another critical factor is implied in Fig. 2A: the test interval, 228 to 259 m, is only a fraction of the thickness of the saturated aquifer. (In this case, the saturated aquifer extends from 91 m btoc to at least bottom of hole at 259 m).

## Analysis of Slug Data

The falling-head and rising-head sequences illustrated in Fig. 2 follow very-large slug stresses of, in the case shown, 60 m and 30 m respectively. These data are generally analyzed by the Hvorslev (1951) method of plotting the logarithm of the ratio of residual stress to total stress, $(H\text{-}h)/(H\text{-}H_0)$, *vs.* recovery time $t$ on an arithmetic scale, as shown in Fig. 2C. Hydraulic conductivity is then derived by:

$$K = \frac{r^2 \cdot \ln\left(\frac{L}{R}\right)}{2 \cdot L \cdot t_o} \qquad (1)$$

Where:

$r$ = radius of unscreened portion of well casing

$R$ = radius of screen or open portion of hole

$L$ = length of screen or open interval (test interval), and

$t_0$ = time to recover 37 % of initial stress.

In most instances, 5 to 15 minutes may pass from airlift initiation until a poor airlift is recognized and the air is shut off to record slug recovery. Although seemingly a violation of a widely-held "rule" of slug testing, Butler (1998) shows that the Hvorslev analysis does not require an instantaneous slug. If the slug is fully introduced before data collection begins, according to Butler, and as long as storage effects do not impact the test, the Hvorslev equation can be applied. The former condition should be considered when identifying the starting point of the slug (pressure release followed by air-water surging can sometimes make this difficult). The latter condition is generally not a concern in fractured-bedrock aquifers.

## Analysis of Discharge Rate

The decline in the rate of discharge during a constant-head pumping or flow test also can be used to calculate a transmissivity for the test interval. Reidel and others (2005), for instance, used discharge data as the primary method of analysis of high-volume airlift tests in highly transmissive basalts in Washington, and compared the results to Theis analyses of the airlift recovery data.Discharge-time data are commonly ignored in analyses of airlift tests because the data can be hard to obtain with precision. More importantly, the discharge data from many airlift tests are rendered invalid as a consequence of ill-advised attempts to maintain constant discharge by varying the air volume during pumping.

Analysis of constant-head discharge is based on Jacob and Lohman’s analysis (1951) for a free-flowing well. The analysis requires time, discharge rate, and “shut-in” pressure. Discharge rate should be measured periodically through the entire duration of the airlift (the initial, violent surge at the beginning can be ignored). The shut-in pressure is usually taken as the static head minus the head measured by the transducer during the airlift (*i.e.* the difference between segments 6 and 8 in Fig. 2A). Values of pressure divided by discharge rate are then plotted arithmetically *vs.* time on a logarithmic scale, and transmissivity is found by:

$$KD = \frac{0.183}{\Delta\left(\frac{P}{Q}\right)} \qquad (2)$$

Where:
$K$ = hydraulic conductivity of test interval,
$D$ = thickness of test interval,
$P$ = shut-in pressure (a constant value),
$Q$ = discharge rate at each time step, and
$\Delta(P/Q)$ = the change in the $(P/Q)$ value per log cycle.

Fig. 3 demonstrates the applicability of the discharge-rate data even when it has not been assiduously collected. Fig. 3A shows a Theis analysis of recovery following a 90 min airlift in an RC borehole, during which the discharge rate declined from 0.16 L/s to 0.025 L/s. Because of the low pumping rate, casing-storage effects are large, and the Theis analysis of the recovery data is questionable (see below). But as shown in Fig. 3B, the discharge-decay analysis, based on only a few data points, corroborates the results of the Theis analysis.

## Analysis of Long-term Recovery Data

Theis (1935) described a simple and robust method to interpret recovery data from a pumping test. Although the Theis recovery method was originally developed for constant-discharge pumping tests, it can also be applied to airlift recovery tests. Rushton and Rathoud (1988) show that the Theis method can be applied to constant-head tests as long as the discharge value used in the analysis is the discharge measured just before pumping ends, and not an early or average value.

Theis Recovery analyses are preferred over slug analyses because long-term airlift pumping produces a greater stress on the aquifer, which extends beyond the immediate borehole walls, and therefore induces more representative responses. The Theis analysis plots the log of the ratio of total test time to recovery time ($T/t'$) on the $X$ axis *vs.* residual drawdown (or change in head) on an arithmetic scale on the $Y$ axis. Where time is sufficiently large, Equation 3 yields a transmissivity of the test interval:

$$T = \frac{0.183 \cdot Q}{\Delta s} \qquad (3)$$

Where:
$T$ = transmissivity of test interval ($m^2/d$),

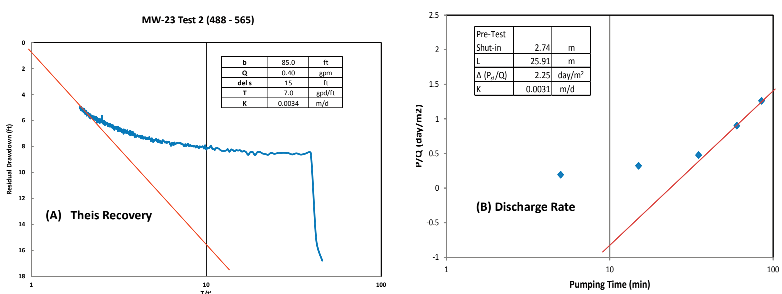


***Fig. 3*** *Discharge-Decay Analysis and Theis Recovery from RC Borehole Test*

$Q$ = discharge rate ($m^3/d$),

$s$ = residual drawdown (or convenient measure of recovery) (m),

$\Delta s$ = change in residual drawdown over one log cycle of $T/t'$.

Fig. 2B shows a recovery curve typical of single-well tests, with some perturbation in early time resulting from surging at the end of the airlift. The useable data fall in the later period of $T/t'$ equal to about 3 to 2. Typical of airlift recoveries, the useable segment represents about 1.5 m of aquifer recovery following about 27 m of casing recovery. Fig. 3A shows another shape common to airlift-recovery curves, which is seen in tests of higher-T intervals where transducers are lowered into wells during the recovery. Again, only latest data are used.

The Theis method does not strictly account for casing storage effects, which occur in the data of all pumping wells (hence, affect all single-well tests). Papadopulous and Cooper (1967) showed that if pumping and recovery time are sufficient, then the Theis method can be applied to drawdown and recovery in pumping wells. They present the following equation to estimate the effect of casing storage on pumping and recovery data:

$$t > \frac{25 \cdot rc^2}{KD} \tag{4}$$

Where:

$t$ = pumping time and/or recovery time,

$rc$ = radius of the non-screened portion of the well,

$K$ = hydraulic conductivity of the formation, and

$D$ = Depth of the well, (thickness of the aquifer)

According to Papadoulos and Cooper, where pumping and recovery times exceed by a factor of 25 or more the square of the casing radius divided by transmissivity, then the casing storage will not affect the outcome of the analysis. Table 1 shows pumping times for 24 airlift tests selected from multiple projects. The table indicates whether or not the recovery data were successfully analyzed using the Theis Recovery method. Unsuccessful tests are so designated because a reliable straight-line segment could not be interpreted in the semi-log plot of late-time recovery; primarily, it is judged, because of excessive casing storage.

The Papodapolous-Cooper relationship is rearranged in Table 1, where 9 out of 10 unsuccessful analyses show pumping-time factors of less than 19 (compare to the suggested factor of 25), and 12 of 14 successful tests had time factors greater than 19.

Table 1 was then sorted according to airlift discharge rate (as seen below), from less than 0.003 L/s (0.05 gpm) to 2.2 L/s (about 35 gpm). Again, 9 out of 10 unsuccessful analyses correspond to tests that sustained discharge rates of less than 0.13 L/s (2.0 gpm), whereas 13 of 14 successful tests discharged at rates exceeding 0.13 L/s.

Both the time factor and the discharge rate are functions of transmissivity (T). In both low- and high-T intervals airlifting initially purges the same large volume of water from the casing. However, that casing volume con-

| Test Number | Screen Interval (m) | Hydr. Condt. (m/day) | Pumping Time (minutes) | Time Factor $t' \cdot KD/rc^2$ | Airlift Rate ($m^3$/day) | Successfull Theis |
|---|---|---|---|---|---|---|
| pack4 test2 | 14.3 | 0.016 | 471 | 50 | 0.3 | No |
| pack5-302 | 17 | 0.034 | 54 | 14 | 2.7 | No |
| MW-11a | 30.49 | 0.001 | 76 | 2.5 | 5.5 | No |
| H11HR-04b | 54 | 0.0047 | 60 | 7.0 | 5.5 | No |
| Sask 477 | 53 | 0.0018 | 60 | 2.6 | 6.0 | No |
| MW-23-565 | 25.9 | 0.003 | 172 | 3.6 | 6.8 | No |
| pack1-382 | 22.3 | 0.004 | 291 | 12 | 7.6 | No |
| Sask528 | 77 | 0.0023 | 180 | 15 | 8.7 | No |
| Hydro-03 | 560 | 0.00064 | 1431 | 236 | 9.81 | Yes |
| pack1-276 | 13.4 | 0.002 | 300 | 3.7 | 10.4 | No |
| Ed628-205 | 80.8 | 0.0044 | 70 | 11 | 10.9 | Yes |
| MK12-333 | 45.7 | 0.001 | 120 | 6 | 12.0 | Yes |
| MW-24-540 | 36.6 | 0.006 | 66 | 3.9 | 12.5 | No |
| 247 test 6 | 80 | 0.003 | 200 | 22 | 14.2 | Yes |
| Sask603 | 77 | 0.0174 | 180 | 111 | 18.5 | Yes |
| Ed627-301 | 274 | 0.0026 | 136 | 45 | 23.4 | Yes |
| 4178 -1828 | 30.5 | 0.3 | 73 | 307 | 25.6 | Yes |
| MW-11b | 30.5 | 0.007 | 78 | 19 | 27.3 | Yes |
| Sask 630 | 50 | 0.07 | 146 | 235 | 48.5 | Yes |
| Ed594-706 | 155 | 0.018 | 62 | 79 | 51.8 | Yes |
| ED594-396 | 250 | 0.008 | 115 | 106 | 60.0 | Yes |
| MK11-196 | 32 | 0.42 | 100 | 1446 | 65.4 | Yes |
| 246 Test 3 | 102 | 0.022 | 120 | 124 | 76.8 | Yes |
| MK-1083 | 125 | 0.35 | 125 | 1471 | 190.8 | Yes |

***Table 1**. Pumping Time and Discharge Rate vs. Theis Analysis*

stitutes a greater percentage of aquifer yield, per time, from a low-T interval. Hence, in low-T intervals, longer pumping is required to sufficiently draw down the aquifer so that aquifer recovery will still be measureable after the casing volume is replaced.

These relationships are useful not only as backward-looking validation of an analysis, but also as a means in the field to determine how to proceed with an airlift pumping and recovery test. In some cases, for instance, if it appears in the first 10 minutes that the long-term airlift rate will be 0.13 L/s (2.0 gpm) or less, then a test might either be stopped early and slug-recovery data recorded, or continued for a much longer period of time in order to overcome the casing storage effect. Conversely, if discharge rates can be easily and accurately measured through time, then the pumping might be continued solely for that purpose.

## Conclusions

Airlift pumping is a simple and robust means of stressing aquifers to obtain hydraulic parameters in deep fractured-rock settings. In small-diameter casings and wells, airlift discharge rates can significantly exceed rates from submersible pumps. Discharge data, if carefully collected, should be analyzed to provide reliable K values. Water-level recovery from short term or aborted airlifts can be analyzed by the Hvorslev method, even though the slug is not instantaneous. The Theis method can be applied to the recovery from the long-term constant-head pumping, using the final discharge value in the calculations. Casing storage effects can invalidate the Theis method, especially at low discharge rates or following short pumping times. Empirically, airlifts that produce 0.13 L/s (2.0 gpm) or less should be stopped early, and slug recovery recorded, or be run for much longer periods of time.

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