Aquifer Stratification Testing System

Operator's Manual

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Introduction

The stratified aquifer test system is a fully self-contained mobile test system designed to characterize water quality stratification in actively pumping groundwater wells. The mobile test system consists of two major subsystems:

1. A dye tracer injection and monitoring system.
2. A discrete depth well sampling system.

The complementary test subsystems are designed to identify both the quantity and quality of water produced over specific depth intervals. Test results can provide extremely useful information for both groundwater producers and researchers. In areas where contaminants are present in produced groundwater, knowledge of the flow and concentration profile within a well may provide producers options for contaminant mitigation by modifying either well construction or well management practices as opposed to implementing expensive treatment options.

The mobile test system, mounted in an enclosed 8' x 12' trailer, is based on a design originally developed by the U.S. Geological Survey (Izbicki et al., 1999), with several enhancements and modifications. The primary design enhancements of this system relative to the USGS system relate to the overall ease and precision of operation through the use of a centralized and enhanced process control system. A key component of the design enhancement is the control panel enclosure, which houses both electrical and pneumatic components that control and monitor many of the test procedure aspects. Once either test subsystem is positioned in the well, which generally requires a minimum of two personnel, a single operator can perform all testing, sampling, and data processing. A second enhancement incorporates an external data logger in the dye tracer monitoring system, allowing for greater precision of elapsed time measurement and extended flexibility of data acquisition, processing, and archival. A third enhancement adds a vacuum pump and associated plumbing system to the sampling system, which decreases both the time required to obtain water samples from shallow submergence depths and the amount of high pressure gas consumed during the sampling process.

Velocity Profiling with Dye-Tracer Injection

The water velocity profile of a groundwater well depends on several factors, including the depth position and discharge rate of the pump, pipe diameter, the screened intervals, and possibly variable transmissivity of the aquifer with depth. Higher transmissivity aquifer zones may contribute a proportionately greater percentage of the total flow relative to lower transmissivity zones. Dye tracer testing measures the average flow velocity between tested depths, from which estimates of the cumulative total well flow and interval average aquifer flow can be calculated.

The dye tracer injection system consists of six major components: (1) a 5-gallon capacity dye tracer holding tank, (2) a high pressure piston pump to circulate and inject the dye, (3) an unloader valve to relieve excessive injection pressures, (4) an electropneumatically actuated cross-over valve to control fluid flow states, (5) a timer relay to control the duration of injection, and (6) an injection hose assembly to deliver the dye tracer to the well (Figure 1).

There are two fluid flow states in the dye tracer plumbing system: high pressure injection and low pressure circulation (Figure 1). Which state is active depends on the operating position of the cross-over valve. During high pressure injection, the cross-over valve directs pump output into the injection hose assembly (Figure 1a). Any excessive pump pressure, determined by the unloader valve adjustment, is returned at low pressure to the holding tank. The duration of the high pressure injection state is controlled by a timer relay programmable in 0.1-second increments and repeatable to ±50 ms. The timer relay operates an electropneumatic valve actuator, which maintains the cross-over valve in the injection state for the specified duration. Injection pressure is monitored with a pressure gauge. When the programmed injection duration expires, the relay opens, the actuator is turned off, and the cross-over valve is reset to the default low pressure circulation position by a spring-return mechanism in the actuator.

During low pressure circulation, the cross-over valve directs pump output at low pressure in a loop between the holding tank and the pump (Figure 1b). The injection hose assembly is connected to the tank return flow to relieve injection pressure by backflow. The injection hose assembly consists of a 3500 PSI-rated hydraulic hose terminated with a check valve having an adjustable cracking pressure between 350 and 600 PSI. A weight is attached below the check valve both to keep the hose straight and to counteract buoyancy.

The check valve cracking pressure, unloader valve setting, and timer setting are determined experimentally prior to lowering the hose into the well. When properly balanced, the timer setting generally ranges between 8 and 12 seconds achieving a pressure of approximately 800 PSI and results in a dye solution volume of approximately 5 to 10 cm^3 (1 to 2 teaspoons) injected over 1 to 2 seconds.

An injection cycle process is initiated by first turning on the pump. The flow path is in the default low pressure circulation state upon power-up. Tracer injection is initiated with a push button, which causes the relay to immediately switch the cross-over valve into the high pressure injection state and the timer begins a count-down for the programmed duration. A pressure wave propagates down the hose assembly and the dye tracer pulse is released into the well through the check valve. When the timer count-down reaches zero, the relay is turned off, the cross-over valve reverts to the low pressure circulation state, and the pressure in the hose is relieved by backflow to the reservoir tank.

The dye tracer used is (nontoxic) Rhodamine WT. The US Environmental Protection Agency has set an allowable concentration of 10 μg/L (ppb) for water entering a treatment plant (prior to treatment and distribution) and of 0.1 μg/L (ppb) for drinking water. The USGS developers of the dye injection system have suggested a dye pulse solution concentration of approximately 200 to 250 mg/L (ppm) (A. Christianson, pers. comm.) results in peak concentrations on the order of 10 μg/L (ppb) at the wellhead.

It is critical that the dye solution have a consistent concentration throughout the injection system. Concentration variability within the injected pulse will result in an incorrect center-of-mass determination resulting in inaccurate tracer pulse travel time and velocity calculations. Proper procedures must be followed to obtain a well-mixed dye solution. The dye reservoir tank is equipped with a system of valves that direct flow variously to the pump or to waste drainage. The reservoir is equipped with an electrical float switch that turns off the pump to prevent sucking air into the system when the reservoir fluid level drops too low. The float switch is activated with a toggle switch located on the control panel.

Ideally, the hose assembly is initially lowered to the presumed pump depth to begin testing. Small depth adjustments are made and the precise pump intake depth is determined at that having the shortest elapsed test time. At least two injections should be conducted at each depth to ensure repeatable results. Injections are performed starting at the pump intake depth and progress in steps at depth intervals both below and/or above the intake depth. Well obstructions may prevent access of the hose assembly and testing of the entire profile. However, this does not necessarily invalidate results for intervals that can be tested, provided that sufficient well construction and total flow data are available.

Injections should not be conducted at or close to depths with probable stagnant conditions. The injected dye concentration may have to be adjusted to strike a balance between both the lowest concentration required to provide detectable values at the well head and sufficiently high concentration to provide a recognizable breakthrough for all depths tested.

Well casing and obstruction diameters must be accurately known to calculate accurate discharge values. If this well information is not available, then the velocity data cannot be transformed to discharge data. However, relative changes in average velocity can still be used to estimate the relative percentages of average flow contributed to the well over different tested intervals. Additionally, the average constituent concentration values can be estimated with the flow velocity or percentage data.

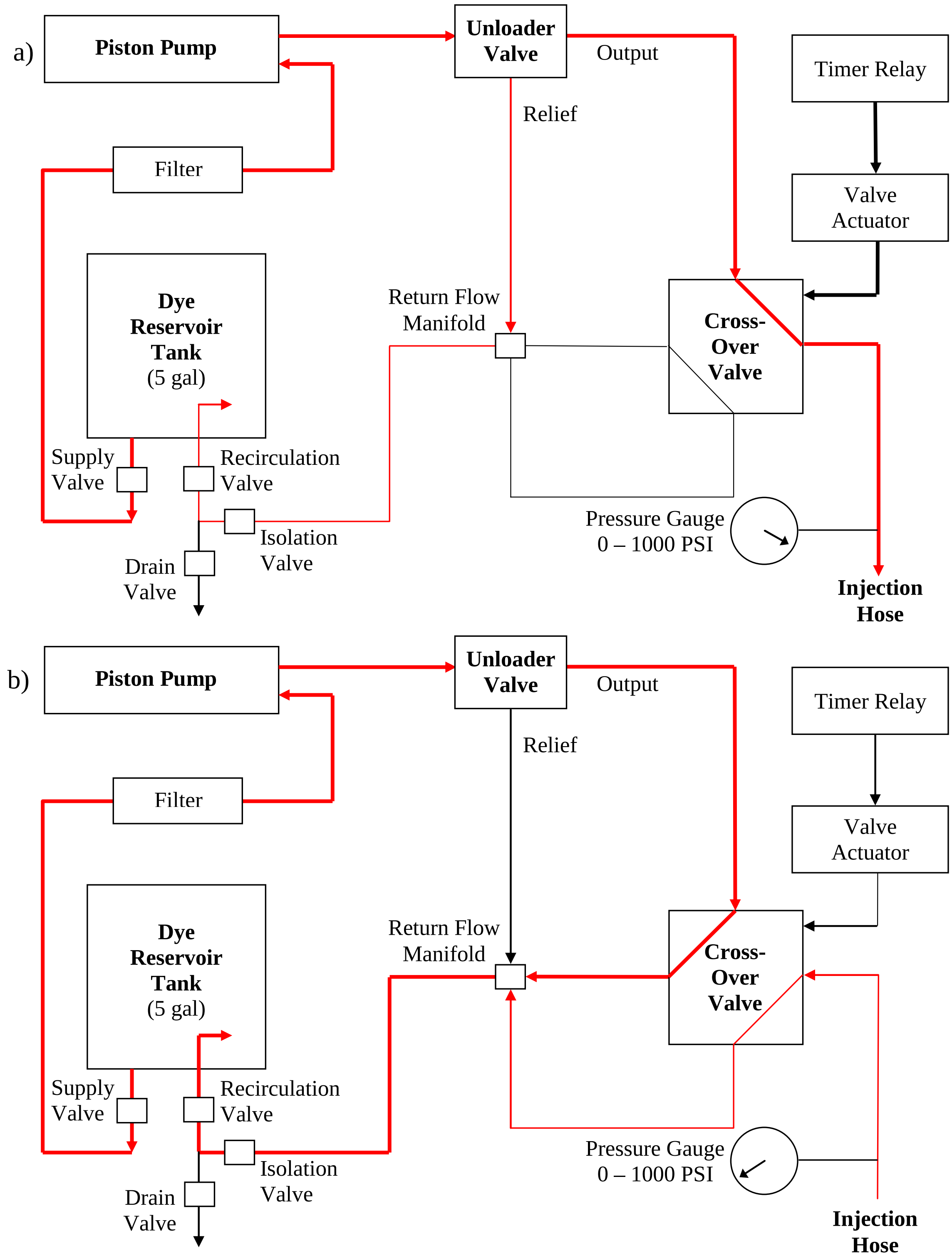

Figure 1. Dye tracer injection system schematic showing (a) high pressure injection and (b) low pressure circulation states. Heavy red lines indicate the primary dye tracer fluid flow paths. Narrow red lines in (a) show flow return path from unloader valve for excess injection pressure. Narrow red lines in (b) show pressure release return flow path from hose following injection.

Dye Tracer Monitoring

The dye tracer monitoring system consists of a fluorometer and associated data logging equipment and data processing procedures. The well effluent is monitored in real-time for dye tracer concentrations using a temperature-compensated fluorometer (Model 10-AU, Turner Designs, Sunnyvale, CA). Water flow is diverted from the well head using a standard hose bib connection and garden hose routed to the fluorometer. The fluorometer is equipped with a continuous flow cell and calibrated for the range from 0 to 100 μg/L (ppb) with a sensitivity of 0.01 μg/L. This represents the linear range of fluorescent response for Rhodamine WT concentrations using this instrument configuration.

The fluorometer output signal is connected to an external data logger (CR10X, Campbell Scientific, Logan, UT). (The fluorometer also has an internal data logger that is used as a backup.) Power for the external data logger is controlled by a toggle switch located on the bulkhead. The external data logger is connected to the push button that initiates injection cycles, ensuring precise measurement of elapsed test time. In addition to elapsed time and fluorometer output, other data are recorded including the test depth, calibration parameters, etc., to ensure data integrity. The data logging software additionally provides real-time graphical output of the fluorometer response and as a convenient method of visually monitoring test progress. The logging software is extremely flexible with regard to data processing. For example, background fluorescence can be monitored prior to a test and automatically subtracted from test results. The elapsed time and fluorometer measurements are normally recorded at one-second intervals. Following an injection cycle, data are downloaded for archival on a laptop PC and immediately processed. Repeat injection cycles are performed to assess consistency between tests at a given depth.

The fluorometer should be plumbed into the well and operated for approximately 30 minutes prior to performing injections. This allows sufficient time for the instrument to reach a stable operating temperature and for background fluorescence to be characterized. The fluorometer should be kept out of direct sunlight to prevent thermal gradients within the instrument, which manifests as false background levels and trends in the output. The end of a particular injection/monitoring cycle is indicated by monitoring the fluorometer output until background (or zero) concentrations are reached following arrival of the dye pulse.

Tracer testing is terminated when approximately 80% of total well production has been accounted for, with the remaining flow attributed to untested intervals above and/or below the minimum/maximum tested depths. This provides a safety buffer intended to prevent injecting dye into potentially stagnant zones that might exist near the top or bottom of the water column. The distance between tested depths is determined by several factors, including well construction, pump discharge, available geological logs, and possible constraints on time available for testing.

Discrete Depth Sampling

The water quality profile of a groundwater well depends on both the discharge profile and the vertical variability of water quality in the aquifer. Discrete depth sampling provides cumulative constituent flux concentrations as the water in the well flows toward the pump inlet. These data can be used with the dye tracer velocity measurements and discharge calculations to profile average constituent concentrations entering the well over the tested depth intervals.

The discrete depth sampling system consists of five major components: (1) a dual-tube hose that delivers regulated pressures into the well and returns sample water from the well, (2) a passive pump connected to the sampling hose, (3) a high pressure gas source that provides energy to drive the sampling process, (4) a system of regulators, valves, pressure transducers, and pressure displays to control and monitor the sampling process, and (5) sample processing equipment to collect, filter, and store the samples.

The hose has two 1/4-in OD by 1/8-in ID FEP Teflon tubes wrapped in a protective polyethylene sheath marked in 1-ft intervals. One tube is designated the pressure side while the other is the sample side. The down-hole end of the hose is connected to a small-diameter passive pump constructed from two check valves, a Y fitting, and a screened intake. The small diameter is intended to allow the pump to pass between the well pump bowls and the casing. There is a weight attached below the pump similar to the dye tracer system.

The sampling system is powered using compressed gas and a vacuum pump. Gas and sample flow is controlled with a system of valves. Pressures are measured with transducers at four locations in the system that provide signals to digital display monitors. The transducers connected to the top three monitors on the control panel are connected to the pressure pathway and have a range of 0 to 500 PSI. The transducer connected to the bottom monitor on the control panel is connected to the vacuum pathway and has a range of -15 to 45 PSI. There is a pressure relief valve on the vacuum pathway to prevent over-ranging the vacuum pressure transducer should the operator inadvertently divert high pressure into the vacuum pathway.

The top display monitor indicates the pressure in PSI unit controlled by the compressed tank regulator, and generally displays a value of 450 PSI. The second display monitor from the top indicates the sample pressure in PSI units controlled by the control panel regulator valve. The third display monitor from the top also indicates the regulated sample pressure, but the value is in ft-H_2O units (1 PSI = 2.30 ft-H_2O). The bottom display monitor displays the (unregulated) pressure in ft-H_2O units in the control panel vacuum pathway.

The sampling process progresses as an alternating series of pressurization and venting cycles that move sample water through the sample hose tubes (Figure 2). Water initially enters both tubes driven by the hydrostatic pressure at the sample pump. A pressure cycle then drives water down the pressure tube and up the sample tube, while the lower pump check valve prevents backflow of sample into the well. The subsequent vent cycle releases the compressed gas introduced during the pressure cycle and the hydrostatic pressure at the pump again forces new sample water into the pressure tube. During the vent cycle, backflow of water stored in the sample tube is prevented by the upper pump check valve because the hydrostatic pressure in the sample tube is now greater than the hydrostatic pressure at the sample depth in the well.

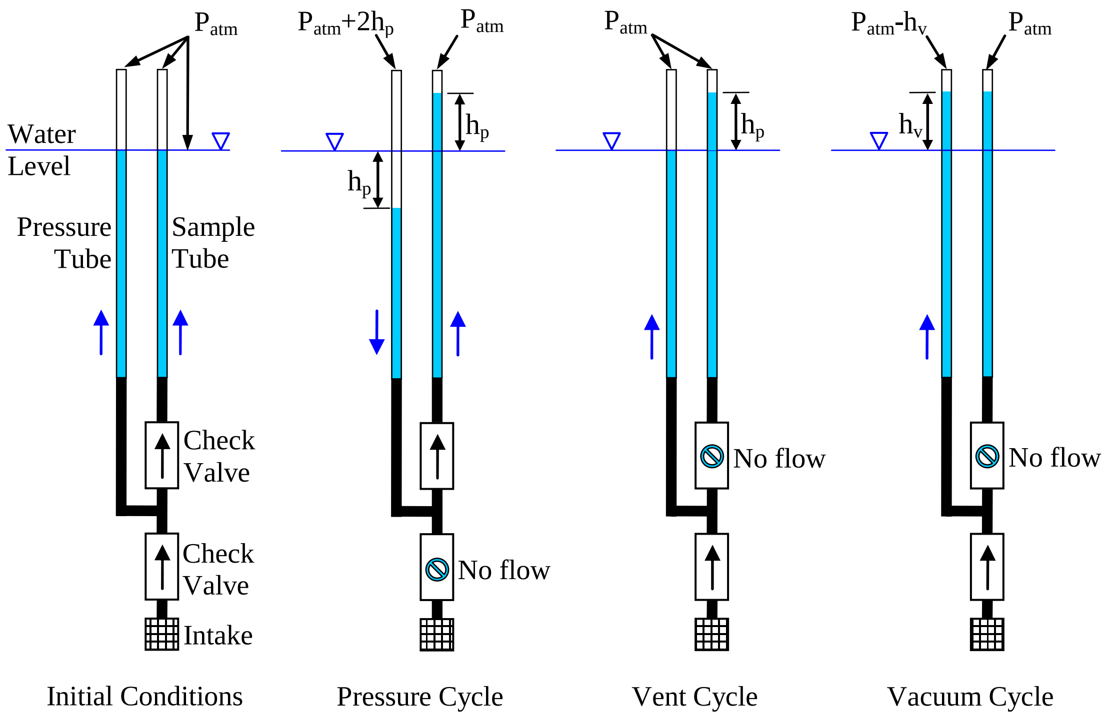

Figure 2. Sample hose and sample pump conditions in response to various sample cycle conditions. Arrows indicate the direction of sample flow.

The process of "stacking" water in the sample tube through alternate pressure-vent cycle pairs is controlled with the control panel valves (Figures 3 to 6). Cycles are repeated until there is sufficient sample volume for the intended purpose, at which point the entire stacked water column is forced up and out of the sample tube. The storage capacity of the pressure/sample tubes is approximately 2.4 ml/ft.

Under shallow sample pump submergence, where hydrostatic pressure gradients and corresponding cycle sample volumes are relatively small, a vacuum-vent cycle pair can be performed following a pressure-vent cycle pair. During a vacuum cycle, a vacuum pump is used to draw more sample water into the pressure tube. Prior to the first pressure cycle (but not afterward), a vacuum cycle can also be used to draw more sample water into the sample tube. With the pump presently in use, water can be drawn up the tube approximately 20 ft above the water level. The use of vacuum cycles can greatly increase the amount of water recovered per cycle, while also reducing the amount of compressed gas consumed.

The pressures required for sequential sample stacking cycles are calculated from the depth to water (DTW, ft), the sample submergence depth (SSD, ft, defined as the depth of the sample below the well water), and the height of water stored in the sample tube from previous cycles measured relative to the sample depth. The sum of DTW and SSD equals the sample depth. If using only sequential pressure-vent cycles, the initial stacking pressure, P_1, expressed in ft-H_2O units is:

$$P_1 = (2 \times SSD) - S \qquad \text{eq. 1}$$

where S is a safety factor distance to prevent pushing compressed gas past the pump and entraining gas in the sample. Subsequent cycle pressures, P_n, for cycle number n are calculated from the previous cycle pressure, P_{n-1}, as:

$$P_n = P_{n-1} + (2 \times SSD) - S \qquad \text{eq. 2}$$

If vacuum-vent cycles are fully utilized by drawing water into both tubes prior to the first pressure cycle, the initial stacking pressure is:

$$P_1 = (2 \times SSD) + (2 \times V) - S \qquad \text{eq. 3}$$

where V is the vacuum pressure applied and here represents the sum total of water height drawn into both the pressure and the sample tubes. Subsequent cycles that subject only the pressure tube to a vacuum cycle have stacking pressures calculated as:

$$P_n = P_{n-1} + (2 \times SSD) + V - S \qquad \text{eq. 4}$$

The sequence of pressure values calculated for either pressure-vent or pressure-vent-vacuum-vent cycling schemes continues until the calculated pressure, P_n, reaches a value that equals or exceeds the sample depth less the safety factor distance, at which point the final stacking pressure, P_F, is used and remains constant for all subsequent cycles:

$$P_F = DTW + SSD - S \qquad \text{eq. 5}$$

When a sufficient sample volume has been stacked, a sample retrieval cycle pressure, P_R, is used to push compressed gas through the pump and drive the stored sample up and out of the sample tube. A pressure increase of approximately 20 ft greater than the sample depth is used:

$$P_R = DTW + SSD + 20 \qquad \text{eq. 6}$$

During the sample retrieval process, the pressure increases to P_R in the pressure tube, the compressed gas pushes past the upper pump check valve and drives the sample tube water upward. The pressure required to move the sample diminishes as the sample water moves upward. Thus, if pressurized gas is allowed to continue to flow into the system, the sample flow rate will accelerate. This has the undesirable side effect of causing the sample stream to break up as it passes through the section of hose loops stored on the hose reel. The sample water emerges from the hose as powerful blasts and surges with entrained sections of pressurized gas.

This situation can be avoided by observing the pressure monitor. As sample moves up the tube, a point is reached where the pressure regulator can no longer supply gas at a flow rate sufficient to maintain the regulated pressure, P_R, and the pressure begins to drop, slowly at first and then more rapidly. Stopping the gas flow after the pressure has fallen by approximately 5 ft-H_2O results in sufficient remnant pressure to expel sample from the hose without excessive pressure. This also reduces compressed gas consumption.

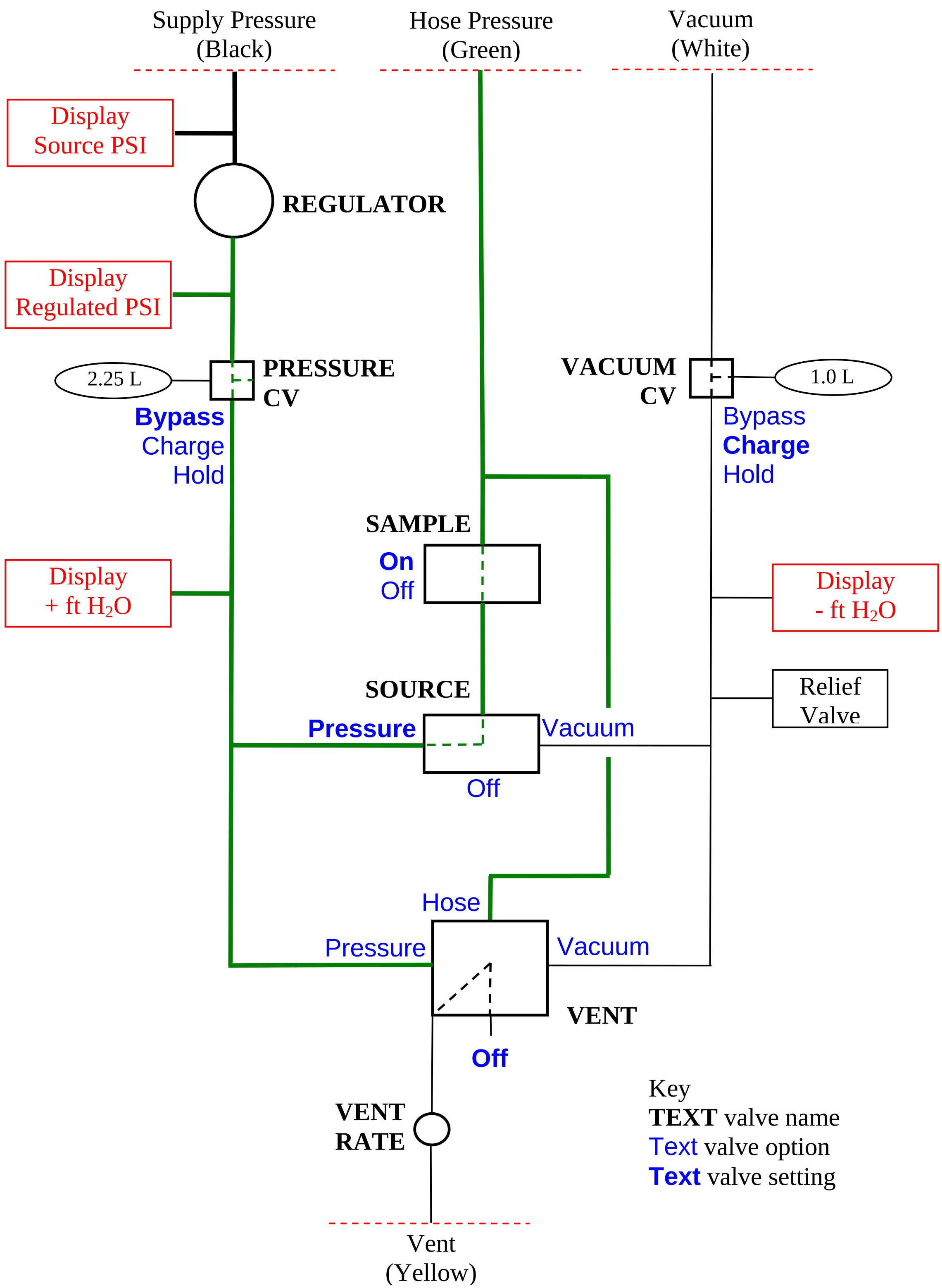

Figure 3: Sample pressure cycle control panel valve settings. Green lines show regulated pressure interconnection pathways. Dashed lines show internal valve pathways.

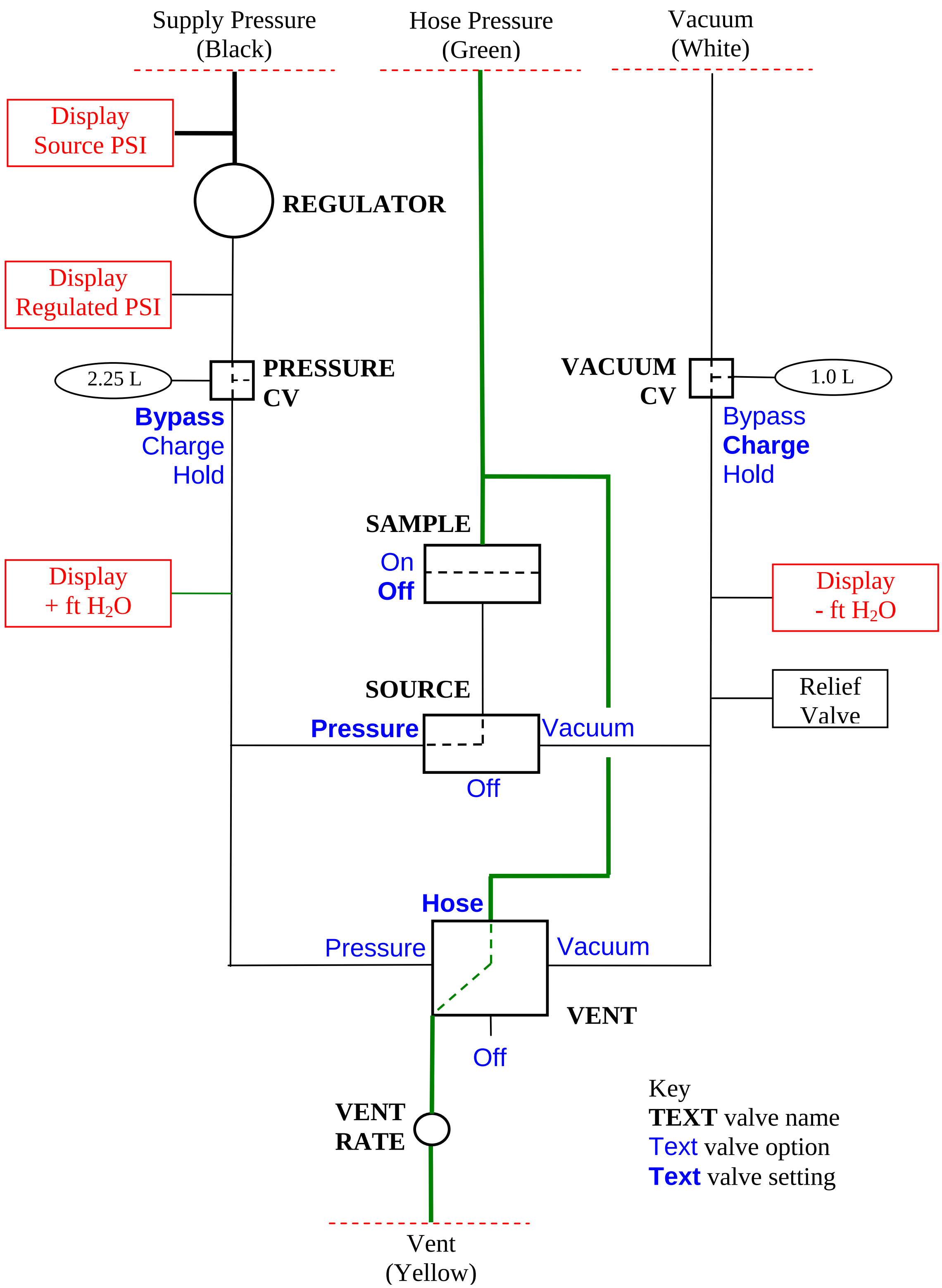

Figure 4: Hose vent cycle control panel valve settings. Green lines show vent interconnection pathways. Dashed lines show internal valve pathways.

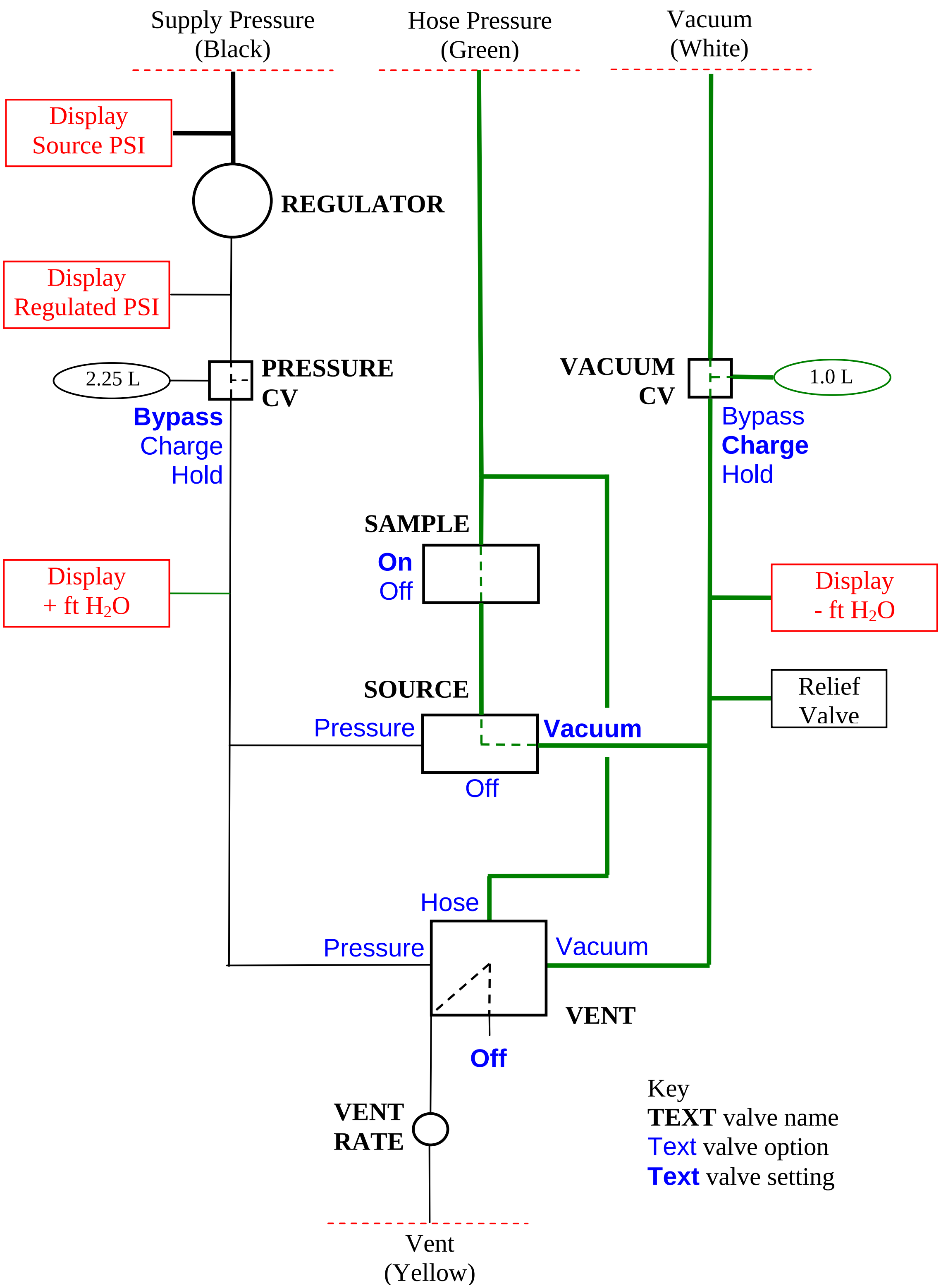

Figure 5: Vacuum recovery assist cycle control panel valve settings. Green lines show vacuum interconnection pathways. Dashed lines show internal valve pathways.

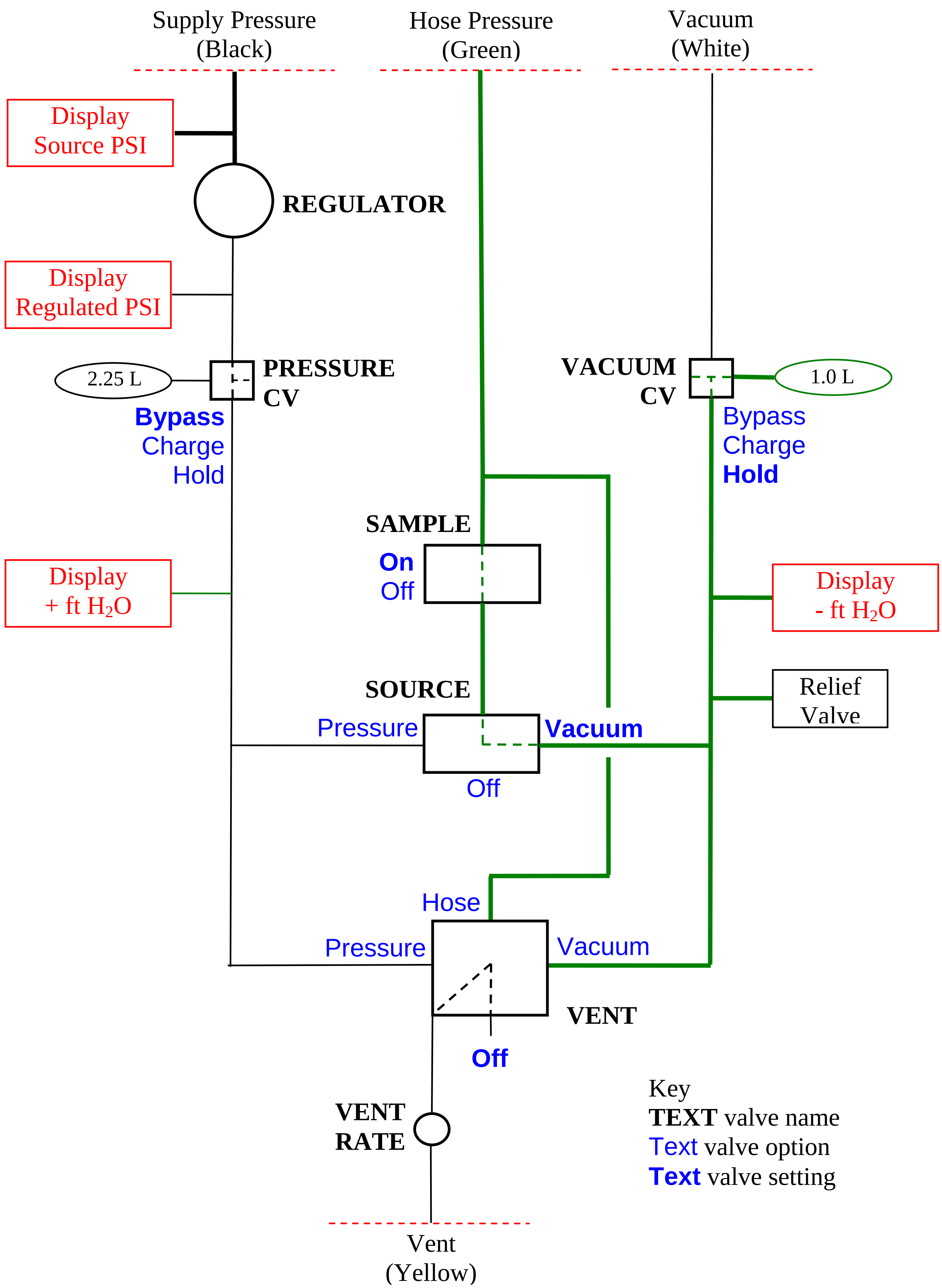

Figure 6: Vacuum recovery assist cycle control panel valve settings with HOLD setting on vacuum control volume. Green lines show vacuum interconnection pathways. Dashed lines show internal valve pathways.

Data Processing

Data processing of stratification test data requires integrating well velocity/discharge results from the dye-tracer injection tests with the constituent concentration analysis results from discrete depth water samples.

The total mass of dye, D^T, recovered during a tracer test is determined by integrating the total well discharge, Q^T, and tracer concentration, C, over time, t. Assuming that both Q^T and the concentration measurement time interval, Δt, are constant during the test period:

$$D^T = \int Q^T C dt = Q^T \int C dt = Q^T \Delta t \sum C \qquad \text{eq. 7}$$

The value of D^T is useful in examining consistency between tracer test injection volumes. The dye-tracer center-of-mass arrival time is used to determine the average flow velocity between tested depths.

The first-arrival time of dye is identified as the first data record at which a consistent increase above background concentration occurs. A running cumulative sum of the concentration measurements is calculated beginning at the first-arrival record and across all subsequent records to the point where concentration returns to background level. Under the same assumptions of constant Q^T and Δt, the center-of-mass arrival time, t^m, is determined as the elapsed test time at which the cumulative sum of dye concentrations represents 50% of the total cumulative sum:

$$t^m = \frac{\sum C}{\sum C_{total}} = 0.50 \qquad \text{eq. 8}$$

The average flow velocity, υ^a, over a given depth interval, i, is calculated as the absolute difference between the bounding test interval depths z_1 (closest to the pump) and z_2 (farthest from the pump) divided by the difference between the respective center-of-mass arrival times:

$$\upsilon_i^a = \frac{|z_2 - z_1|}{t_2^m - t_1^m} \qquad \text{eq. 9}$$

The cumulative well discharge, Q^c, is estimated as an average over interval i, from the interval average flow velocity, and the interval average cross-sectional area:

$$Q_i^c = \upsilon_i^a \pi r_i^2 \qquad \text{eq. 10}$$

The interval average cross-sectional area, πr^2, within the well casing radius, r_c, must be adjusted for displacement resulting from the sum of obstructions, r_o, due to riser pipes, electrical cables, etc., that are present between the injection depths:

$$r_i^2 = r_c^2 - \sum r_o^2 \qquad \text{eq. 11}$$

The interval average aquifer discharge, Q^a, is estimated as the difference between the cumulative well discharges for the tested interval i and the interval i-1 next farthest from the pump:

$$Q_i^a = Q_i^c - Q_{i-1}^c \qquad \text{eq. 12}$$

Discrete depth samples provide a constituent flux concentration, C^f, in the well water at a given depth, z. The constituent average aquifer-flux concentration, C^a, flowing into the well over the depth interval i between depths z_1 (closest to the pump) and z_2 (farthest from the pump) is estimated as the difference between the products of the cumulative well discharge estimates and the interval constituent well flux concentrations divided by the interval average aquifer discharge:

$$C_i^a = \frac{Q_i^c C_{z_1}^f - Q_{i-1}^c C_{z_2}^f}{Q_i^a} \qquad \text{eq. 13}$$

The units of discharge cancel out in eq. 7. Thus, aquifer-flux concentration calculations may be performed by substituting average discharge with either average velocity or percentage of total average velocity measurements, provided that the cross-sectional flow area remains constant throughout the tested depth intervals.

Utility Systems

120-Volt AC Electrical Power

The trailer is equipped with an on-board, gas-powered 3000-watt, 120-volt AC generator can be used as an alternative power source when external AC power is not available. If external power is available, the circuit must be capable of safely servicing 15-amp and preferably 20-amp loads. Internal or external power is connected to the trailer systems through the outlet located on the interior front wall of the trailer below the circuit breaker panel. External power should be connected to the trailer using a heavy-duty extension cable. If external power is not available, the generator can supply sufficient current to power any of the systems, though operating multiple systems simultaneously might result in circuit overload and tripping of the generator overload-sensing circuitry. The output from the generator is sufficient to drive any one of the three electrical motors on the trailer (either of the two hose reel motors or the dye tracer piston-pump motor), with sufficient available capacity for lighting.

There are four main circuits, each protected with a 20-amp circuit breaker. Ground Fault Circuit Interrupter (GFCI) safety devices are installed on all four circuits. The GFCIs provide operator protection against a short-circuit injury.

- Circuit 1 powers the overhead fluorescent lighting and an accessory power outlet located in the operator's bay at the rear of the trailer.
- Circuit 2 powers the 12VDC converter.
- Circuit 3 powers the dye tracer piston pump.
- Circuit 4 powers both hose reel motors.

12-Volt DC Electrical Power

When 120VAC power is connected (either from the generator or external source), the DC power converter provides sufficient current to simultaneously charge a deep cycle battery and to operate all DC systems. When 120VAC power is not connected, all DC systems obtain power directly from the battery, which is rated for 100 amp-hour service. A toggle switch located on the battery enclosure can be used to isolate the DC supply from the rest of the trailer systems, though the power converter will continue to charge the battery.

DC power from the converter/battery is distributed to 5 circuits through an automotive-style fuse box located in the bulkhead. The circuits provide power to the control panel (4 amps), vacuum pump (6 amps), data logger (2 amps), and two accessory power ports (10 amps each). The power ports are located on each side of the bulkhead to power the fluorometer and computer.

Water Supply Tank

A 25-gallon capacity general purpose water tank equipped with a demand pump is mounted in the front of the trailer. The pump operates on 12VDC power and can provide up to 60 PSI output. The pump is attached directly to the charger/battery source and is not fused. The power switch is located on the pump. There is an adjustable spray pattern wand with on-off switch attached to a 15-ft hose. Only clean water should be added to the tank.

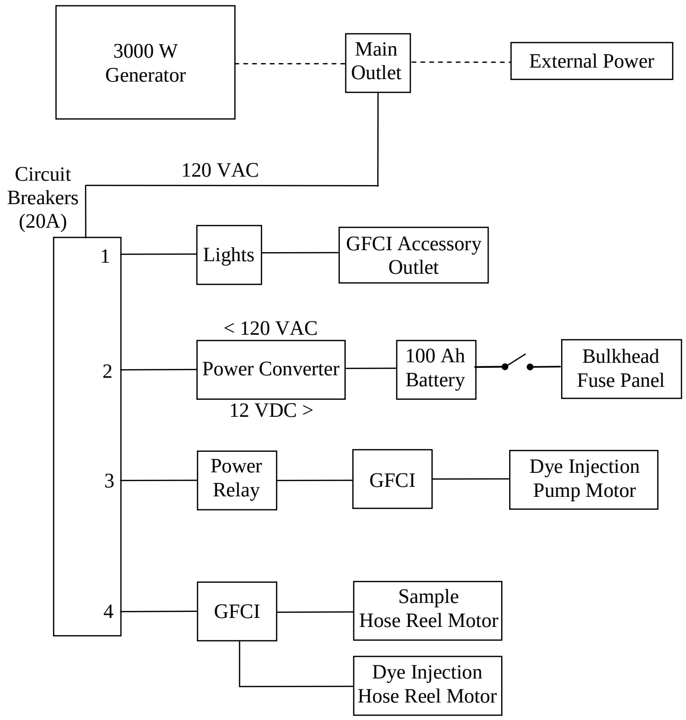

Figure 7: AC electrical system schematic

Appendix I
Dye-Tracer Testing Procedures

Initial Setup

1. Connect to 120VAC power if available.
2. Set control panel electrical switches to OFF positions.
3. Connect control panel power cables (power/control 1 & 2).
4. Set accessory gas pressure regulator to OFF (fully counter-clockwise).
5. Set control panel main power switches to ON positions.
6. Connect main pressure lines between gas tanks and changeover regulator
7. Open gas tank valves.
8. Open changeover regulator input valves.
9. Observe changeover regulator input gauges to assess tank fill status.
10. Observe changeover regulator output pressure gauge, bulkhead supply pressure gauge, and control panel supply pressure gauge. All should read nominal 450 PSI.
11. Adjust accessory gas pressure regulator to ON (fully clockwise). Bulkhead accessory pressure gauge should read nominal 100 PSI.

Install Fluorometer Sampling System

1. Connect a garden hose shut-off valve to the fluorometer flow cell input (lower fitting) and set the valve to the CLOSED position.
2. Connect a garden hose Y fitting to the test well sample port. Set the Y fitting valves to the CLOSED positions and OPEN the test well sample port valve. Check for leaks.
3. Connect a 5/8" garden hose between the Y and the shut-off valve on the fluorometer flow cell input.
4. Connect a garden hose to the fluorometer flow cell output (upper fitting) and route the down-stream end to an appropriate location away from the test area.
5. Ensure that the hose runs are as straight as possible and that there are no kinks in the hose. Also try to locate the hose to minimize the chances of it getting stepped on during the test. NOTE: Never install a shut-off valve or otherwise restrict flow downstream from the fluorometer flow cell. The flow cell is rated to 25 PSI and may be damaged by higher upstream pressure or by a water hammer effect resulting from closing a downstream valve.
6. Open the Y shut-off valve leading to the fluorometer and the shutoff valve at the fluorometer flow cell input.
7. Measure and record the flow rate through the fluorometer plumbing.

Measure Test Well Background Fluorescence

1. Wait until a few gallons of test well water have passed through the fluorometer plumbing.
2. Begin logging the fluorometer to measure test well background fluorescence.

Fill Dye Tank

1. Set dye tank SUPPLY valve to ON position.
2. Set dye tank RECIRCULATION valve to ON position.
3. Set dye tank ISOLATION valve to ON position.
4. Set dye tank DRAIN valve to OFF position.
5. Add required water and dye volumes to tank. Use an initial concentration of approximately 200 ppm active ingredient. The Rhodamine WT concentrate is supplied by the manufacturer as a 20% by volume solution. The injection hose holds approximately 2.5 gallons (9.5 L).

Fill Injection Hose

1. Turn injector pump ON and allow dye solution to circulate between the pump and the dye tank to achieve uniform concentration, 3 to 5 minutes. Also wait for any air bubbles to dissipate.
2. Place end of injector hose in a waste container.
3. Set control panel injection timer to 600 seconds.
4. Press the INJECT button on the control panel.
5. Observe tank level markings as the injection hose fills. Once dye solution flow from the hose, allow approximately 1 gallon of solution to flow into the waste container. This step purges remnant dye solution from the hose.
6. Press the RESET button on the control panel to stop pumping.
7. Turn injector pump OFF.

Install Check Valve

1. Install a new brass check valve and weight-hanger fitting on end of injection hose. Observe direction-of-flow arrow stamped on check valve body. The check valve must be installed below the weight hanger.
2. Adjust check valve opening pressure to minimum value (fully counter-clockwise). Be careful not to drop the set screws.
3. Set control panel injection timer to 60 seconds.
4. Turn injector pump ON.
5. Place end of injector hose in dye tank.
6. Press the INJECT button on the control panel. This step purges air from the end of the hose introduced during check valve installation.

Set Dye Injection Volume

1. Adjust check valve cracking pressure to maximum value (fully clockwise). Then reduce cracking pressure by turning counter-clockwise 0.5 to 1.5 turns.
2. Set relay timer to 10 seconds.
3. Turn injection pump ON.
4. Place end of injector hose over a volumetric measuring container.

5. Press the INJECT button on the control panel. Observe the injection pressure gauge. Injection pressures should generally be below 800 to 850 PSI. If pressure approaches the 1000 PSI gauge maximum value, press the RESET button located below the injection timer on the control panel.
6. Adjust relay timer and/or check valve and repeat step 5 until a consistent 5 to 10 ml dye injection volume is achieved. Also adjust unloader valve to raise/lower injection pressure. The dye pulse should occur over as short a period as possible.
7. Check for consistency between injections by pausing 3 to 5 minutes between tests. This will allow some time for gasses dissolved under pressure in the hose to come out of solution and form bubbles. These bubbles will act as pressure wave propagation buffers during an injection cycle and will result in lower injected dye volume.

Final Hose Preparation

1. Setup a tripod and pulley system at the wellhead to provide a smooth pathway for lowering and raising the hose in the well. The tripod should be secured to prevent shifting.
2. Rinse the outside of the hose, weight hanger, and check valve to remove any dye introduced by handling.
3. Thread dye hose through cable counter and pulley system leading toward wellhead.
4. Install weight to end of weight hanger and apply electrical tape.
5. Disconnect injection hose at the inlet connection.
6. Lower hose assembly in test well until the check valve is located at the pump intake depth.

Dye Injection Test

1. Connect injection hose at the inlet connection.
2. Start fluorometer internal data logger.
3. Start backup external data logger.
4. Turn the dye safety switch on the control panel to ON. This will prevent injections when the water level in the supply tank falls below about 1 gallon possibly resulting in air being sucked into the injection pump intake.
5. Turn injection pump ON and circulate for 10 to 15 seconds.
6. Press the INJECT button on the control panel. The injection process cycle will begin and will automatically stop after the time set on the timer relay has expired.
7. Turn the injection pump OFF when injection cycle is complete.
8. Watch fluorometer display for breakthrough.
9. Allow time for ppb values to return to background levels. Near-background concentrations of dye may remain in the well for several minutes after the main pulse has flushed through. Intermediate data processing may be required to determine trends if wait times become excessive.
10. Process data to determine time lag of dye center-of-mass.

11. Repeat test at least once to verify time lag.
12. Disconnect injection hose at the inlet connection.
13. Position the hose assembly at the next depth, reconnect inlet hose, and repeat steps 1 to 8.
14. Stop testing when approximately 10 to 20 % of well production remains unaccounted for.
15. NOTE: Injection cycle time may need to be increased (by suggested 0.1 s increments) as distance between the injection and pump depths increases to obtain significant peak dye concentrations.
16. NOTE: The fluorometer response to Rhodamine WT is linear to 100 ppb. Center-of-mass calculations using values greater than 100 ppb will not be accurate.

Post-Testing Procedures

Injection Hose Purge

1. Remove injection hose assembly from well.
2. Remove brass check valve from end of injection hose.
3. Place end of injector hose in dye waste container.
4. Adjust accessory pressure to 0 PSI.
5. Connect compressed gas hose between bulkhead Accessory Pressure port and dye injection hose inlet.
6. Adjust accessory pressure to between 20 and 40 PSI.
7. Purge injection hose of dye solution.
8. Adjust accessory pressure to 0 PSI .
9. Disconnect compressed gas hose from bulkhead Accessory Pressure port and dye injection hose inlet.

Drain Dye Reservoir Tank

1. CLOSE reservoir tank Isolation and Supply Valves.
2. Attach drain tube to barbed fitting on reservoir tank Drain Valve.
3. Place end of tube in dye waste container.
4. OPEN reservoir tank Drain Valve and drain contents.
5. Lightly rinse the reservoir tank with clean water and drain rinse water.
6. CLOSE reservoir tank Drain Valve and disconnect drain tube.
7. Add liquid chlorine bleach to dye waste container.
8. NOTE: Never add bleach to the reservoir tank. Bleach will damage the injector piston pump seals.

Appendix II
Discrete Depth Sampling Procedures

Initial Setup

1. Connect trailer electrical system to external 120VAC power if available.
2. Check that the gas tanks are isolated upstream from the changeover regulator by either closing the gas tank valves (fully clockwise) or closing the tank changeover regulator input valves (fully clockwise).
3. Set the accessory gas pressure regulator located on the bulkhead to CLOSED (fully counter-clockwise).
4. Set the supply line vent valve located below the gas tank changeover regulator to OPEN (fully counter-clockwise).
5. Set all control panel electrical switches to their OFF positions.
6. Connect the two cables between the corresponding control panel and bulkhead connectors labeled PWR/CTL 1 (4 conductors) and PWR/CTL 2 (7 conductors).
7. Set control panel pneumatic components to:
   - Regulator: CLOSED (fully counter-clockwise)
   - Pressure CV: BYPASS
   - Vacuum CV: CHARGE
   - Source: OFF
   - Sample : ON
   - Vent: OFF
   - Vent Rate: OPEN (fully counter-clockwise)
8. Remove the color-coded protectors from the control panel, bulkhead, bubbling tower, sample hose reel, and air hose quick connects.
9. Connect the color-coded quick connect air hoses between the control panel and the bulkhead (supply:black and vacuum:white), between the control panel and the bubbling tower (vent: yellow) and between the control panel and the sample hose pressure input (sample:green).
10. Set both control panel main power switches to their ON positions. Wait for the pressure displays to boot before proceeding. Display values other than ZERO indicate either a residual pressure/vacuum within the system or that the meter zeros need to be reset (tared).
11. Operate the VENT valve to successive positions (PRESSURE, HOSE, VACUUM) pausing at each position sufficiently to vent all systems.
12. Tare pressure monitor displays if necessary.
13. Set the supply line vent valve located below the gas tank changeover regulator to CLOSED (fully clockwise).
14. Connect both the main pressure lines between the gas tanks and the changeover regulator. Only one tank is actually in use at a given time. The selected tank is indicated by the arrow printed on the large handle located on the left side of the regulator.
15. Set the gas tank valves to OPEN (fully counter-clockwise).
16. Set both of the changeover regulator input valves to OPEN (fully counter-clockwise). Gas will flow into the system.

17. Observe the changeover regulator input pressures (the left and right gauges) to determine tank fill status. Fully charged tanks should show a nominal 2200 PSI.
18. Observe the changeover regulator output pressure (the center gauge), the bulkhead supply pressure gauge, and control panel supply pressure monitor. All three should read nominal 450 PSI.
19. Install a pump on the sample hose. Ensure that the pump fittings are secure and wrap electrical tape around the entire length of the pump (excluding the pump intake)
20. Install a weight to the bottom of the pump and wrap electrical tape around the exposed cable loops that might get snagged in the well. The length and density of the weight used will depend on the sampling depths. Greater sampling depths require more weight in order to transmit a "feel" for encountered obstacles.
21. Measure and record the distance between the sample pump intake and the lower-most depth marked on the sample hose sheath.
22. Measure and record the distance between the sample pump intake and the bottom of the weight below the pump.
23. Setup a tripod and pulley system to provide a smooth pathway for lowering and raising the sample hose in the well. The tripod should be secured to prevent shifting.
24. Connect a garden hose Y fitting to the test well sample port. Set the Y fitting valves to the CLOSED positions and OPEN the test well sample port valve. Check for leaks.
25. Prepare computer spreadsheet to calculate the number of sample cycles and the cycle pressure increments required to stack water samples to provide the necessary hose flushing and sample volumes.

Well and Water Parameter Monitoring

1. Connect a hose between one of the Y outlets and a continuous water parameter monitoring instrument flow cell. Follow applicable protocol for well water parameter stabilization prior to initiating water quality sampling (i.e., monitor specific conductance, temperature, pH, DO, etc.).
2. Make necessary measurements and/or observations of well flow meter and record flow rate.
3. Measure and record depth to water.

Position Sample Pump

1. Position the sample pump at the target sampling depth by operating the hose reel to raise/lower the hose/pump assembly in the well. Include the offset distance between the pump intake and the lower-most sample hose depth marking. The maximum sampling depth is limited by the distance between the pump intake and the bottom of the hanging weight below the pump.
2. Periodically check during deployment that the hose has not become hung up on some obstacle in the well by manually lifting the hose assembly and getting a "feel" for its weight and "bounce".

3. Use caution especially when retrieving the hose. The hose reel motor has sufficient power to rip the sample pump and/or weight from the sample hose should either become hung up within the well.

Sampling with Vacuum Cycles

Sampling is performed through an iterative procedure of vacuum and pressure cycles. Including vacuum cycles can increase sample recovery volume and decrease the number of pressurization cycles (and therefore compressed gas consumption) required to obtain a fixed sample volume. The use of vacuum becomes significant under shallow sample pump submergence conditions.

Initially set the control panel controls to:

- Regulator: CLOSED (fully counter-clockwise)
- Pressure CV: BYPASS
- Vacuum CV: CHARGE
- Source: OFF
- Sample : OFF
- Vent: OFF
- Vent Rate: CLOSED (fully clockwise)

1. *Initial Venting* – sample water enters both the pressure and the sample tubes.
   - Set controls:
     - Vent: HOSE
     - Vent Rate: ADJUST OPEN (counter-clockwise)
   - Watch the vent bubbler and wait until bubbling stops prior to proceeding.
2. *Initial Vacuum Cycle* – draws sample water into the pressure tube.
   - Connect the sample tube output to the control panel sample output.
   - Set controls:
     - Source: VACUUM
     - Sample: ON
     - Vent: OFF
     - Vacuum Pump: ON
   - Watch the vacuum monitor display. Run the vacuum pump until the meter reading stabilizes (generally no longer than 1 to 1.5 minutes). The stabilization value depends on ambient temperature of the pump and should be somewhere between -20 and -22 ft H_2O.
   - Set controls:
     - Vacuum Pump OFF
     - Vacuum CV: HOLD
   - Watch the vacuum monitor display. The vacuum will decay as water moves into the pressure tube. If the vacuum decays below the desired value, then recharge the vacuum by setting controls:
     - Vacuum Pump ON
     - Vacuum CV: CHARGE
   - Alternate the last two steps until the vacuum holds steady (or changes very slowly).

- Set controls:
    - Vacuum Pump OFF
3. *Initial Vacuum Vent Cycle* – restores atmospheric pressure in both tubes.
    - Set controls:
        - Vent: HOSE
    - Wait until the vacuum monitor reading approaches ZERO.
    - Disconnect the sample hose output from the control panel sample output and connect the sample hose output to the sample flow control valve.
4. *Pressure Cycle* – pushes water from the pressure tube into the sample tube.
    - Adjust the regulated pressure to the appropriate value
    - Set controls:
        - Vent: OFF
        - Source: PRESSURE
    - Watch the regulated pressure monitor display. Wait until the meter reading approaches the set value and bubbling from the sample hose stops.
5. *Pressure Vent Cycle* – restores atmospheric pressure and allows new sample water to enter the pressure tube .
    - Set controls:
        - Sample : OFF
        - Vent: HOSE
    - Watch the vent bubbler and wait until bubbling stops prior to proceeding.
6. *Vacuum cycle* – draws sample water into the pressure tube.
    - Set controls:
        - Source: VACUUM
        - Vacuum CV: CHARGE
        - Sample: ON
        - Vent: OFF
        - Vacuum Pump ON
    - Run vacuum pump and utilize Vacuum CV valve as described in Step 2
    - Set controls:
        - Vacuum Pump OFF
7. *Vacuum Vent Cycle* – restores atmospheric pressure in pressure tube.
    - Set controls:
        - Vent: HOSE
    - Watch the vacuum monitor display. Wait until the meter reading reaches ZERO.
8. Continue by repeating Steps 4 to 7 until sufficient sample volume is stacked.

Sampling without Vacuum Cycles

Vacuum cycles can be omitted when pressure cycling alone can efficiently produce sufficient sample volumes.

1. *Initial Venting* – sample water enters both the pressure and the sample tubes.
   - Set controls:
     - Vent: HOSE
   - Watch the vent bubbler and wait until bubbling stops prior to proceeding.
2. *Pressure Cycle* – pushes water from the pressure tube into the sample tube.
   - Adjust the regulated pressure to the appropriate value
   - Set controls:
     - Vent: OFF
     - Source: PRESSURE
     - Sample: ON
   - Watch the regulated pressure monitor display. Wait until the meter reading approaches the set value and bubbling from the sample hose stops.
3. *Pressure Vent Cycle* – restores atmospheric pressure and allows new sample water to enter the pressure tube .
   - Set controls:
     - Sample : OFF
     - Vent: HOSE
   - Watch the vent bubbler and wait until bubbling stops prior to proceeding.

Post-Sampling Pressure Bomb Flushing

Perform these procedures following discrete depth sampling to clean out the sample hose.

Initial Setup

1. Set accessory pressure regulator to OFF (fully counter-clockwise).
2. Connect main pressure lines between gas tanks and changeover regulator.
3. Open gas tank valves.
4. Open changeover regulator input valves.
5. Observe changeover regulator input gauges to assess tank fill status.
6. Observe changeover regulator output pressure gauge and bulkhead supply pressure gauge. Both should read nominal 450 PSI.
7. Set all valves on pressure bomb to OFF positions.
8. Connect hose between bulkhead Accessory Pressure port and pressure bomb pressure (upper left) valve.
9. Adjust accessory pressure regulator to ON (fully clockwise). Bulkhead accessory pressure gauge should read nominal 100 PSI.
10. Connect hose between bulkhead Accessory Vacuum port and pressure bomb vent (upper right) valve.
11. Connect hose between DI water reservoir and pressure bomb fill (lower right) valve.

12. Connect hose between one of the sample hose lines and pressure bomb output (lower left) valve.
13. Disconnect sample pump from sample hose. Place hose end in bucket.

Fill Pressure Bomb

1. Set pressure bomb vent valve to ON position.
2. Turn ON vacuum pump and allow pressure to drop in pressure bomb sufficiently to prevent backflow of any stored water to the DI water reservoir.
3. Set pressure bomb fill valve to ON position. Water will flow from DI water reservoir into pressure bomb.
4. Set pressure bomb fill valve to OFF position.
5. Replace/refill DI water reservoir if necessary and repeat steps 3-5 to obtain desired hose flush volume storage in pressure bomb. Pressure bomb has 1 gallon capacity.
6. Set pressure bomb vent valve to OFF position.
7. Turn OFF vacuum pump.

Flush Sample Hose

1. Set pressure bomb pressure valve to ON position.
2. Set pressure bomb output valve to ON position.
3. Flush all stored water through sample hose.
4. Set pressure bomb pressure valve of OFF position.
5. Set pressure bomb output valve to OFF position.
6. Set pressure bomb fill valve to ON position to vent pressure.
7. Refill pressure bomb and repeat flushing procedure for other sample hose line.