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1.0 EXECUTIVE SUMMARY

Our contribution to the 2001 Vadose Zone Transport Field Study (VZTFS) was funded by the Department of Energy under the SUBCON project RL31SS31, Hydrologic Characterization of the Hanford Vadose Zone at Representative Sites. The purpose of the testing was to perform dynamic electrical measurements using high-resolution resistivity (HRR) technology for assessment of through casing resistivity technology (TCRT). . We used the existing casing infrastructure to act as a sensor network for data acquisition. Using the existing steel-cased-well infrastructure at the Transport Field Study Test Site simulates conditions that exist at Hanford Tank farms where steel-cased wells (dry wells) are currently being used to monitoring gamma fluxes and water contents around leaking tanks. The use of the dry wells for plume monitoring is a desirable objective and this objective has been achieved in the FY 2001 tests at the VZTFS site. The results unequivocally demonstrate that HRR technology is capable of accurate leak detection and plume monitoring. This report discusses the results of this years' study.

As with year 2000, measurements were made in three general phases: (1) prior to the first injection, (2) during injections, and (3) after all injections were completed. We based nearly all measurements on the existing 32 steel casings. We also placed electrodes at the bottoms of the 32 casings and physically isolated them from the casing walls. And, as with last year, we placed an electrode at the bottom of the PVC injection well. The incorporation of the injection-well electrode substantially enhanced the sensitivity of the method. It has become clear that direct contact with the leaking solution has significant advantages over more complex external volume measurements.

Based on the results so far, the following observations and conclusions have been made.

1. Measurements using steel casings exclusively as electrodes provided:
    a. *positive indication* of the existence of the leak, i.e. leak detection,
    b. *coarse quantitative volumetric information* about the injection,
    c. *accurate location of the leak source,*
    d. *qualitative travel times* for the injected solution,
    e. *good lateral resolution* of the spread of the solution, and
    f. *poor vertical resolution* of the spread of the solution.

2. Measurements using direct electrical contact with the injected solution provided:
    a. *highly accurate timing of the onset of the leak*,

   b. *minimum volume detection limit of one liter*,
   c. *qualitative indication of reactivated leaks*, as shown by interrupted injections,
   d. *accurate, quantitative travel times* for the injected solution,
   e. *quantitative volumetric estimates* of the injection,
   f. *precise location* of the leak source, and
   g. *simple, mathematical relationships* between injected volume and data.

3. Refinement of data processing algorithm and techniques should reduce calculation time to nearly real-time results.

4. The technology can be implemented non-invasively, although pre-existing invasive structures such as steel well casings can be incorporated and will enhance the results.

5. Deployment of the system is straightforward requiring only simple electrical connections to appropriately grounded metallic structures.

6. Deployment can be made relatively inexpensively and can be adapted to virtually any on-site conditions.

7. Monitoring may be controlled remotely or made autonomous.

8. Results may be telemetered in real-time to a centralized location.

9. The technology can be deployed using existing infrastructure, although site specific modifications would enhance the performance.

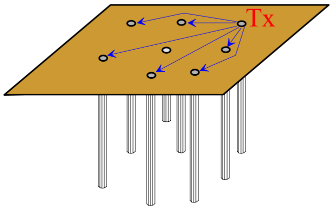
2.0 INTRODUCTION

As part of the RL31SS31 SUBCON project, Hydrologic Characterization of the Hanford Vadose Zone at Representative Sites, Battelle Pacific Northwest National Laboratory contracted with HydroGEOPHYSICS to conduct electrical geophysical measurements to dynamically monitor the sodium thiosulfate injection performed during April 2001. Survey efforts were completed at the 32-well Sisson and Lu injection test site (herein referred to as the Site). The Site was established nearly twenty years ago in the 200 Area within the Hanford Site Ward and Gee (2000 and 2001).

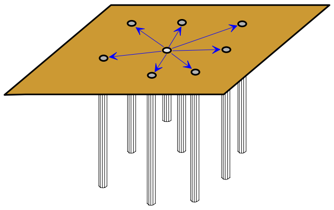
The electrical surveys were conducted: (1) before any injections were made; (2) during the initial injection; (3) after two of the injections were completed; and (4) after all five injections were completed. Data acquisition was completed during three separate periods: March 28th through April 1st, April 25th through April 28th and May 21st through 23rd.

Electrical measurements were made using three types of electrodes for sensors. The three types of electrodes utilized were; (1) the 32 existing steel casings, (2) electrodes placed at the bottoms of the 32 casings and isolated from the steel walls (bottom-hole electrodes), and (3) an electrode placed in the bottom of the PVC injection well. In the year 2000 VZTFS we had some encouragement with electrode types 1 and 3, but electrode type 2 was abandoned due to time constraints. This year we fabricated the bottom-hole electrodes on site and added them into the suite of measurements.

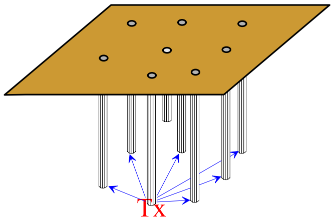
There were five configurations of electrical measurements:



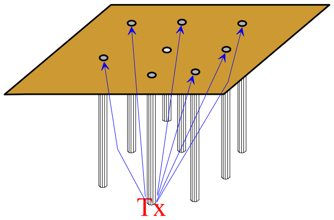
1. *Measurements between steel casings*. This configuration consisted of electrically energizing an individual steel casing and measuring the resultant potentials on all other steel casings.



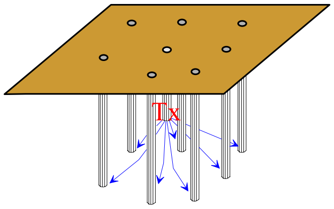
2. *Measurements between an electrode in the injection well and steel casings.* This configuration consisted of electrically energizing the electrode placed at the bottom of the injection well and measuring the resultant potentials on all 32 steel casings.



3. *Measurements between fabricated electrodes placed at the bottoms of all casings.* This configuration consisted of electrically energizing individual electrodes placed at the bottom of each steel casing and measuring the resultant potentials at all other bottom-hole electrodes.



4. *Measurements between the fabricated bottom-hole electrodes and steel casings.* This configuration consisted of electrically energizing individual bottom-hole electrodes and measuring the resultant potentials at all the steel casings, other than the one containing the energized electrode.



5. *Measurements between the injection-well electrode and bottom-hole electrodes*. This configuration consisted of electrically energizing the injection-well electrode and measuring the resultant potentials at all 32 bottom-hole electrodes.

We made different numbers of measurements depending on the length of time to complete a set for all electrode combinations. Early in the study we realized that some measurements did not produce information sufficiently different from other similar measurements. Consequently, we stopped any further measurements on those sets.

Method	Data Sets	Points Per Data Set	Total Points
1	10	544	5,440
2	210 / 183	32 / 48	15,504
3	2	544	1,088
4	2	544	1,088
5	2	32	64
		Total	23,184

Table 1 – data acquisition totals

We alternated data acquisition periods with Lawrence Livermore National Laboratory's (LLNL's) ERT study during the initial injection. After that we were scheduled to work between others and had minimal interference. We were able to acquire data while radar measurements were being made and while neutron data were being acquired while neither interfering nor being interfered with. We learned early on that the data acquired using the injection-well-electrode could be gathered quickly and appeared to be the most diagnostic of the various electrode arrangements. Consequently, we leaned heavily on those data sets and also established a routine for automated data acquisition that allowed virtually continuous measurements (approximately every 20 minutes, with 1/3 reciprocal data).

PNNL project manager and on-site coordinator was Mr. Glendon W. Gee, Senior Staff Scientist. Numerous PNNL personnel were on site during the initial attempt at injecting the prepared solution.

hydroGEOPHYSICS personnel who completed the field data acquisition portion of the survey were Mr. Marc Levitt, Geological Engineer, and Dr. James B. Fink, President of hydroGEOPHYSICS. Subsequent processing was performed on-site and in the Tucson office by Mr. Marc Levitt, Mr. Chris Baldyga, and Dr. James B. Fink; hydroGEOPHYSICS personnel.

2.1 Objective of Investigation

The objective of the survey was to use TCRT technology to characterize the dynamic subsurface hydrogeology of the Site using hydroGEOPHYSICS' proprietary processing procedures on data gathered using the existing 32 steel well casings and the injection well. Additionally, three-dimensional modeling and volumetric estimations of detected injection solution were desired, as well as any detectable preferred infiltration pathways.

2.2 Site Location

The U. S. Department of Energy's (DOE) Hanford Site is located approximately twenty miles northwest of the town of Richland, Washington. Access to the Site was by all-weather paved roads and a short dirt road. The surrounding area was relatively flat and fairly densely covered with sagebrush. Remote electrode locations were placed well away from the cordoned-off radiological hazard areas and accessed by walking through the sagebrush.

2.3 Survey Area & Logistics

From a geophysical standpoint, the Site is readily accessible and posed few logistical problems in acquiring data.

2.4 Casing and wire arrangement

Figure 1 is a plan map showing the location of the 32 steel casings, the injection well, and other related features.

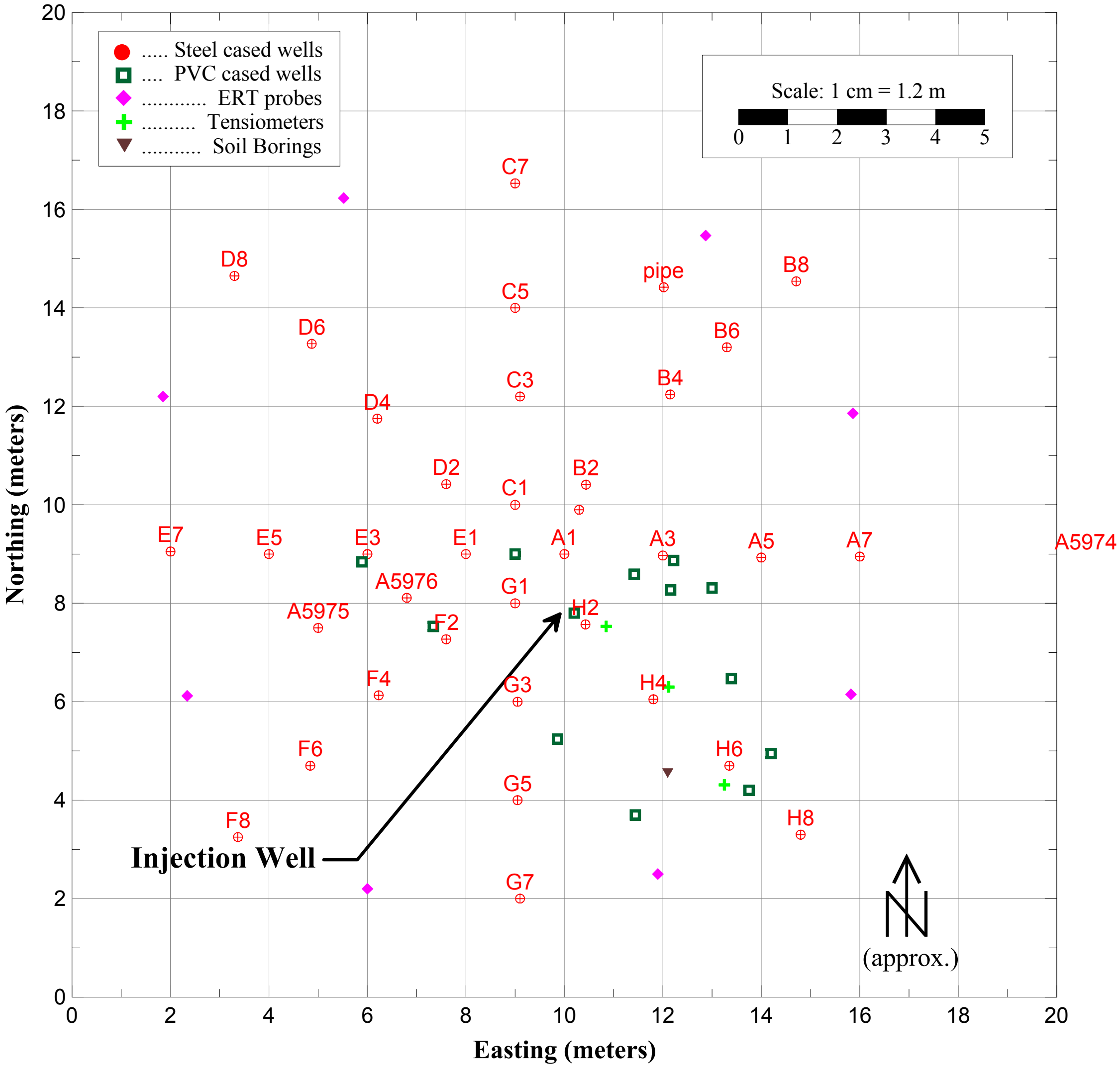


Figure 1 - location and feature map - Sisson and Lu site

Our numbering system for the casings conforms to that of previous studies. The casings are labeled with a combination letter and number, such as, A3. The letters indicate the radial directions in which the casings are located. Those are: east “A”, northeast “B”, north “C”, northwest “D”, west “E”, southwest “F”, south “G”, and southeast “H”. The numerical portion of the label indicates the distance in meters from the center of the casing array. Cardinal direction casings are located 1, 3, 5, and 7 meters from the center. Diagonal direction casings are located 2, 4, 6, and 8 meters from the center. The new injection well is located in the southeast quadrant approximately one-half meter away from casing H2.

All electrical measurements were made using four grounded electrical contacts at any given time. Two contacts were for current injection and two were for potential measurement. Most measurements used the 18 meter (60 feet) long steel casings as electrodes which, because of the length of the casings, required special processing. Both transmitting and potential measuring electrodes had remotely located counterparts. Last year’s remote electrodes were reused. No additional surface electrodes were installed either at the remote electrodes or within the casing array.

2.5 Equipment

As with last year’s study, the instrument used for the electrical measurements was an OYO Corp. McOHM-21. The McOHM-21 is a DC-powered electrical resistivity instrument. The McOHM-21 is owned by PNNL and use of the instrument and peripherals was kindly authorized by Mr. Mark Sweeney. HydroGEOPHYSICS also owns a McOHM-21 and provided additional peripherals for the study.

Photo 1 – McOHM-21 with transmitter scanner

Photo 2 – receiver scanners with custom cabling

The combination of both systems allowed the simultaneous connection of up to 96 electrodes over the standard 32 provided by the individual systems. The unit was used in conjunction with OYO scanners and individual wires to the casings. The McOHM-21 has the capability of automatically switching between electrodes without having to physically move the wire connections after initial set-up. Automatic switching saves on physical labor and time, cuts down on human transcription and tracking errors, and better allows the operator to control array logistics. We made the best of this capability and programmed the McOHM-21 to make several overnight runs in order to obtain dynamic data. The McOHM-21 has an integral color-display CRT that allows real-time display of the transmitted and received waveforms. Stacking of the received waveforms ranged from 4 to 16. Maximum current output is 200 milliamps. An internal 3.5-inch floppy diskette drive allows for data storage and retrieval. Each data set acquired was labeled and archived for subsequent processing.

The greatest advantage the McOHM-21 unit has over other similar instruments, is the ability to pre-program a survey and repeat the program without operator intervention. While it had some nice advantages, it also had some rather frustrating design shortcomings. For example, the system is very sensitive to ambient temperature. The high-density data have an oscillating character that correlates very nicely with the diurnal variation of temperature. It is a minor source of noise, but it is of sufficiently low amplitude that we don't feel it has masked the desired signal. It is also very power hungry. It can operate from automotive batteries but requires 3 to 4 batteries to make it through a 12 hour period.

In spite of the convenience and strengths of the McOHM-21 unit, future measurements will be made with different instrumentation that should have fewer thermal problems, lower power requirements, and larger (and more current) data storage capability.

The bottom-hole electrodes were fabricated on site and consisted of short (6 inch) stainless steel electrodes surrounded by diatomaceous earth contained in nylon stockings. These were then dropped into each steel casing. This arrangement allowed the placement of the electrodes at the bottoms of the uncapped steel casings and prevented the steel electrodes from having metal-to-metal contact with the steel casings.

Photo 3 – Steel electrode in diatomaceous earth

Photo 4 – Lowering electrode down casing

2.6 Data Acquisition

During the initial setup (background measurements) we tested all combinations and permutations of hookups between the steel casings, injection well, and bottom-hole electrodes. Based on the outcome of the initial tests we focused our efforts on what appeared to be the most diagnostic combinations. We then programmed the system to acquire consecutive, repetitive data-sets for each measuring period. The majority of data sets were collected continuously during each site visit. Figures 2a, 2b, and 2c show the time-distribution of the two principal data sets acquired during the three trips to the site. The purpose for making repetitive measurements after the injection was to dynamically monitor migration of the injected plume.

Figure 2a – Time Graph of Data Acquisition Periods - Trip 1

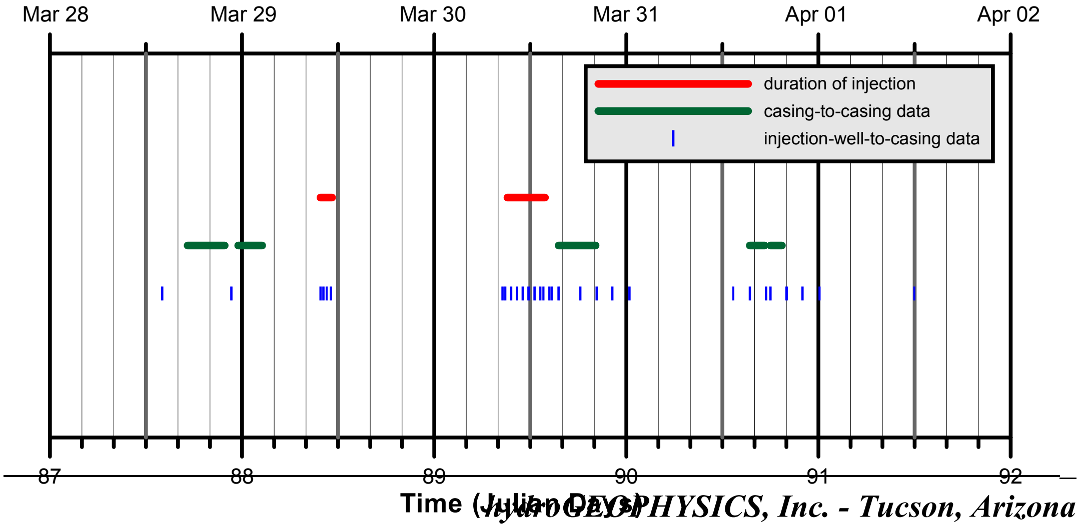


Figure 2b – Time Graph of Data Acquisition Periods - Trip 2

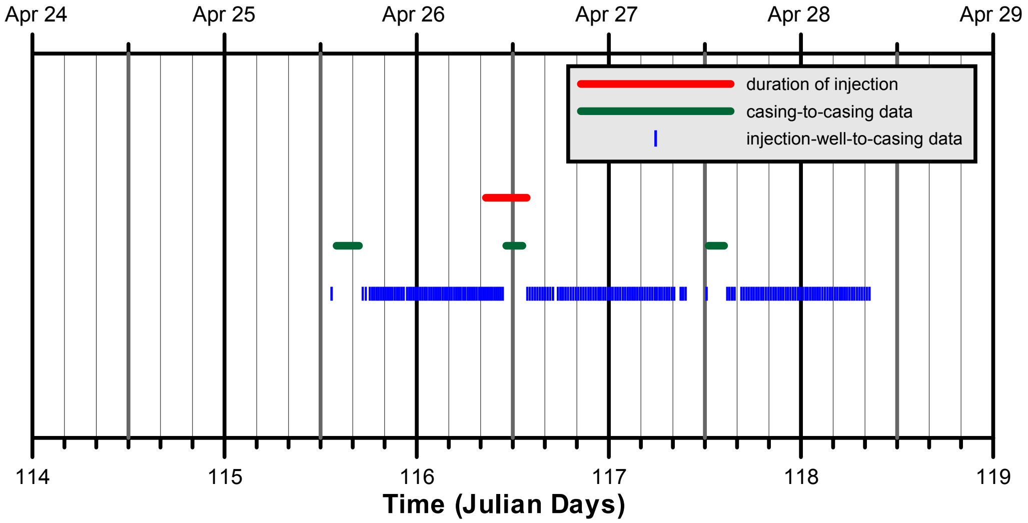
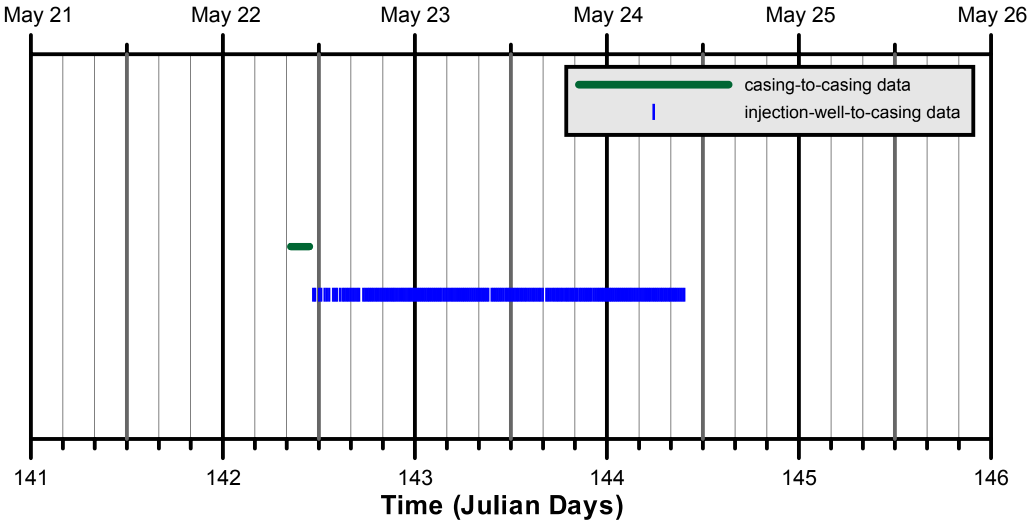


Figure 2c – Time Graph of Data Acquisition Periods - Trip 1



2.7 Data Processing

All data were processed with hydroGEOPHYSICS' proprietary software package either on-site, in the Richland area, or in the Tucson office.

Data values presented are essentially resistance measurements, i.e. voltages normalized to current and sometimes to distance.

For the difference plots, residual potentials for each repeated data point were determined by subtracting background values from observed data. In some cases, obvious trends, either as a function of time or distance, were removed from the data to enhance more subtle changes.

3.0 METHODOLOGY

Leak detection methods have traditionally relied on either: (1) a loss of liquid volume inside a container, or (2) a gain in liquid volume outside a container. We adapted our HRR technology to the Sisson and Lu environment to demonstrate in-situ (outside the container) volume determination and binary leak detection (i.e. leak/no leak). We used the existing infrastructure at the Sisson and Lu site (32 steel well casings and 1 PVC injection well) to serve as active and passive electrical sensors (electrodes). We made a variety of measurements to determine which infrastructural arrangement would be most sensitive to the smallest leak volume and which arrangement would be most accurate in estimating the leak volume. The various arrangements and results are discussed below.

We initially tested all electrode combinations and permutations of the 32 steel well casings and a single electrode placed in the bottom of the PVC injection well. In every configuration we energized one electrode and measured the potential at other electrodes. We found that some combinations were very time consuming (because of the large number of combinations) and some went rather quickly (because of the limited number of combinations). We tried to streamline acquisition for the slowest arrangements by minimizing redundancy. We evaluated various data-stacking options and used the least number of stacks that would produce repeatable data. We eventually discarded some arrangements, and, in the end, determined that two arrangements had the most promise. We found that each arrangement produced useful results and where those results were similar, we opted to continue with the more favorable arrangement (based either on time or usefulness of the data).

One of the methods we used during the 2000 and 2001 VZTFSs included placing an electrode inside the injection well. We have previously successfully performed leak detection projects by placing an electrode in a container (usually a geomembrane-lined pond) and monitoring potential changes as the pond fills. This method of leak detection is independent of volume, but, with sufficient control, such as a known volume of a leak, it can be crudely calibrated. What separates this method from other volumetric methods is its high sensitivity to leaks, particularly with electrically conductive solutions. It is essentially a binary indicator; either there is a leak or there isn't. We believe this method of placing an electrode essentially within the container (in the case of the Sisson and Lu site the injection well) represents a third method of leak detection that is volume independent. The data acquired using this method are discussed under Method 2 in Section 4.1.2.

We have also successfully traced contaminant plumes by electrifying them with steel well casings or electrodes placed in wells open at the plume horizon. This is simulated at the Sisson and Lu site by energizing virtually any of the steel casings and measuring the others. Data acquired using this approach are discussed under Method 1 in Section 4.1.1.

Three of the methods evaluated used on-site fabricated electrodes placed in the bottoms of the 32 casings. None of these three methods were considered worth pursuing at the cost of diluting effort on the other two methods. The results for these three methods are discussed under Methods 3, 4, and 5 in Sections 4.1.3, 4.1.4, and 4.1.5, respectively.

3.1 Electrical resistance and resistivity

The geophysical resistivity method is based on the capacity of earth materials to conduct an electrical current. The concept behind applying the resistivity method is to detect and map changes or distortions in an imposed electrical field due to heterogeneities in the subsurface. Changes in soil texture and moisture content will cause changes in an imposed electric field. Distortions of the electric field can be measured on the ground surface, in boreholes, or with a combination of the two. Resistivity measurements are made with a minimum of four electrodes in contact with the ground. These electrodes are always considered to represent point sources. Resistivity calculations depend on the point-source nature of the field measurements. Various electrode arrangements have been used over the decades, most of which involve collinear arrays such as Schlumberger, Wenner, dipole-dipole, three-array, pole-pole (also called "normal" in borehole logging), and many more. Each array shows merit in specific environments and all (ideally) produce useful information. Data acquired for all arrays consists of a current-normalized potential difference. Then, typically, the data are "reduced" to a homogeneous, isotropic half-space by using a geometric factor that takes into account the inter-electrode distances on the half-space surface. Alternatively, current-normalized potentials can be treated independently without invoking half-space constraints.

The data acquired for the VZTFS study violate the point-source assumption because of the very high aspect ratio of the steel casings which were used as electrodes. The data presented in this report have also been processed with a proprietary software package that can remove the non-point-source characteristics from the observed measurements. All data are kept in normalized potential form and no attempt to create "apparent resistivity" values was made. This actually allows the data to be presented in a more meaningful manner. We have presented the casing data in various formats; e.g. potential versus time, potential versus distance, potential versus injected volume, cross-sectional distributions of potential and volume distributions of potential.

4.0 RESULTS & INTERPRETATION

4.1 Results

The results are presented in a variety of formats that, hopefully, convey the spatial and temporal characteristics most relevant to the objectives of the study.

All results are presented using normalized potentials. These range from a few milliohms to tens of ohms, a spread of approximately five orders of magnitude. Such a large range of data values, in itself, suggests a high probability of feature recognition and characterization. This large range is due entirely to the high electrical conductivity of the injected solution and its effect on the ground. Interestingly, at the end of the study after 5000+ gallons of thiosulfate had been injected, another 3000 gallons of much lower conductivity river water were injected to "flush" the system. The electrical conductivity of the ground appeared to increase significantly as a result. Figure 3 shows the full time period from initial injection to post injection. The stepped black line is the cumulative volume of injected solution, the blue line is the solution conductivity (mostly off scale), and the red line is the observed potential between the injection well and casing A1. The solution conductivity shows an appropriate decrease when the river water is used at the end of the injections, but the in-ground conductivity (red line) continues to increase.

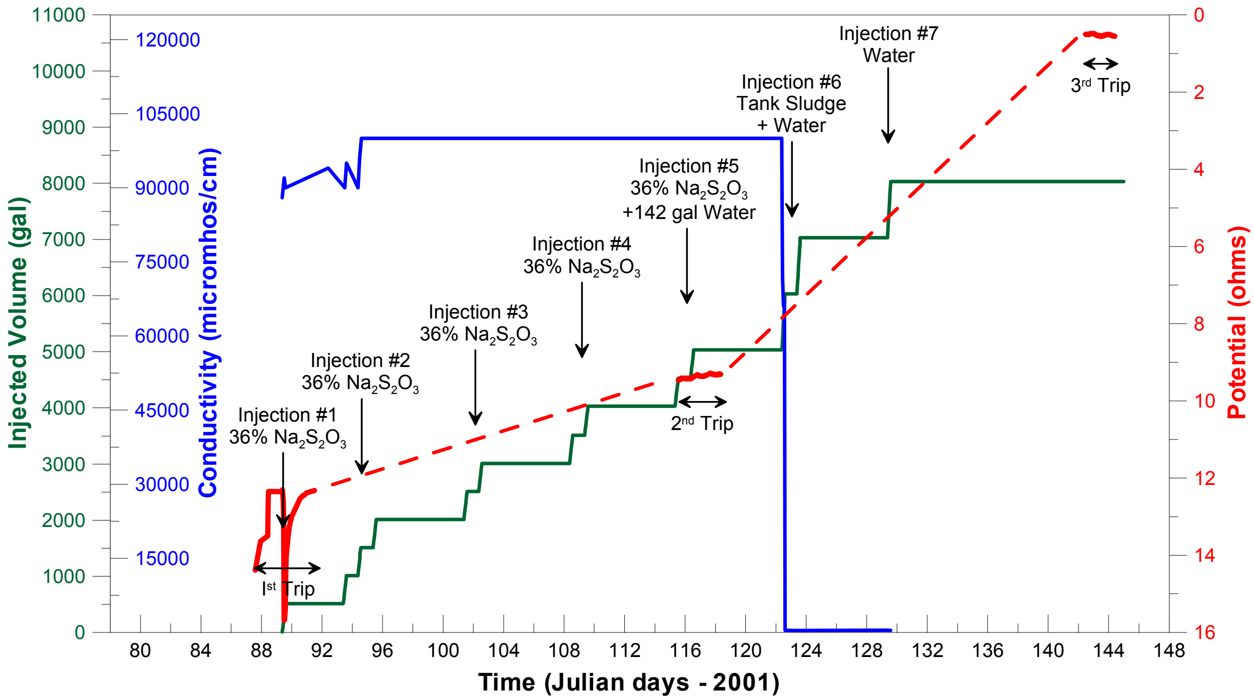


Figure 3 – comparison of potential readings vs. injected volume and conductivity

In retrospect, it might have been useful to continuously monitor the site, especially during this flushing exercise as the results from the injection measurements and the post-injection data differ substantially. Nevertheless, we observed the change electrically and see a crude correlation between the observed potentials and volume.

Usually, higher potentials represent drier soil conditions and lower potentials represent increased moisture content. We encountered some unusual effects, particularly during the initial injection, that were counter to that, generally applicable, relationship. These effects are discussed in Section 4.1.2. We also observed dipolar responses after injections where the actual target volume was located between closures of high and low potential. These results are discussed in Section 4.1.1. Regardless of their implications or interpretations, on all plots high potentials are expressed in warm (red hued) colors and lower potentials are shown in cool (blue hued) colors.

Electrical contact with the grounded steel casings was made at a stainless steel bolt threaded into each casing near the top of the casing. The holes were drilled, threaded, and prepared last year by PNNL personnel.

Several reciprocal measurements were made where the reverse arrangement between energized electrode and sensor was used; i.e. the previously energized electrode became the sensor and the previous sensor became the energized electrode. Over 98% of the reciprocal measurements were within one percent of the forward measurements.

In order to compare the electrical data to the neutron density data, we attempted to process the neutron data in the same three dimensional volume software previously used. We immediately ran into problems with significant differences between last year's data and this year's. In order to generate a volume, our three-dimensional modeling package would only produce believable results by using soil moisture levels of less than 6%. This is lower than the residual moisture level. Although visually the results compared favorably with our inverted data, we couldn't reconcile the difference between the apparent low moisture content and the known injected volume. Consequently, in the interests of time, we abandoned processing the neutron data.

4.1.1 Measurement between steel casings

Measurements from one steel casing to another, preferably called "casing-to-casing" measurements consisted of simple voltage measurements made at the top of each casing due to an "injected" electrical current from another casing.

If all combinations for 100% redundancy were made, then there would have been 992 total measurements per event and it would have taken approximately 6 hours to complete. We opted to minimize the time by making 496 measurements with only 48 reciprocal measurements for a total number of 544 data points per event or data-set. This took roughly 3 hours.

The data consist of at least one measurement between every casing pair. With 496 observations in the well-cluster there are a number of ways to view the data. We opted to show the effects of the initial injection at two times after it was completed; 1. One hour after completion, and 2. One day after completion. These data are shown in Figures 4, 5, 6, 7, and 8.

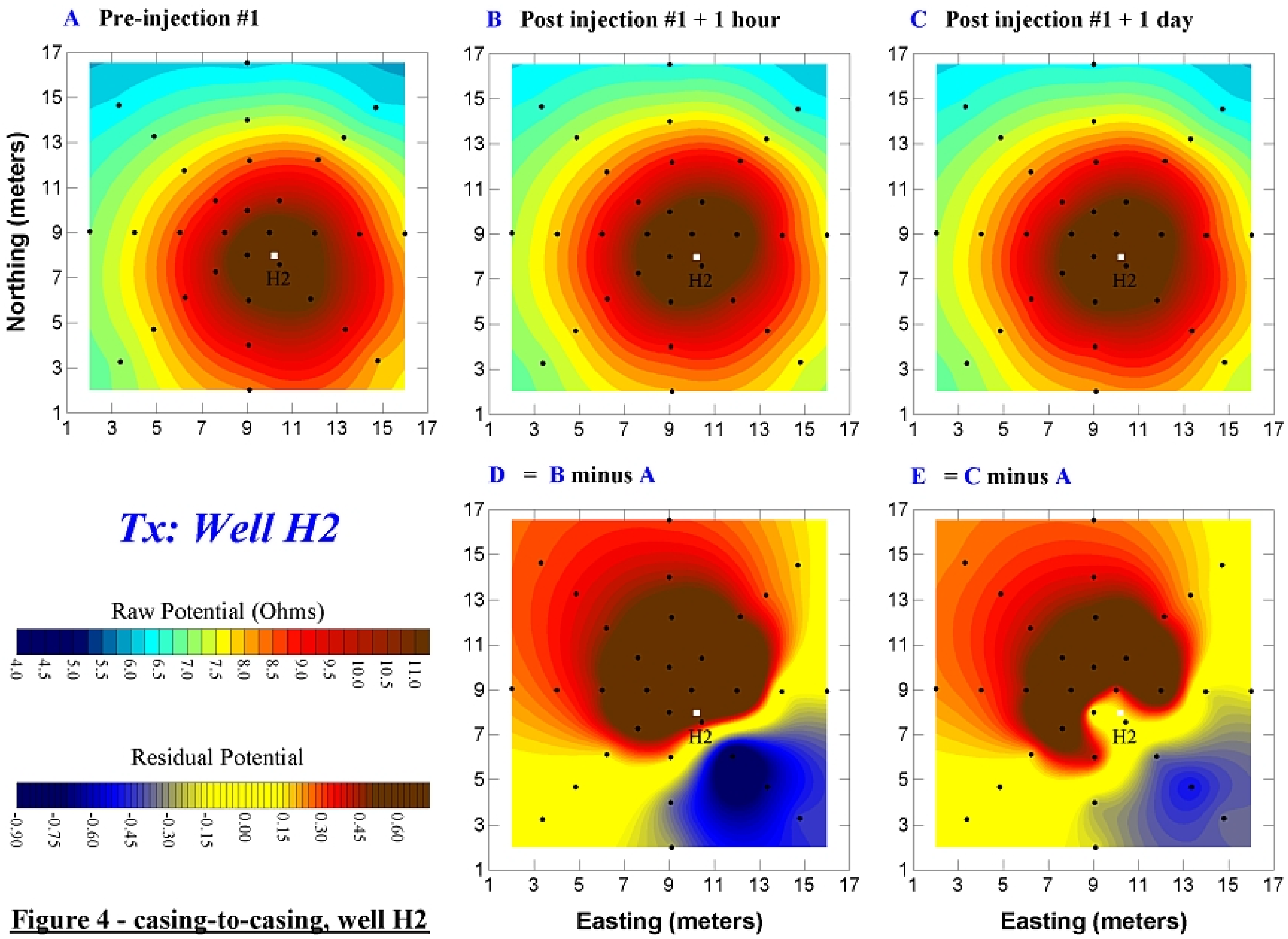


Figure 4 - casing-to-casing, well H2

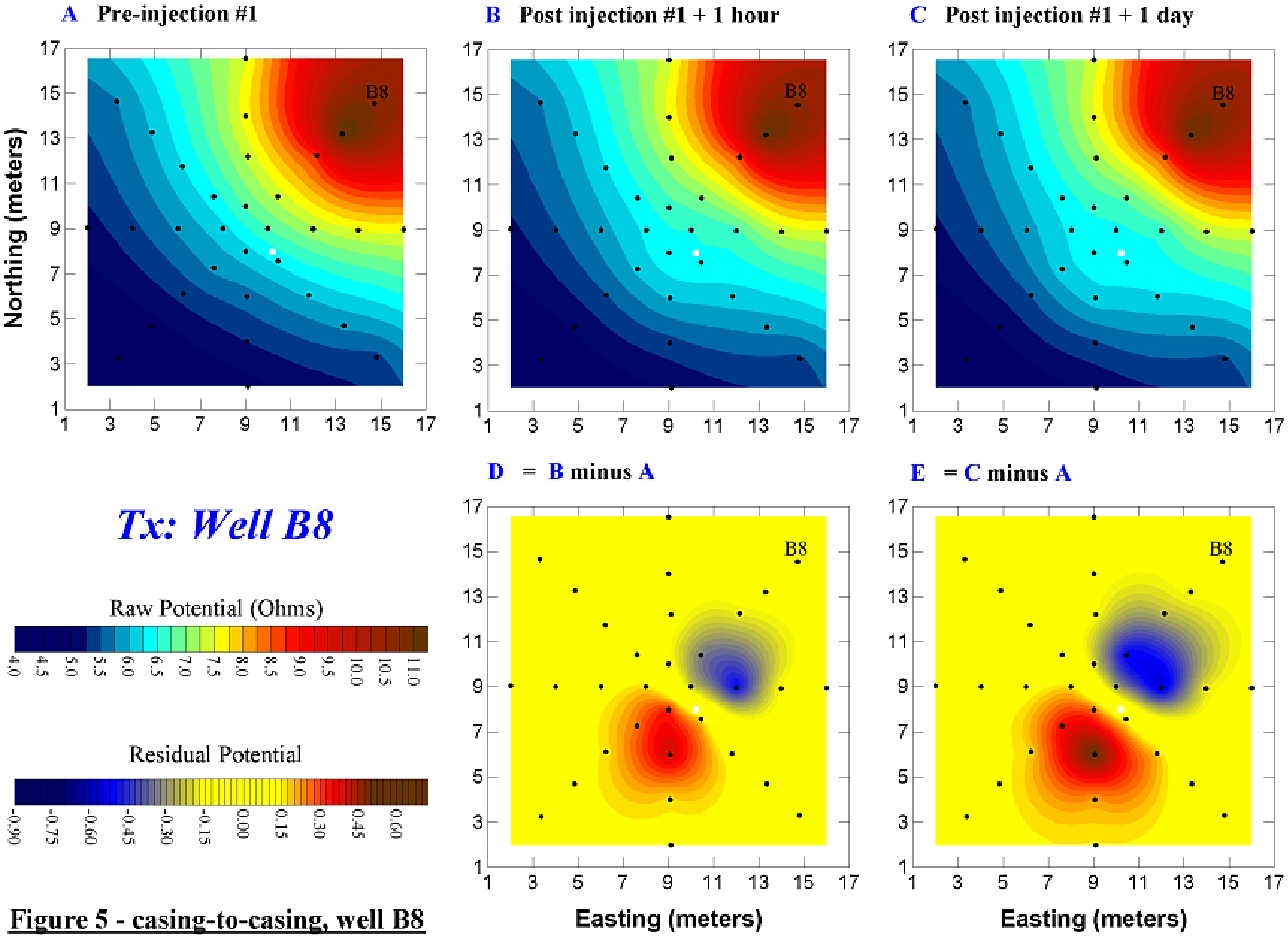


Figure 5 - casing-to-casing, well B8

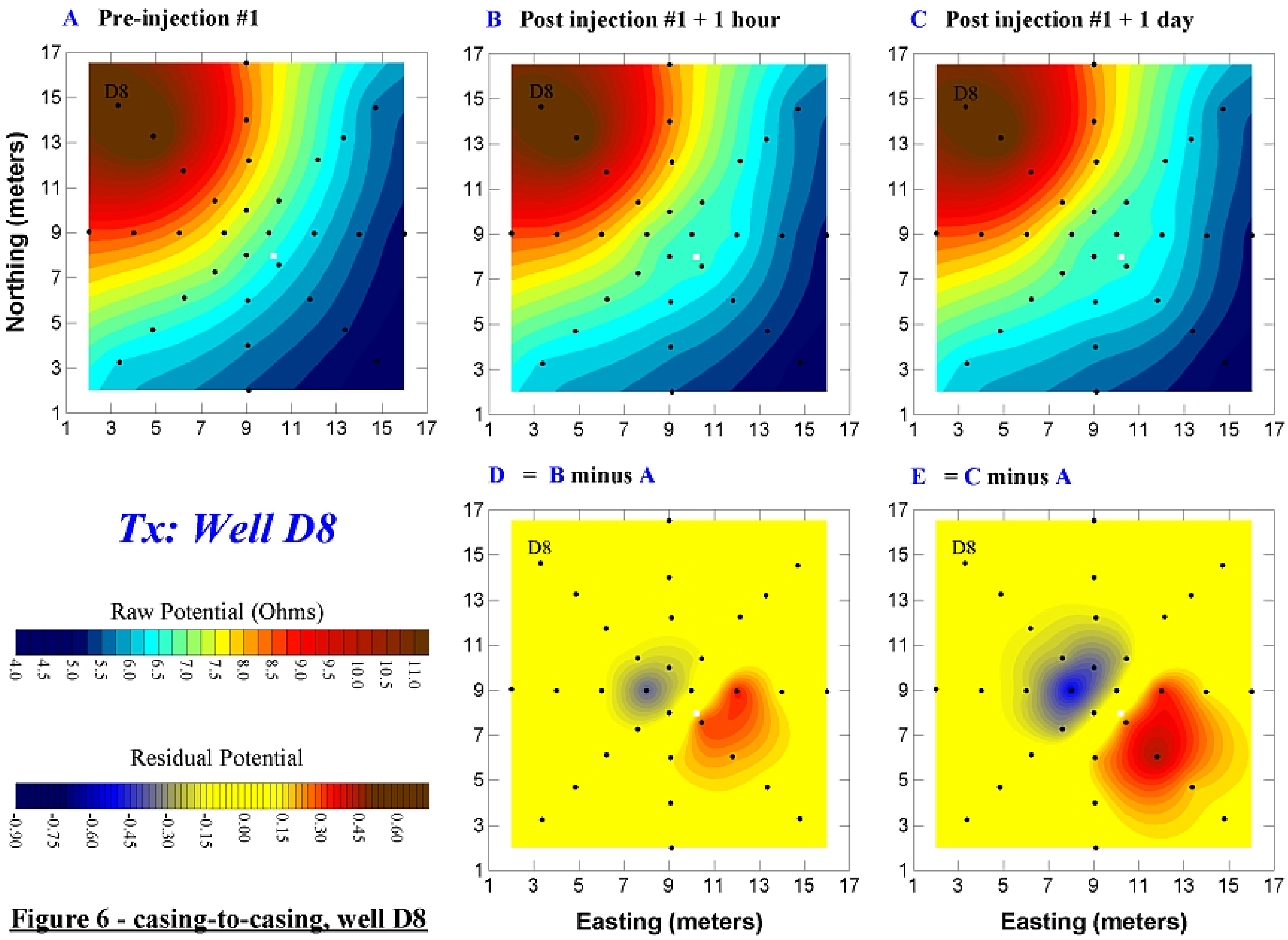


Figure 6 - casing-to-casing, well D8

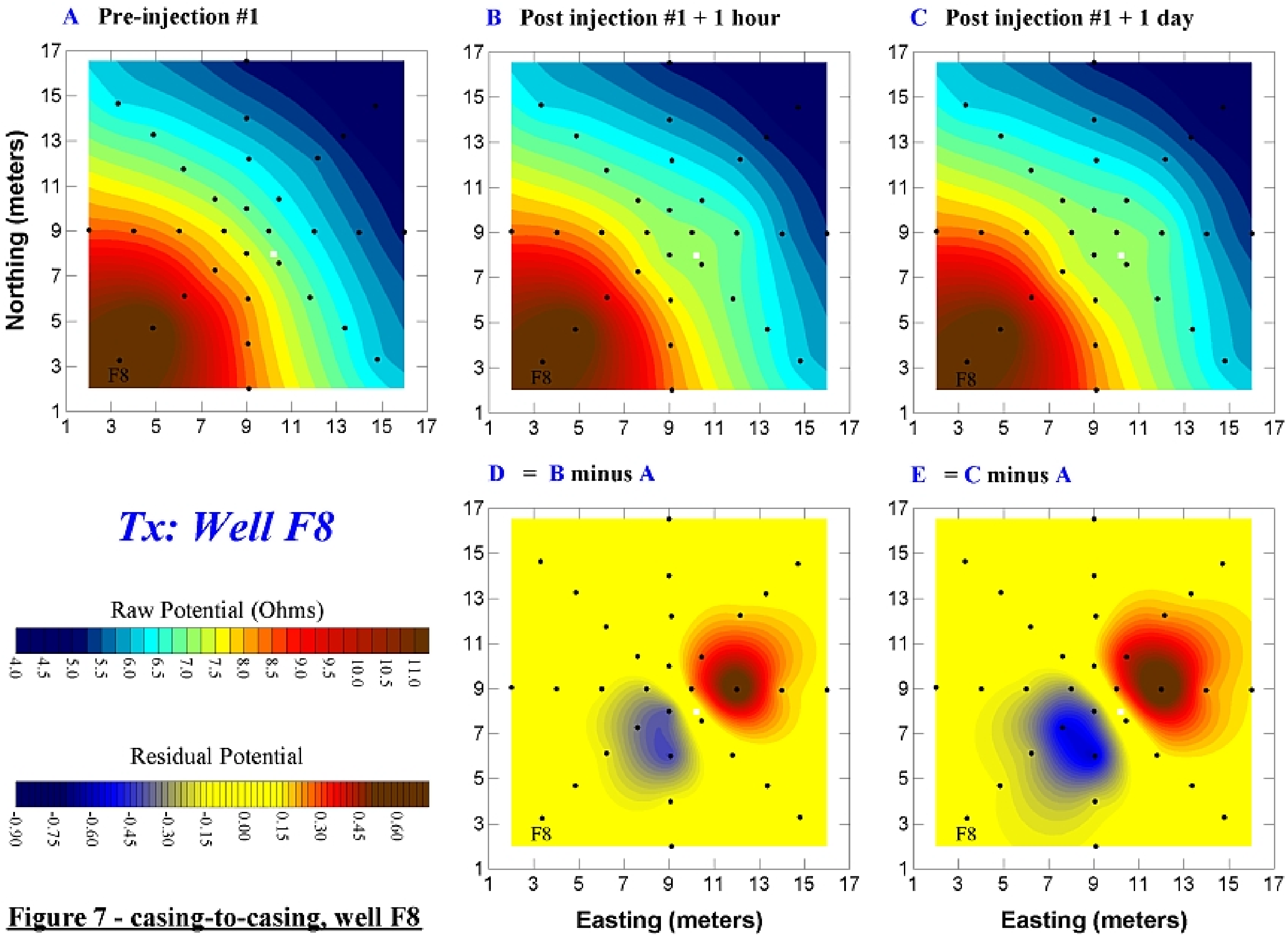


Figure 7 - casing-to-casing, well F8

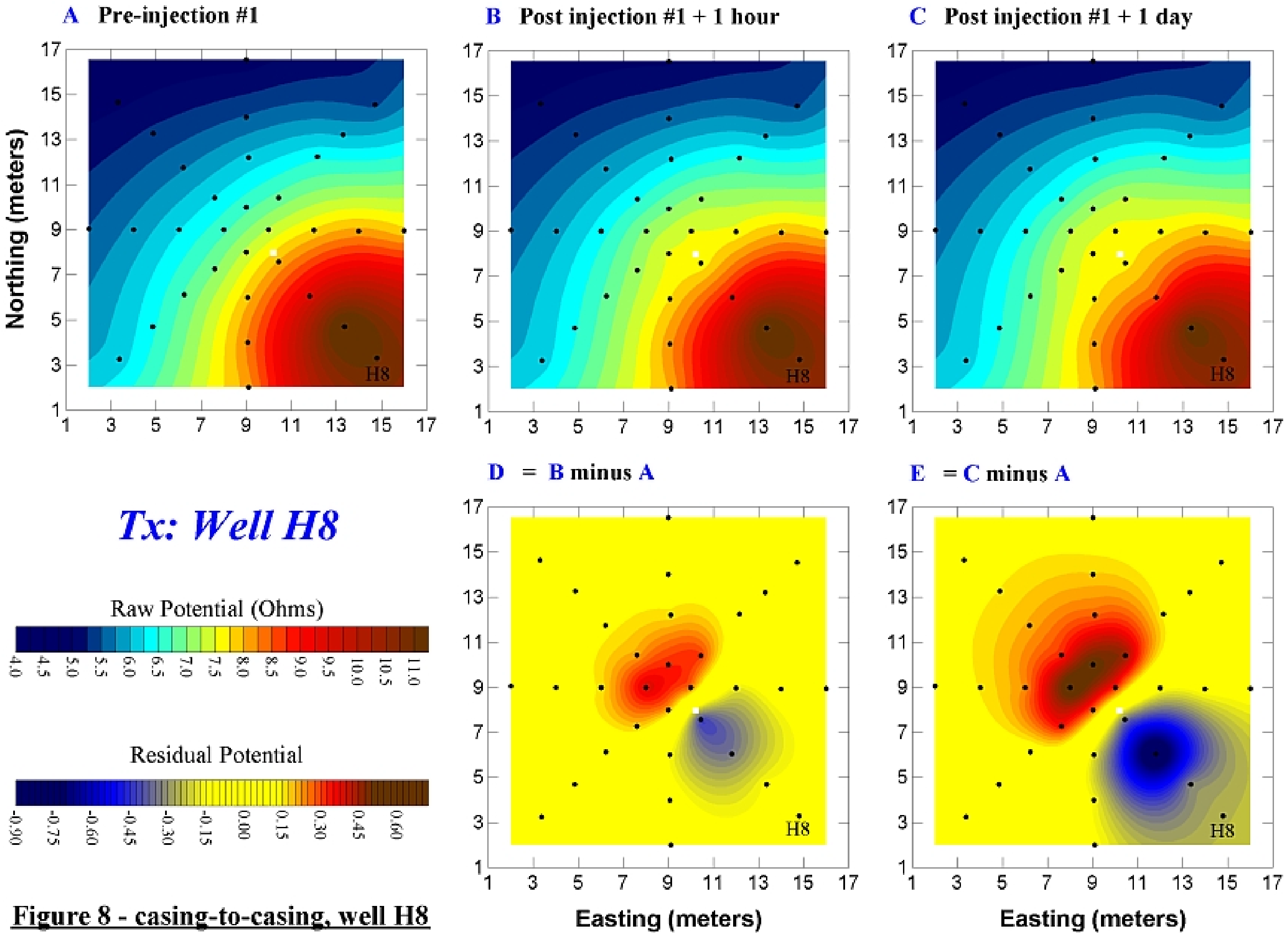


Figure 8 - casing-to-casing, well H8

These Figures show five images per figure and color scales for reference. Before discussing the source of the images the presentation sequence should be noted. The sequences of images on these figures shows the data before and after processing. Going from upper left to lower right in storyboard fashion;

(1) the upper left image labeled “A” in all Figures is the pre-injection data set acquired the day before the initial injection attempt. It is considered to be “background.”
(2) the upper-center image labeled “B” shows the observed data acquired immediately after the completed first injection; i.e. between one to three hours after completion.
(3) the upper-right image labeled “C” shows the observed data acquired the following day after the injection. This was done to observe changes due to continued infiltration.
(4) the lower-center image labeled “D” shows the one-hour post-injection data processed by subtracting the background (image A).
(5) the lower-right image labeled “E” shows the one-day post injection data processed by subtracting the background (image A).

Figure 4 shows the potential distribution around energized well H2. H2 was selected for this example because it is located closest (within ½ meter) to the point of injection. Note that the primary fields in the three upper images all have very similar appearances; a circular appearance to the contours centered around well H2. This circular pattern is to be expected regardless of whether the source is a point or a line. Note also that there is no evidence of distortion due to the presence of the other steel casings.

The lower two images show the same data in images B and C but with the background in A removed. The strong dipolar character of the residual data is indicative of a conductive body at the inflection between the high and low closures. The difference between D and E is due to continued migration of the injected volume and a change in shape and location of the volume.

To demonstrate that proximity to the injection is not required to produce diagnostic information, the following four figures show the effects of energizing the most distal casings in each direction from the center of the casing array. The casings used were B8, D8, F8, and H8.

Note in each case that the primary field consists of circular contours centered on the source well. Again, and in each case, removing the background response from the post-injection data reveals a dipolar character to the residual data. The dipolar feature is due to the presence of a conductive body located at the inflection between the high and low closures. Note also that the character of the dipolar feature is consistent regardless of the location of the excitation source. The low is always on the source side of the body and the high is always on the “lee” side of the body.

As with the H2 data, the one-day, post-injection data show an increase in size of response (compared to the one-hour, post injection data) indicating a change in physical characteristics of the conductive body.

All of the casings were used as sources, so, 32 of these plots could be produced. They would all show essentially the same thing. Collectively, the entire data set could be inverted to models with well-defined shapes and volumes. However, other results took priority over modeling these data because of the accelerated project schedule.

It should be evident that continuous monitoring of the casings would produce dynamic information regarding the expansion and migration of the injected solution. Rates of change of the causative body could be related to solution travel times.

In short, the casing-to-casing method is capable of producing volumetric and dynamic results. It has demonstrated at least a 500 gallon minimum sensitivity. We estimate that its threshold might be between 200 and 300 gallons. It may well be less, but the obvious controlling factor is the distance from source to leak. The method accurately locates the leak laterally. Vertical resolution is very poor although the size of the dipolar response feature offers a qualitative indication of depth. Nothing needs to be in contact with the injected solution. The capability for scaling up this method is quite good.

4.1.2 Measurements between injection well and steel casings

Measurements between the injection well and the steel casings consisted of simple voltage measurements made at the top of each casing due to an “injected” electrical current from a stainless steel electrode placed at the bottom of the PVC injection well. Electrical contact with the steel casings was made at a stainless steel bolt threaded into each steel casing near the top of the casing. The holes were drilled, threaded, and prepared last year by PNNL personnel. Several reciprocal measurements were made where the steel casings were energized and the potential was measured in the injection well. Over 98% of the reciprocal measurements were within one percent of the forward measurements.

Time series discussion

This particular configuration appears to have been the most useful arrangement for several reasons. One, the presence of an electrode in the injection well allowed the *immediate detection* of the commencement of injection. Two, the sequence of measurements was *rapid* because of the limited number of possibilities (only 32 measurements, one per casing, not counting reciprocal measurements). Three, the rapid sequence of measurements allowed *accurate transit times* from casing to casing to be measured. Four, because of the relatively high density of steel casings the *volume of the injection could be detected and monitored* by using a first-order approximation of the plume shape regardless of heterogeneities in the host medium.

This immediate trigger is unobtainable with any volumetric sensing method because it relies on somewhat different physics. It depends on a *change in state of the electrical pathway*. An electrode in the injection well is equivalent to having an electrode either inside a container of conductive solution (and connected to the solution) or connected to the container itself (assuming the container is metallic) which, in turn, establishes an electrical pathway to, and through, the solution. The triggering mechanism results from a rapid increase in electrical conductivity in the host medium (i.e. outside the container) to any sensing electrode, regardless of whether it is a surface electrode, a steel well casing, another metallic container, or a convenient grounded metallic pipeline. Grounding characteristics of the container will certainly influence the observed responses, hence, the need for evaluating this arrangement in the mock tank study.

This configuration is *highly sensitive to a change from no-leak to leak*. It is a binary indicator; it shows that either there is a leak or there isn't. We also tested it for sensitivity going from previous-leak to subsequent-leak where it obviously showed a *reduced sensitivity*, but *still produced a response* to a re-activated leak.

We also observed that the no-leak-to-leak transition showed a *high sensitivity to volume* changes as a function of time.

For purposes of quality control we acquired reciprocal data by energizing various steel casings and measuring the resultant potentials at the injection well electrode. The total number of measurements for each measuring event was 32. Because of the low number of measurements for this configuration we acquired repetitive data to observe dynamic (temporal) effects as well as spatial variations.

The injected solution (30+% thiosulfate and sodium chloride) would ordinarily be expected to lower observed potentials in the vicinity of the injection well. We observed *increased* potentials near the injection well and *decreased* potentials away from the injection well. These phenomena are shown in Figures 9, 10, and 11.

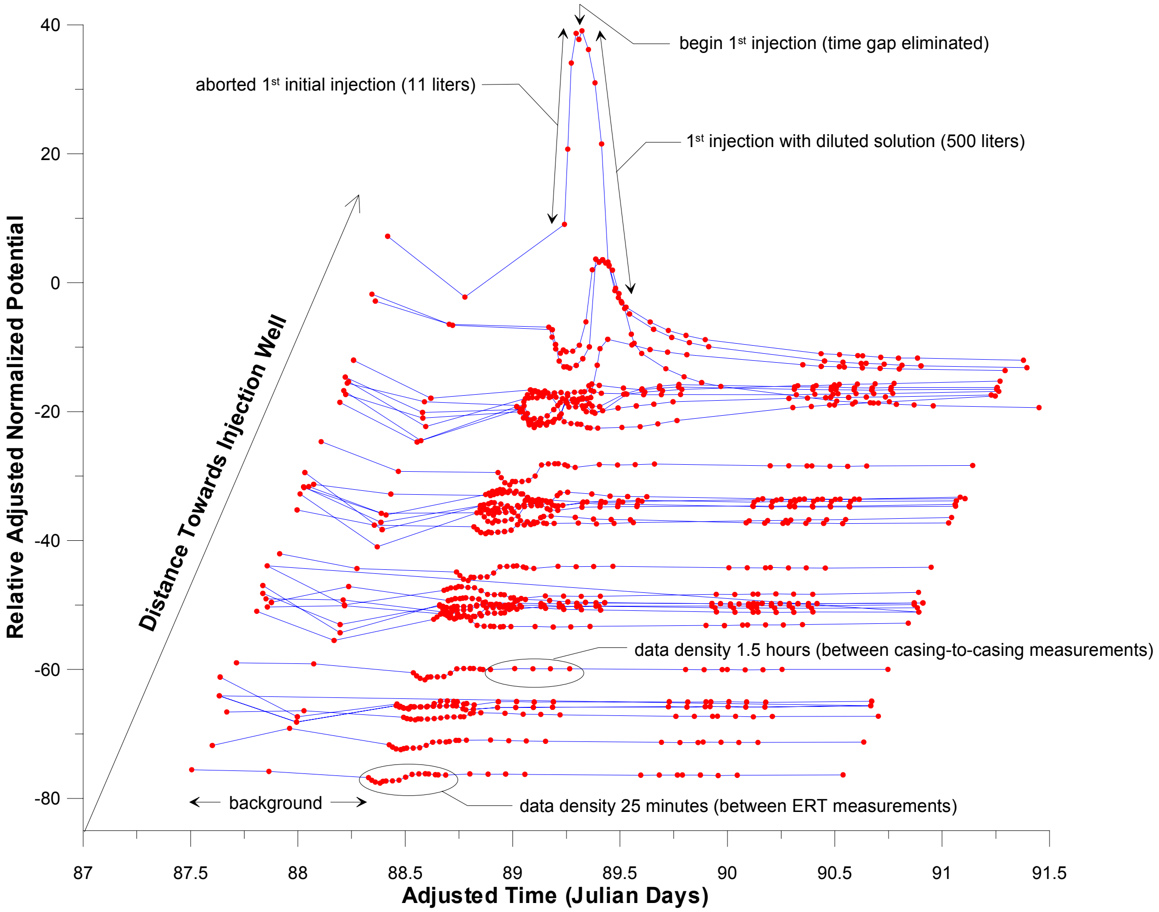


Figure 9 – stacked profiles of potential distribution - all wells

Figure 9 shows a series of stacked profiles that represent monitored potentials at all casings as a function of time for the initial injection. Time increases from left to right, potential increases upwards, and distance from the injection well decreases going away from the x-axis. The time gap between the aborted initial injection on March 30 and the completed injection on March 31 has been removed for clarity and continuity. The abscissa scale is labeled "Adjusted Time (Julian days)" to reflect this compression.

The first two data points on the left side of each time series are background measurements. The remaining data points were acquired either during or after the injection. The most salient features are the high potentials observed for the wells nearest the injection well. These initially posed a problem in understanding and conceptualization. The increase in potential was entirely unexpected.

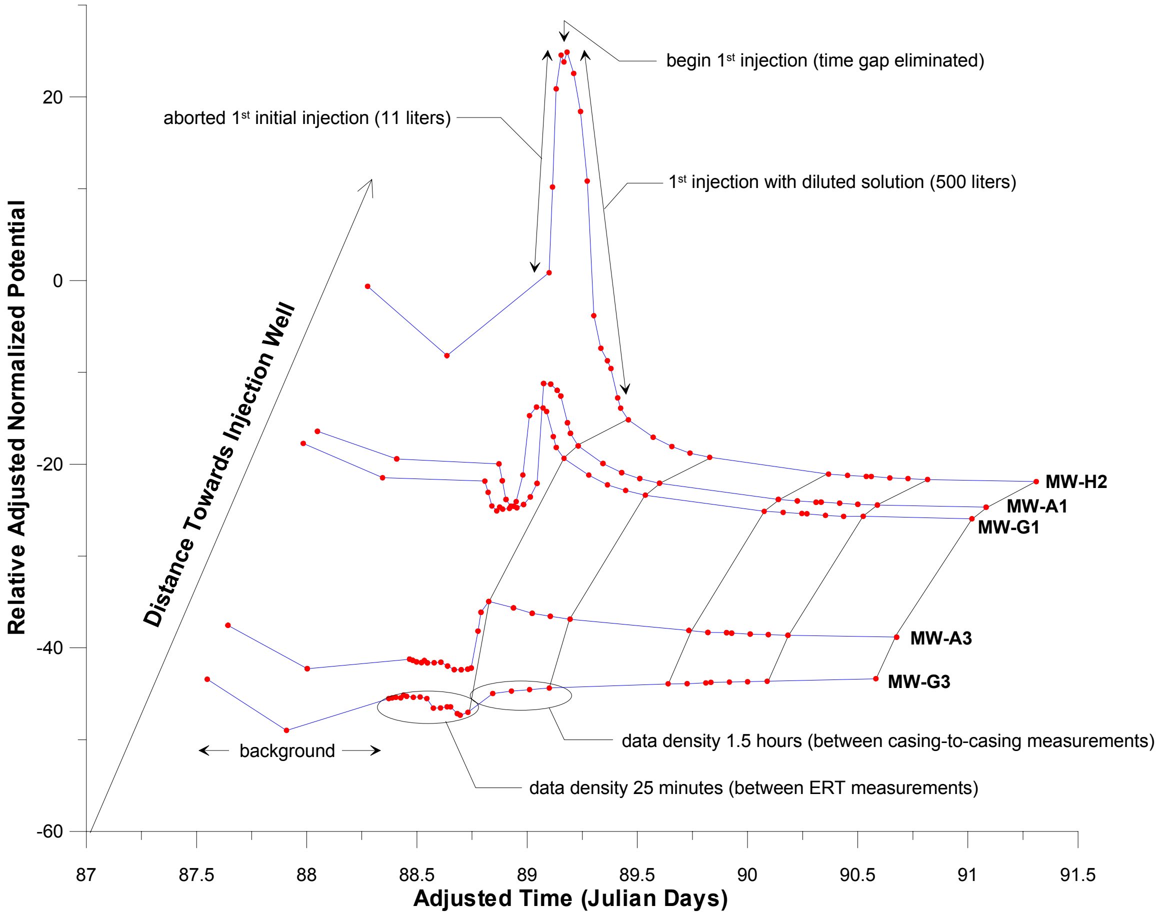


Figure 10 – stacked profiles of potential distribution - first 5 wells

Figure 10 shows the four nearest wells to the injection well and is simply an expanded view of a portion of Figure 9. These time series show immediate and opposite responses for the two nearest wells. Well H2 shows an increase in potential immediately following the smallest amount of injected solution (approximately 5 gallons). Well A1, the next nearest well, shows an immediate decrease in potential. This decrease in seen in all other wells albeit at decreasing amplitudes with distance.

As the solution encroaches upon the casing the nature of the potential changes. It goes from an increasing character to a narrow plateau followed by a decrease. We interpret this sequence of events to represent: (1) the approach of an expanding conductive volume of liquid represented by the increase in potential as the volume gets closer to the casing, (2) initial contact and the beginnings of envelopment of the casing by the expanding solution volume, and (3) the continued expansion of the volume increasing the wetted surface of the casing and decreasing the potential.

Using this reasoning, we postulate that the volume of injected solution can be estimated based on the distance between the injection well and the various affected casings. The following table shows the results of the calculated volumes versus the known injected volumes. We only have data for the three site visits, but it is enough to confirm the notion that volumes may be crudely estimated based only on the temporal response of potential at a single casing. This is a very different approach compared to inverting data sets to a model and requires negligible time and simple mathematics.

Injected Volume (gal)	Calculated Volume (gal)	Estimated Volume (gal)	Percent Error
551	13820	709	+30%
4530	27800	1430	-70%
5030	28480	1500	-70%
8020	197000	10167	+27%

Table 2 – volume analysis

Injected Volume: Based on flow meter readings from records 28, 147, 284, 480 provided by PNNL.

Calculated Volume: Areas determined around each well are based on reserve-type polygons. Volume calculations were performed by multiplying the lamina thickness (0.1 m) by the polygonal area around the well by the potential for that lamina (determined by using an appropriate distribution function to non-linearly distribute the potential along each casing. There was a total of 180 lamina for each well. All wells were then summed for a total calculated volume.

Estimated Volume: The calculated volume (abscissa) was plotted against the injected volume (ordinate). A least squares line was plotted through the data and forced to intercept zero. The slope of this line (~20) was used to scale the calculated volume to the injected volume to obtain the estimated volume.

Percent Error: The deviation of the estimated volume from the injected volume was calculated and presented in percent error form. Positive error signifies a larger estimated than injected volume.

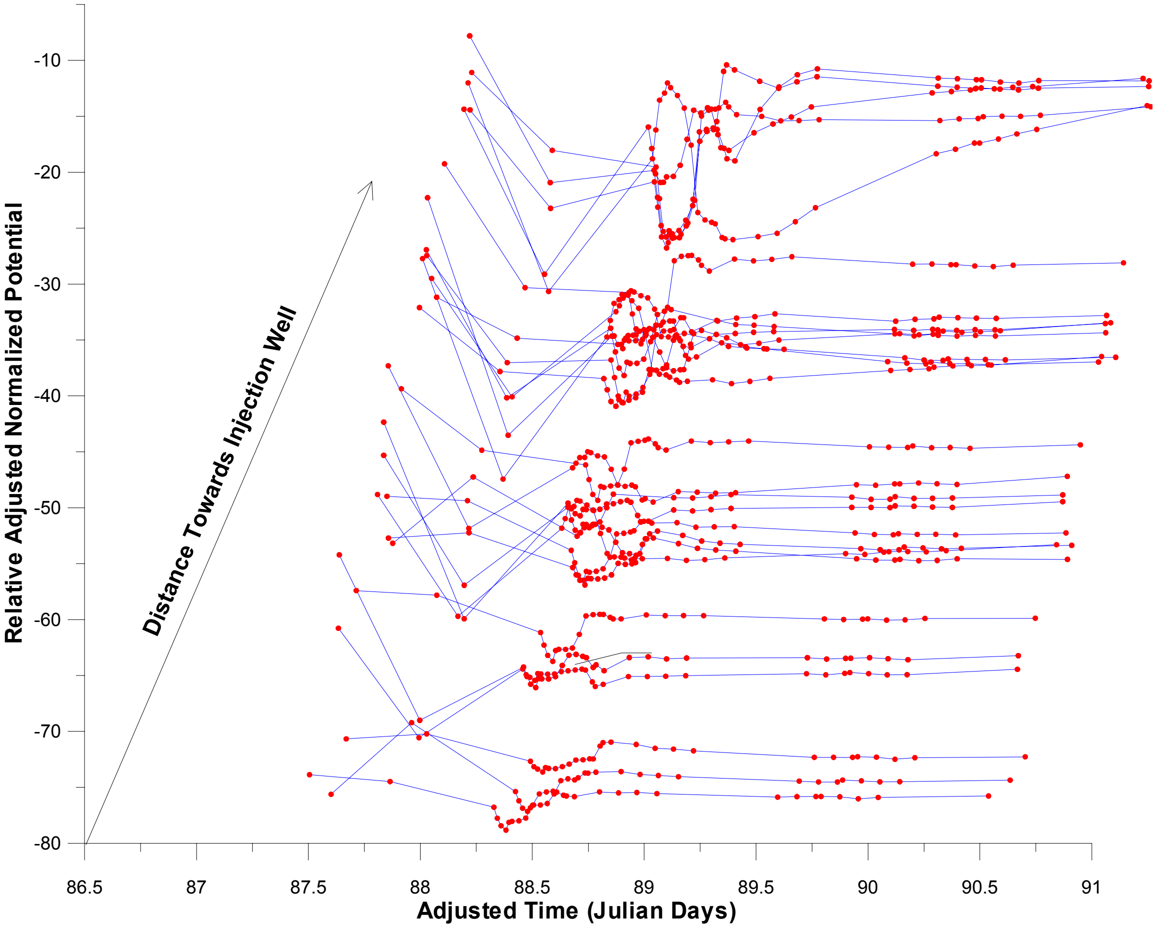


Figure 11 – stacked profiles of potential distribution - last 27 wells

As a side note, the numbers presented at the June meeting were erroneous due to using wrong factors and not adequately checking the work prior to presentation. The results presented here show a larger scatter to the results which seems more appropriate considering the crude approximations involved. Figure 11 shows the time series for the remaining 27 wells. In each case an immediate drop can be detected at the onset of the injection. The relatively frequent data samplings demonstrate the utility of rapid and continuous data acquisition before, during, and after such studies or in practice.

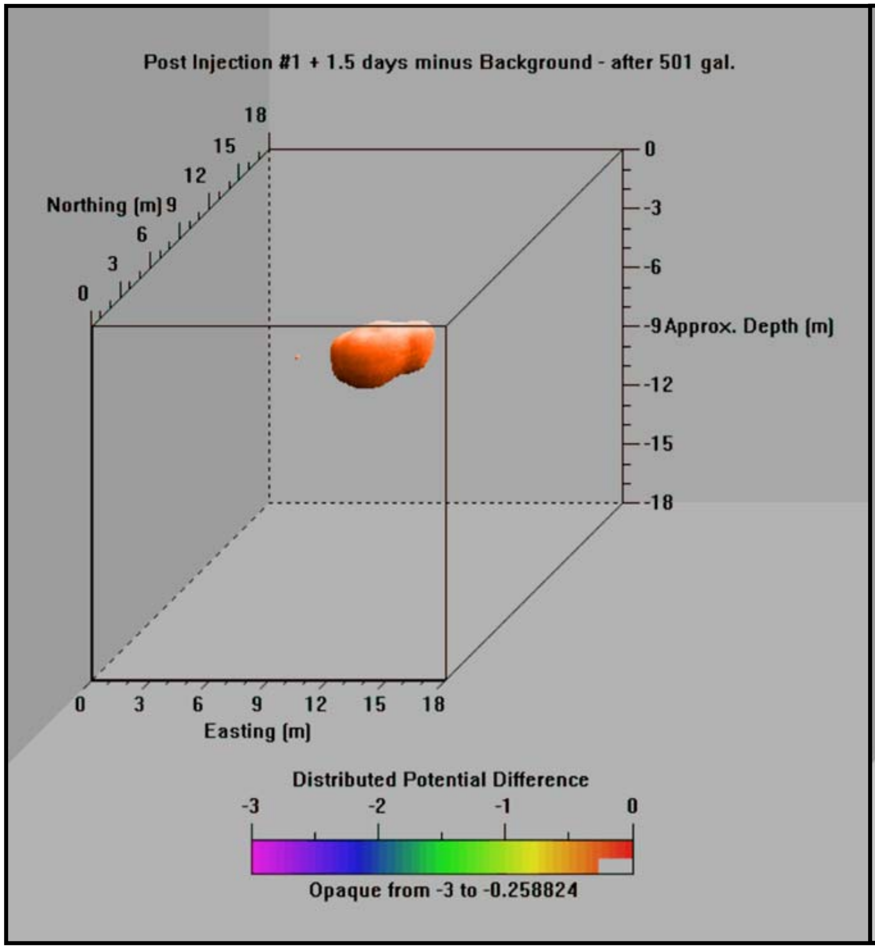
The effect of increasing potential at the nearby casings has some interesting aspects. First, we note that we have a relatively accurate time of the onset of injection because of the change of state previously mentioned (unfortunately it is somewhat complicated by the one-day delay between the aborted injection and the successful second attempt). The knowledge, by itself, of the time a leak starts can be very useful, particularly if it can be applied to tank sluicing.

We also note that the transition from increasing potential at a casing to a peak value can be determined within a few minutes. These two times define the travel time or transit time for the injected liquid regardless of volume. The measured time for well H2 was 0.02 Julian days (approximately 48 minutes). We know that the injection well and H2 are 0.66 meters apart. This results in an estimated velocity of 32 meters per day. Subsequent velocities for the next nearest wells are approximately 8 meters per day. With some additional knowledge of the media porosity and unsaturated flow conditions, a hydraulic conductivity for each velocity might be determined.

Distribution function discussion

Last year, as an exercise, we applied a distribution function to the injection-well-to-casing data. As with last year, we assumed a non-linear distribution of either current or potential along the steel well casings and created an estimated volume based on the shape of the distribution function. These functions were integrated, normalized, and differenced at one-meter intervals along the length of the casing (actually from 5 meters to the bottom, because of the depth of injection at 4.6 meters). The resultant data are presented in volume form in Figures 12 and 13.

Two volumes were generated. They represent the data taken 1½ days after the initial 500 gallon injection (on the left) and 1½ days after 5000 gallons had been injected (on the right). The visual difference in volume is conspicuous. We calculate the volumes to be 13 cubic meters and 106 cubic meters, respectively. Estimating an effective porosity of 16% gives us 560 and 4520 gallons, respectively.



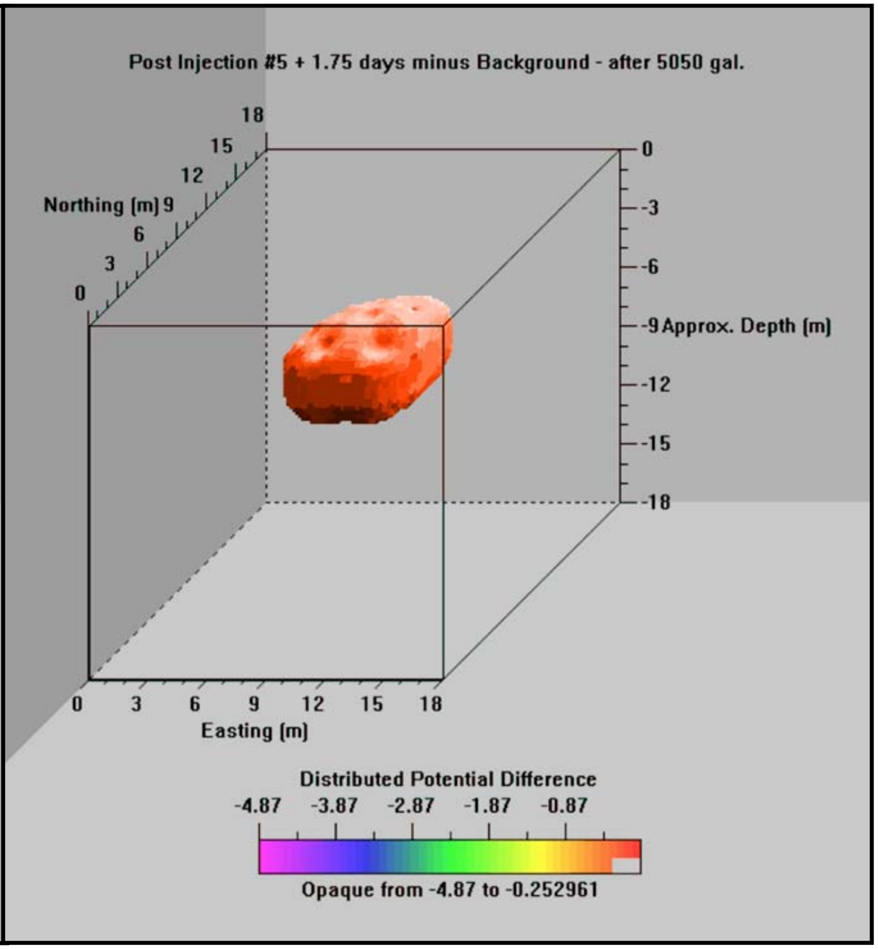


Figure 12 - 3-D view of injection-to-casing potential difference - injection 1

Figure 13 -3-D view of injection-to-casing potential difference - injection 5

The volumes presented can be adjusted up or down within a limited range of potentials. More frequent data sampling, additional modeling, and correlation with the injected volumes should produce a potential versus injected-volume "calibration."

In short, direct contact with the injection source offers some significant advantages over more remote volume sensing. The in-source electrode offers immediate indication of the onset of a leak. It works best (has very high sensitivity) going from no-leak to leak, but, it also works between leaks at reduced sensitivity. The measurement sequence between the injection well and the casings is rapid, shows dynamic effects of the plume movement, and produces near real-time results. The alternative processing procedure of non-linearly distributing the potential along the casings and generating three-dimensional modeling offers the option of a second method to reinforce the time-series data interpretations while using the same data sets.

4.1.3 Measurements between bottom-hole electrodes

This configuration is analogous to the casing-to-casing measurements with the exception that the measurements originate from the bottoms of the casings. We did not anticipate significant, if any, differences between these measurements and the casing-to-casing measurements, but, we have observed large differences on other projects in single wells where little was known about the manner of well completion.

Consequently, we made two sets of bottom-hole electrode measurements in the same manner as the casing-to-casing measurements. One data set was acquired during the background measurements, the other data set was acquired after the initial injection had been completed. Upon comparison with the casing-to-casing measurements, so little difference was seen that no further data acquisition seemed justified.

These data sets are not discussed here.

4.1.4 Measurements between bottom-hole electrodes and steel casings

As a precaution, we also made a set of measurements using the bottom-hole electrodes as current sources and the tops of the casings for potentials. Again, in comparing data sets with the casing-to-casing data, they were so similar that no further effort was spent on this configuration.

These data sets are not discussed here.

4.1.5 Measurement between bottom-hole electrodes and injection well

As another permutation, we acquired data-sets for this configuration. Again, as with other measurements using the bottom-hole electrodes, comparison with the casing-to-injection-well data showed little difference. No further effort was spent on this configuration.

These data sets are not discussed here.

5.0 SUMMARY & RECOMMENDATIONS

The characteristics of the specific goals for the VZTFS are ideal for electrical methods. The leaked solutions are highly conductive and the vadose-zone host medium is relatively resistive. As a result of this year's VZTFS, it is evident that electrical methods should play a role in subsequent studies. We have demonstrated that specialized installations of electrodes are not necessary, making HRR methods cost effective. We have produced diagnostic results using existing infrastructure, in particular, steel well casings. We have produced volumetric information for leak detection as well as dynamic characteristics of the leaked volume.

The testing of the TCRT method using HRR techniques have demonstrated that it is feasible to use existing infrastructure such as steel-cased wells that exist at tank farm at Hanford as monitoring points for plume migration and plume detection studies. Additional study of the impacts of the steel liner of the tank in combination with steel cased wells is planned for study in August and will be a second complete deployment of the TCRT method for leak detection at the Hanford Site.

We have demonstrated that our HRR methods as applied to the Sisson and Lu site and using only the existing infrastructure of the 32 steel cased wells, one PVC injection well, provided:

1. positive leak indications within minutes of the onset of injection,
2. quantitative volumetric estimations using multiple methods,
3. accurate location of the leak source using multiple methods,
4. excellent lateral definition of the leaked solution using multiple methods,
5. a minimum detection limit of one liter for one method,
6. a minimum volume detection limit of approximately 200 to 500 gals for one method
7. qualitative indications of reactivated leaks for one method,
8. no indication or resolution of fingering with any of the methods,
9. excellent repeatability of data in a complex environment, and
10. poor vertical resolution due to the length of the casings.

These methods can be adapted to a variety of circumstances as shown by the various arrangements each of which produced useful results. Two methods; casing-to-casing and injection-well-to-casing received the most attention because of their simplicity of measurement and reliability of results. They rely on different electrode arrangements and are complementary. Extensive processing has been performed only to realize that minimal processing can produce acceptable results.

These kinds of electrical measurements are relatively easy to perform and can be done with off-the-shelf equipment. Data acquisition is much simpler than the conceptual understanding required to adequately implement the methods. An understanding of the behavior of electric fields in the vicinity of buried conductors is very beneficial, especially when using those same grounded structures for data acquisition.

We highly recommend further tests in increasingly complicated situations. Continued processing of some of the existing data would also further the understanding of what can be derived from the data. Better shortcuts to faster processing with the aim of real-time results should also be sought.

6.0 FUTURE CONSIDERATIONS

Further processing

A variety of electrical measurements were made for this study. More data were acquired than could be processed for this report. More processing could be done. What processing has been done clearly indicates the effectiveness of the tested electrical methods. We are confident that most of the data sets acquired during both the 2000 and 2001 VZTFS contain even more information than has been extracted. Many of the data sets have not been used.

We would encourage the consideration of further processing of existing data sets. Two goals for additional processing would be: (1) to determine the minimum requirement for casings that would still produce an unequivocal result, and (2) to determine if some combination of data sets other than what has been tested might produce even more diagnostic results. We have not attempted either of these during this years' or last years' VZTFSs.

Additional injections

It would prove useful to perform a series of low volume injections using one method at a time. Present results have demonstrated that 500 gallons can be detected and modeled. We recommend considering a series of 1000 gallon, continuous injections, spaced over several months. Each electrode arrangement would be monitored *continuously* before, during, and after each of the injections. The present data sets were acquired during time windows determined by the various methods used, others' needs, long overall injection times, and distance from our own home office. The lack of continuity occurs at critical times for some of the methods. Other methods had no opportunity to operate during the most dynamic periods for the plume. Sufficient time should be allowed to permit the site to recover between injections.

This report is based on our best understanding of the electrical properties of earth materials and is limited to the areas where the surveys were performed. We would appreciate any feedback regarding the interpretation based on additional surveying or invasive characterization. We acknowledge and appreciate the support provided by PNNL personnel.

Respectfully submitted,

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