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Analysis Report for AP-070

Analysis of the AEC-7R Pumping Test Conducted From 3/9/15 to 3/13/15

AP-070: Analysis Plan for Hydraulic-Test Interpretations

Task Number 4.4.2.3.1

Authors: Dale O. Bowman, II, 6212 — 9/14/15 Date
HydroResolutions LLC

Technical Review: Kris Kuhlman, 6224 — 09/14/2015 Date
Applied Systems Analysis & Research Department

QA Review: Shelly Nielsen, 6210 — 9-14-15 Date
S. M. Stoller Corporation

Management Review: Christi Leigh, 6212 — 9-15-15 Date
Repository Performance Department

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1. Introduction

This report discusses the analyses of hydraulic tests performed in the Culebra Member of the Rustler Formation (Figure 1) at the Waste Isolation Pilot Plant (WIPP) site at the AEC-7 well pad (Figure 2). These analyses were performed in accordance with the Sandia National Laboratories (SNL) Analysis Plan for Hydraulic-Test Interpretations, AP-070, Revision 2 (Beauheim, 2009). The computer code used for analysis was nSIGHTS (n-dimensional Statistical Inverse Graphical Hydraulic Test Simulator), version 2.50. A detailed description of the approach followed in these analyses can be found in Beauheim et al. (1993, Appendix B) and Roberts et al. (1999, Chapter 6).

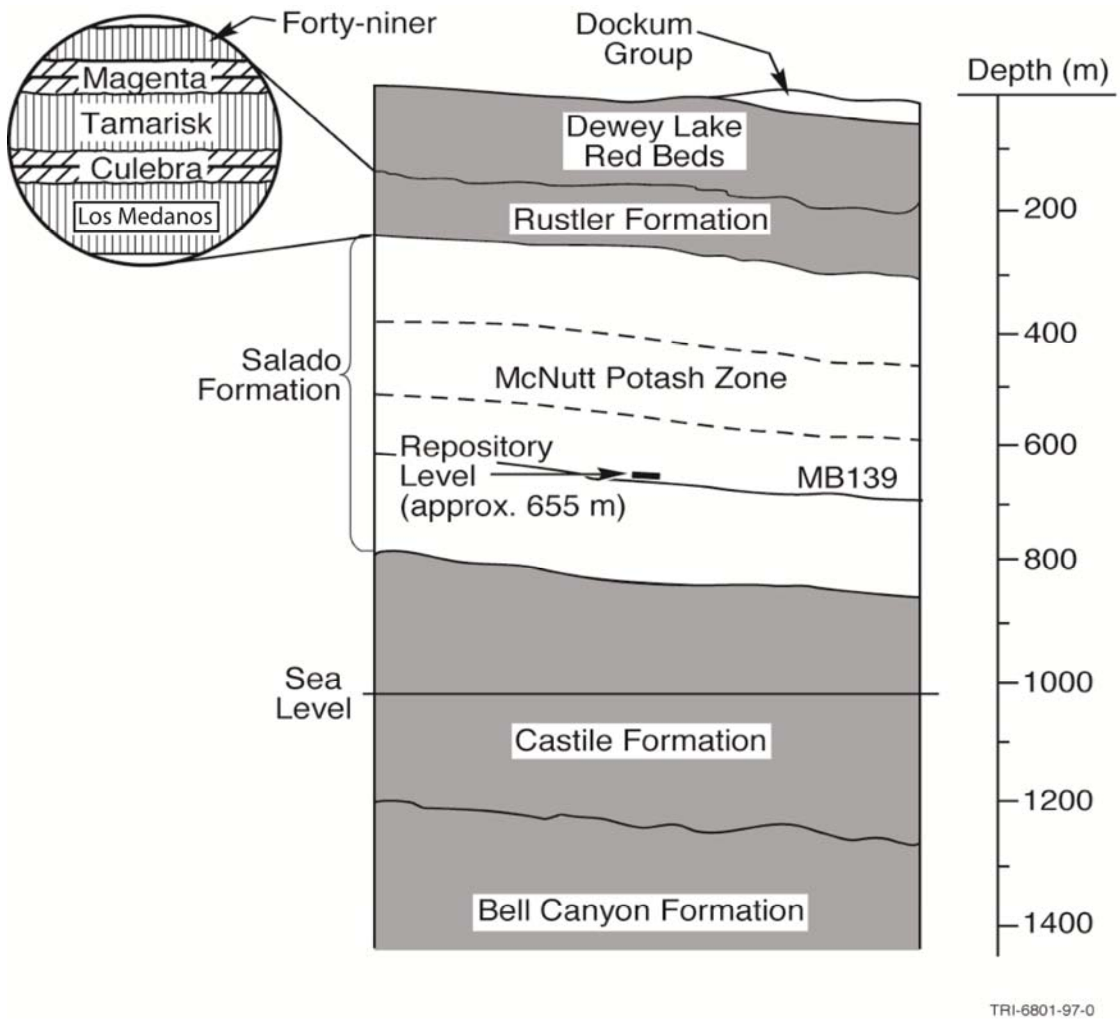

Figure 1. WIPP stratigraphy.

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2. Test and Analysis Procedures

Six purge tests and an irregular (as made so by a lack of check valves) pumping test were performed in the AEC-7R replacement well on 10/3/13, 12/16/13, 1/13-17/14, 4/17/14, 4/21-24/14, 6/16-19/14, and 7/14-17/14 for the purpose of removing non-formation water, excess Dewey Lake/Santa Rosa sediments, and obtaining water quality samples. These purges removed a total of 7172 gal. of water and approximately 100 gal. of sediment from the AEC-7R well. Analysis of the first purge indicated that the well could sustain approximately a 0.5 gpm pumping rate. Purge test analyses (Section 3.1.1) show the initial fit of the data and its corresponding aquifer parameter estimations. We note that this was just a preliminary fit used solely for guidance for the full test and its model parameters do not represent the final aquifer parameter estimates. The location of the AEC-7R well pad in the WIPP well network is shown in Figure 2. Pumping test analyses included the fitting of Cartesian pressure data, pressure change, and pressure derivative (log-log diagnostic) as described by Bourdet (1989).

All the nSIGHTS test simulations incorporated pre-test pressure records of various durations as "history" periods where the observed pressures were specified in the simulations.

Test analysis involved finding the values of the fitting parameters that produced the best-simulated matches to the pressure data collected during the constant-rate test and subsequent recovery period. In addition to the formation properties of interest (principally transmissivity (*T*)), tubing string radius and wellbore skin were also included as fitting parameters in the pumping-test analyses so that nSIGHTS could exactly match the amount of wellbore storage observed during the test. The main objective of this analysis is to estimate *T* for subsequent use in *T*-field generation and WIPP performance assessment calculations, and to validate the construction of the replacement well against analyses conducted on data from the previous Culebra well on the AEC-7 wellpad. Correlation between estimated *T* values and the other fitting parameters reported in Appendix B would be of interest if these correlations resulted in large uncertainty in the estimated *T* values. The uncertainty in the estimated *T* values, however, is relatively small, so any correlation between *T* and other fitting parameters is not of concern.

The uncertainty quantification method applied to the analyses in this report is a process referred to as *perturbation analysis*. In this process, preliminary analyses are performed in which a reasonable fit is obtained to the specified constraints defined in the nPre configuration file. The resulting values of the fitting parameters are the *baseline solution* set – a single value for each fitting parameter that provides a satisfactory fit to the data (*satisfactory* being a judgment call on the part of the analyst). Perturbation analysis begins by assigning a plus/minus range corresponding to the parameter space one wishes to investigate to each of the baseline fitting-parameter values. These plus/minus fitting-parameter ranges for each analysis are listed in Appendix B. Starting at the baseline value, the fitting parameters are randomly perturbed to fall somewhere within their assigned ranges and are then optimized from these random starting points. The objective of perturbation analysis is to sample the parameter space adequately and locate all of the minima within the parameter space. By definition, the parameter-space minimum that provides the best quantitative fit to the data, measured in terms of the smallest unweighted sum of squared errors (SSE), is the *global minimum* (assumed true solution), and the other minima are referred to as *local minima*. Local minima are effectively localized depressions in the

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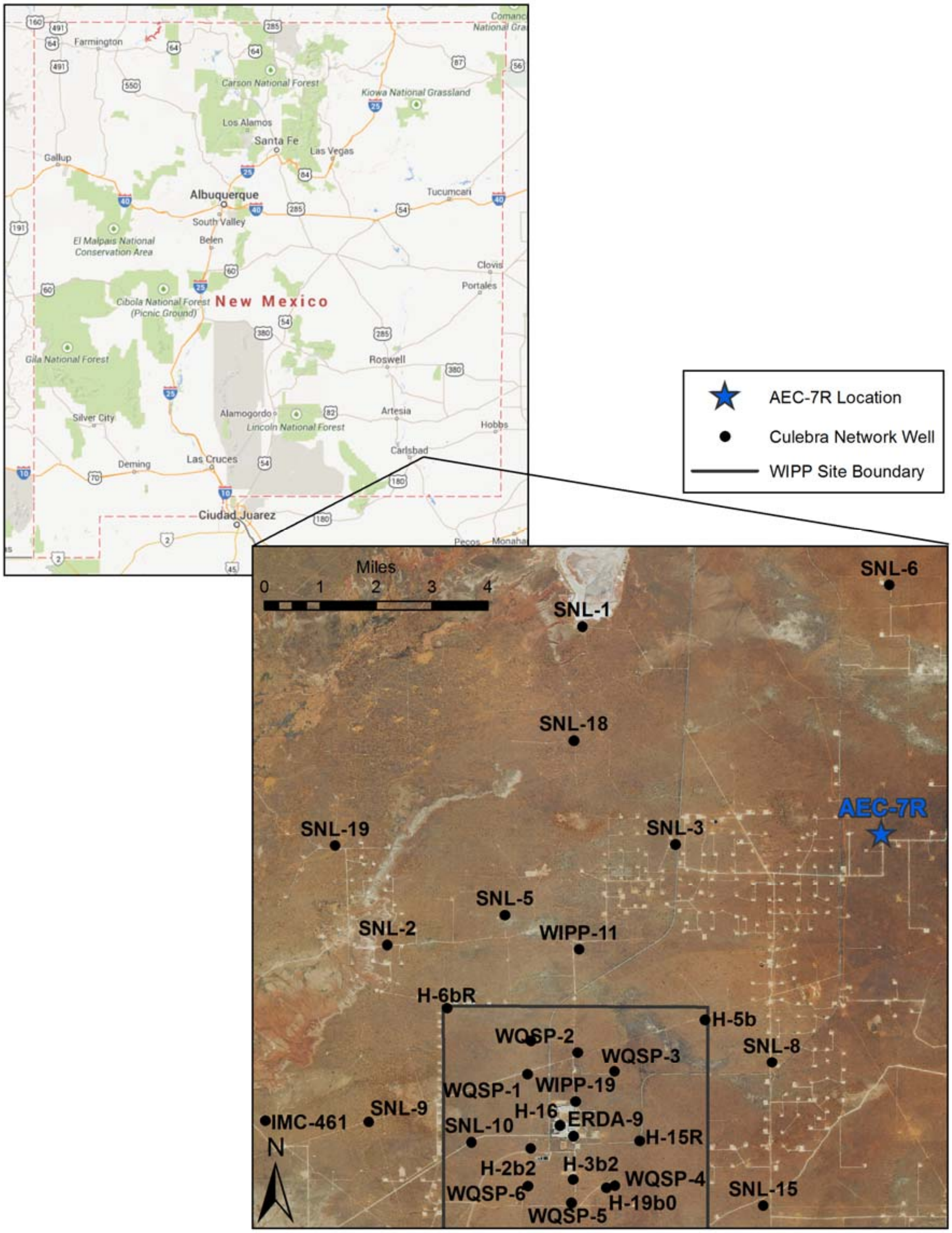

Figure 2. Location of the AEC-7R Culebra well located on the AEC-7 wellpad. The AEC-7R pumping well is designated by a blue star.

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parameter-space topography that trap the inverse regression algorithm during its attempt to find the global minimum – the smallest unweighted SSE. If multiple data types are included in the match, e.g., if pressures, pressure derivatives, etc., are matched simultaneously, then the weighted SSE values for each component are combined and the overall goodness-of-fit measure is denoted in nSIGHTS as the *fit value*.

Five hundred perturbation/optimization runs were performed for each of the analyses discussed in this report. A visual assessment of parameter-space plots for each fitting variable and a visual assessment of the fits themselves were all used to determine the value of the "fit discriminant". The fit discriminant is used to reduce the perturbations under consideration to only those within the best-fit minimum, and sufficiently close to be subjectively considered "acceptable" fits. All perturbation results for which the fit value was less than the fit discriminant were deemed acceptable solutions and are included in the final range of reported values for each fitting parameter. In some cases, the original baseline solution may not fall within the global minimum defined through perturbation analysis. The final number of satisfactory perturbation results for each test is reported in the Section 4 figure captions.

3. AEC-7R Analysis Results

Discussions of AEC-7R and associated test analyses are given below. A summary of the *T* estimates obtained from perturbation analysis of each test is shown in Table 1. The full range of *T* values from which the statistics in Table 1 are derived is presented as a scatter plot in the sections below and a full listing is contained within the nPost configuration file for each analysis.

Table 1. Culebra Transmissivity and Storativity Estimates.

AEC-7R Test	Mean *S*	Geo. Mean *T* (m^2/s)	Log Geo. Mean *T* (m^2/s)	Log Min. *T* (m^2/s)	Log Max. *T* (m^2/s)	Variance $(m^2/s)^2$
Purge 1	3.78E-05	6.04E-08	-	-	-	-
2015 Pumping Test	1.71E-05	6.44E-07	-6.19	-6.47	-5.77	1.58E-15

3.1. AEC-7R

The Culebra interval of well AEC-7R was drilled and completed between 8/11/2013 and 8/27/2013 (DOE 2015). The well was drilled to a depth of 891 ft with the Culebra interval screened from 855 ft to 875 ft. At the Culebra, the inner diameter (ID) of the well is 4.31-in and the pump is hanging on 1.59-in ID tubing. The siting and creation of the AEC-7R well was based on the need to replace the previous AEC-7 well in support of hydrologic testing and monitoring of the Culebra Dolomite south of the WIPP site. A physical description of the well is detailed in Figure 3.

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Six purge tests and two pumping tests were initiated in the Culebra at AEC-7R between 10/3/13 and 7/16/14. The first purge test was analyzed to gain insight on the hydraulic parameters associated with the replacement well to better frame the pumping rate and duration for the final pumping test. The other purges were designed to rid the well of sediment which comprised 20% of our volume return in the initial purges. The return during the final pumping test was at 1% or less, volumetrically. The first irregular pumping test gave bad data returns due to a lack of check valves obscuring recovery data with dewatering effects from the tubing string (Figure 5). The simulation for the purge test consisted of a history period prior to pumping and a recovery period once purging concluded. The data and model used in the analysis is shown in Figure 4.

A 1075 gallon, second pumping test was initiated in the Culebra at AEC-7R from 3/8/15 to 3/13/15. The simulation of this pumping test consisted of a history period that extended partially after pumping began, a drawdown period, and a recovery period. The data acquired for the test is shown in Figure 6.

The AEC-7R nSIGHTS simulations each consisted of three sequences. The details of each sequence, i.e., start/end time, pressure, etc., are specified in the AEC-7R.nPre file and are listed in Appendix B.1.

The specified AEC-7R conceptual models were chosen because they were the simplest models consistent with the available information that produced an acceptable fit to the data; acceptable by consensus of the modeler and an associate modeler. The model used was in infinite-acting, radial systems with a variable *T*, wellbore storage, and a negative, time-dependent skin.

A gravel pack surrounding the screened portion of the well, localized fracturing, and approximately 100 gallons of sediment removed from the aquifer at the Culebra likely account for the existence of negative skin with respect to *T* estimates. The skin is likely time dependent due to existing sediment gradually clogging and unclogging the well screen. The range of *T* values derived from this analysis are shown in Figure 7. The *T* estimates gained through this analysis are described in the preceding Table 1.

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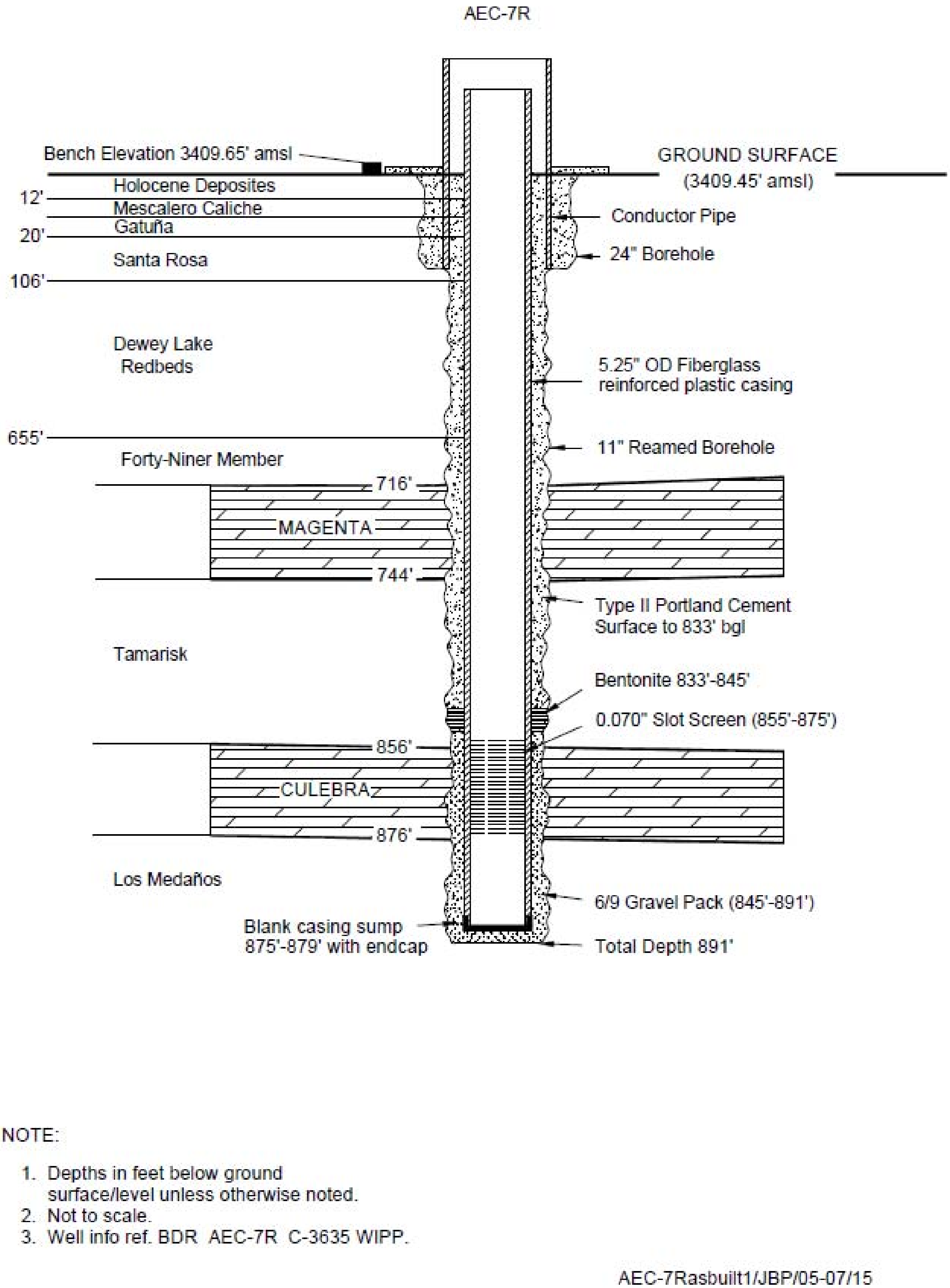

Figure 3. AEC-7R well configuration during testing.

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3.1.1 Purge Test Analysis

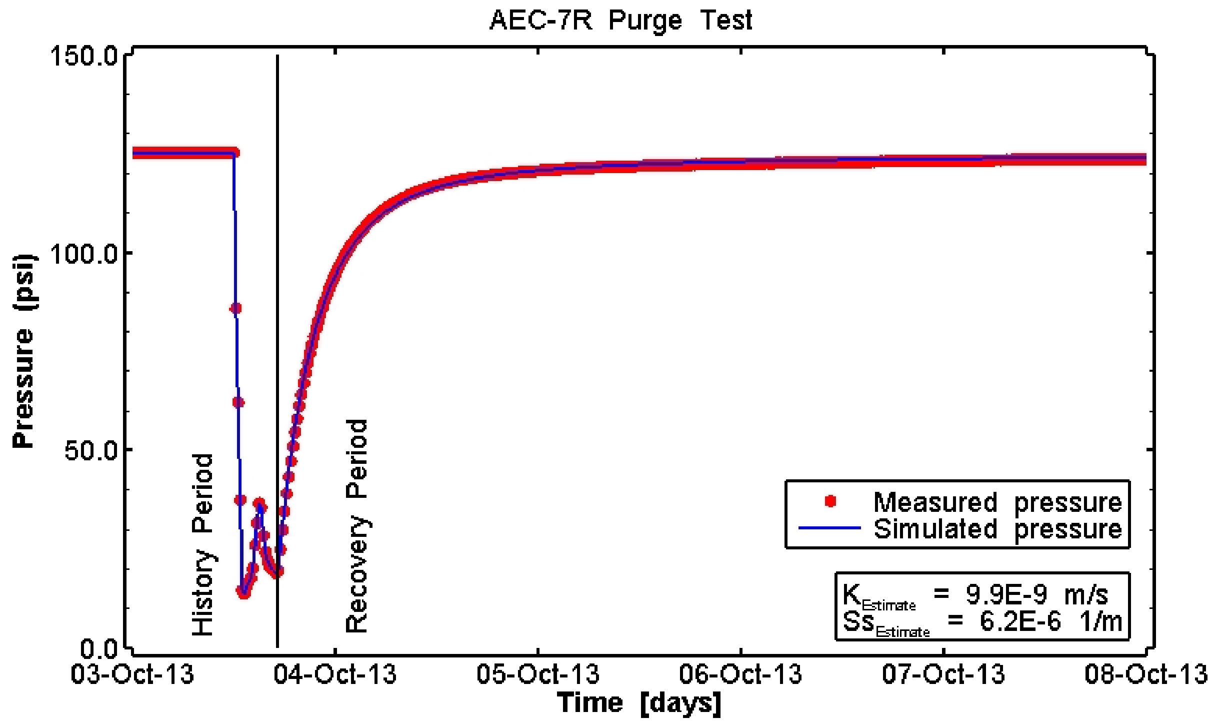

Figure 4. Pressure data and model fit of the first Culebra purge test in AEC-7R.

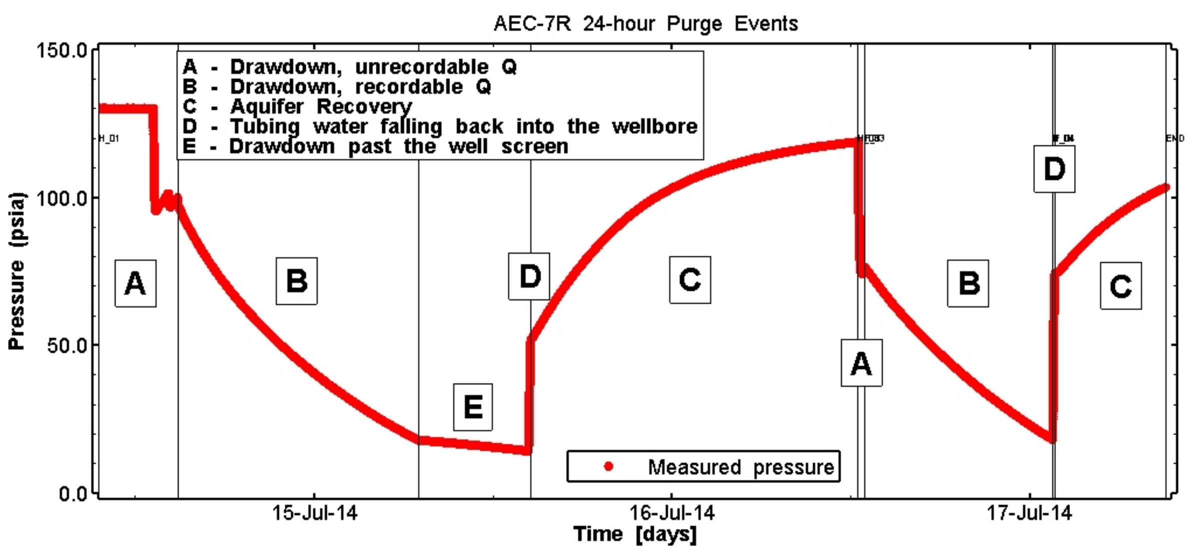

Figure 5. Pressure data and change explanation of the first Culebra pumping test in AEC-7R.

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3.1.2 Pumping Test Analysis

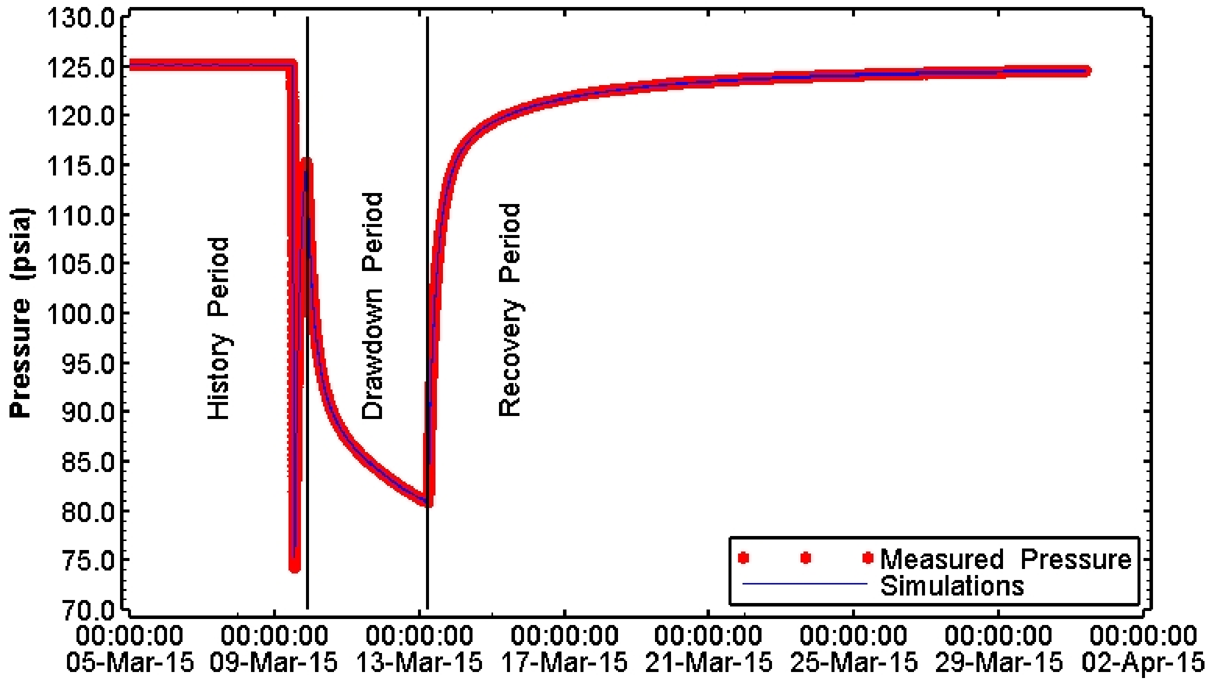

Figure 6. Pressure data and 128 model fits of the final Culebra pumping test in AEC-7R.

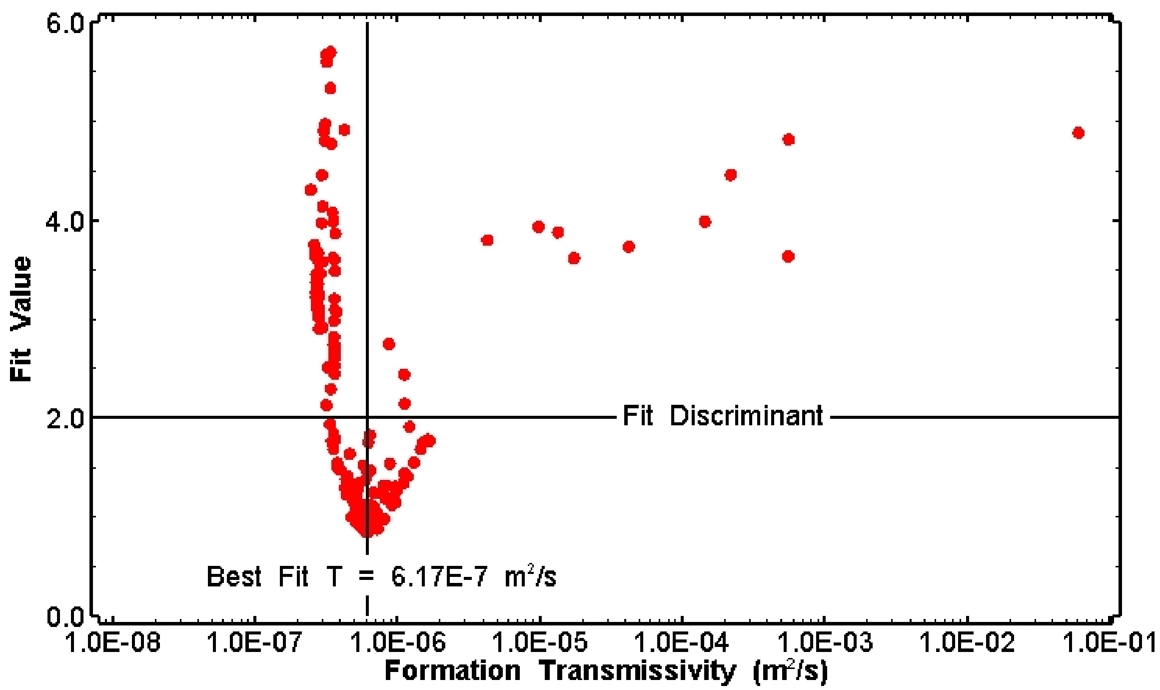

Figure 7. X-Y scatter plot showing the transmissivity parameter space derived from the AEC-7R perturbation analysis with fit discriminant and best fit values.

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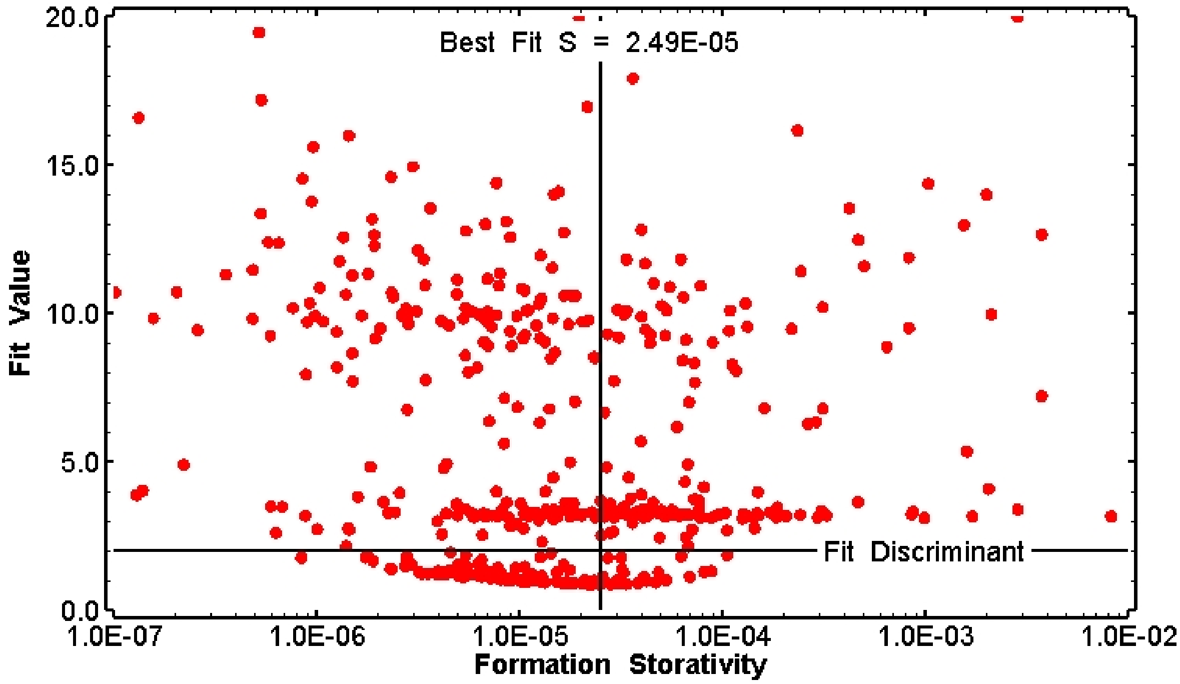

Figure 8. X-Y scatter plot showing the storativity parameter space derived from the AEC-7R perturbation analysis with fit discriminant and best fit values.

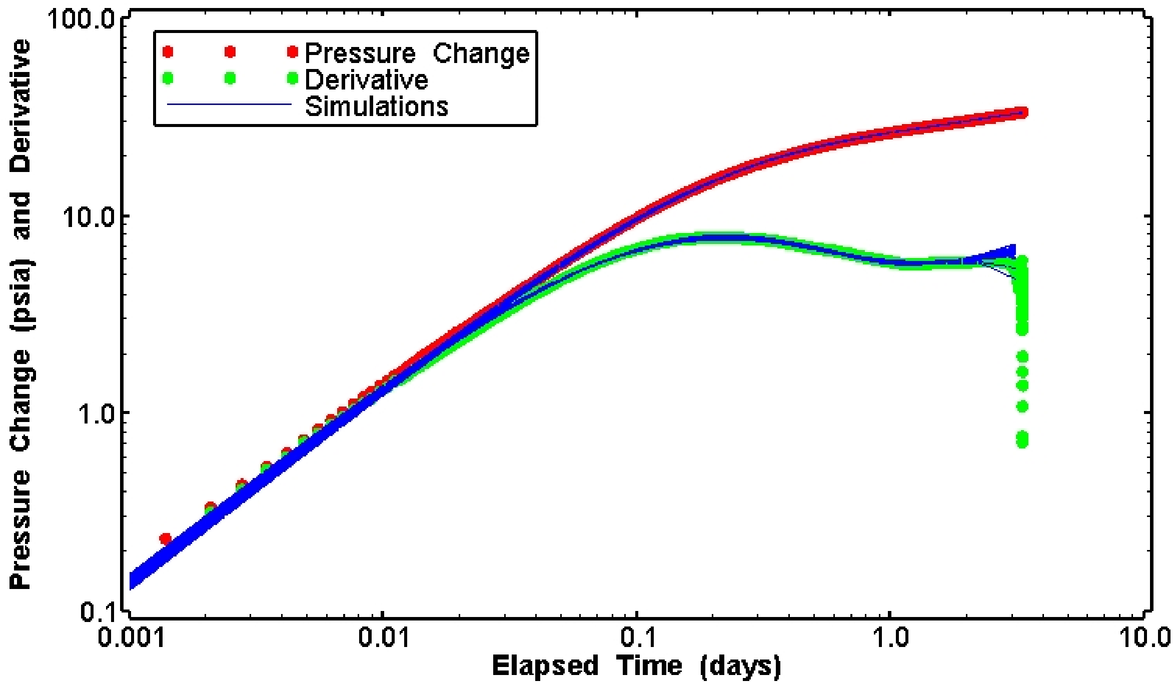

Figure 9. Log-log plot showing 128 simulations of the AEC-7R drawdown period pressure change and derivative response.

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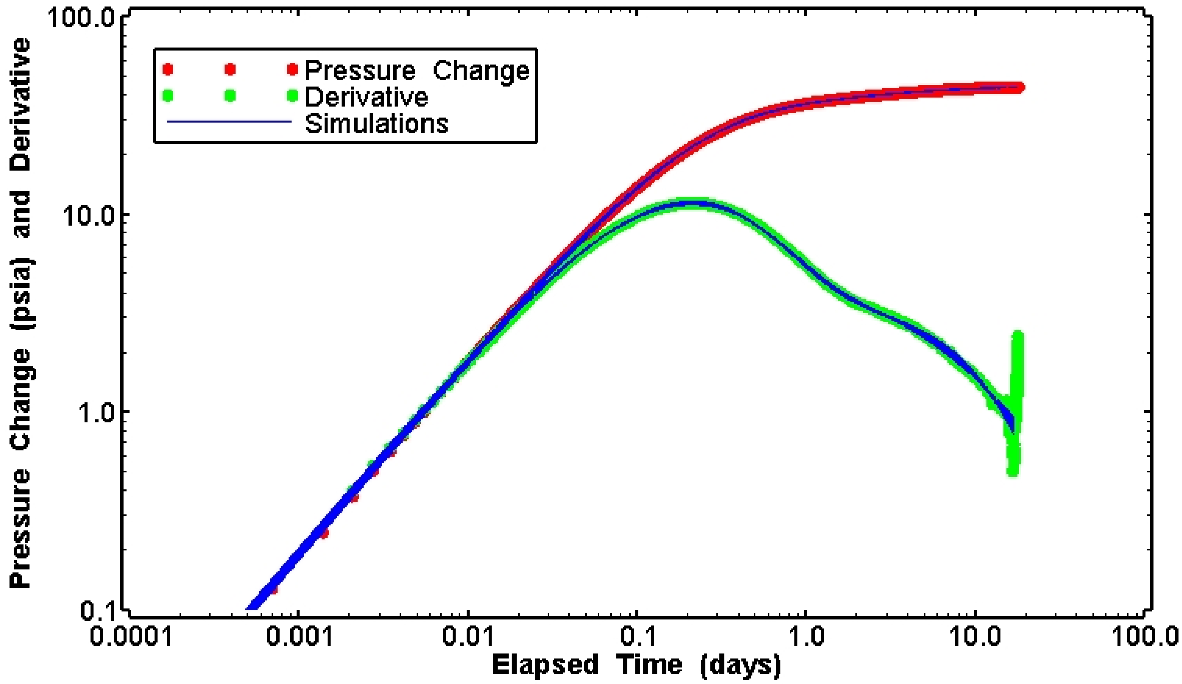

Figure 10. Log-log plot showing 128 simulations of the AEC-7R recovery period pressure change and derivative response.

4. References

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Appendix A – AEC-7R Hydraulic Test – 3/9/15 to 3/13/15

Well	Date and Time Start DAS	Date and Time Stop DAS	Date and Time Start Test	Date and Time Stop Test	Borehole Diameter (in)
AEC-7R	3/9/15 9:00	3/13/15 6:43	3/9/15 21:54	3/13/15 5:55	4.31

Inside Tubing or Casing Diameter (in)	Culebra Interval (ft bgs)	Fluid Density (g/cm^3)	Field Notebook	Data Source Report(s)
2.155	855-875 (20 ft)	1.065	WSWT-16,17	BDR (C-3635)

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Appendix B – nSIGHTS Listings

B.1 AEC-7R nSIGHTS Listings

```
************
nPre/64 2.50
************

Version date    25 June 2012
Listing date    16 Jul 2015
QA status       non-QA Open Source
Config file     C:\SANDIA_PROJECTS\WIPP_wells\Culebra\AEC-7R\AEC-7R_X.nPre
```

Control Settings

Main Settings

Simulation type	Optimization	
Simulation subtype	Normal	
Phase to simulate	Liquid	
Skin zone ?	yes	
External boundary	Fixed Pressure	

Liquid Phase Settings

Aquifer type	Confined	
Aquifer horizontal permeability	Isotropic	
System porosity	Single	
Compensate flow dimension geometry	yes	
Leakage	None	

Test Zone Settings

Test zone volume can vary	no	
Test zone compressibility can vary	no	
Test zone temperature can vary	no	
Default test-zone temperature	20.00	[C]
Solution variable	Pressure	
Allow negative head/pressure	yes	

Parameters

Formation

Formation thickness	20.000	[ft]
Flow dimension	2.0	[]
Static formation pressure	Optimization	
Minimum value	120.000	[psi]
Maximum value	140.000	[psi]
Estimate value	125.270	[psi]
Range type	Linear	
Sigma	1.00000E+00	
External boundary radius	1000000	[m]

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Formation conductivity	Optimization	
Minimum value	1.00000E-12	[m/sec]
Maximum value	1.00000E-02	[m/sec]
Estimate value	7.49966E-08	[m/sec]
Range type	Log	
Sigma	1.00000E+00	
Formation spec. storage	Optimization	
Minimum value	1.00000E-08	[1/m]
Maximum value	1.00000E-02	[1/m]
Estimate value	1.36497E-06	[1/m]
Range type	Log	
Sigma	1.00000E+00	

Skin

Radial thickness of skin	Optimization	
Minimum value	1.0E-05	[m]
Maximum value	100.0	[m]
Estimate value	49.5819077	[m]
Range type	Log	
Sigma	1.00000E+00	
Skin zone conductivity	f(t) point	
Skin zone spec. storage	Optimization	
Minimum value	1.00000E-12	[1/m]
Maximum value	1.00000E-02	[1/m]
Estimate value	5.39791E-06	[1/m]
Range type	Log	
Sigma	1.00000E+00	

Fluid

Fluid density	1065.00	[kg/m^3]
Fluid thermal exp. coeff.	0.00000E+00	[1/C]

Test-Zone

Well radius	2.155	[in]
Tubing string radius	Optimization	
Minimum value	0.2	[in]
Maximum value	4.0	[in]
Estimate value	2.0971126	[in]
Range type	Linear	
Sigma	1.00000E+00	

Numeric

# of radial nodes	250	[]
# of skin nodes	50	[]
Pressure solution tolerance	1.45038E-11	[psi]
STP flow solution tolerance	1.58503E-11	[USgpm]

---

f(x) Points Parameters

Skin zone conductivity

Points type	f(t)

Information Only

Time #1	3635099820.040000	[day]
Y value#1	Optimized	
Time #2	Optimized	
Minimum	3635107200.000000	[day]
Estimat	3635180654.395000	[day]
Maximum	3635366400.000000	[day]
Y value#2	Optimized	
Time #3	Optimized	
Minimum	3635375040.000000	[day]
Estimat	3635623709.040000	[day]
Maximum	3636144000.000000	[day]
Y value#3	Optimized	
X opt range type	Linear	
X opt sigma	1.00000E+00	
Y opt minimum value	1.00000E-12	[m/sec]
Y opt maximum value	1.00000E-02	[m/sec]
Y opt range type	Log	
Y opt sigma	1.00000E+00	
Parameter curve type	Linear	

Calculated Parameters

Formation

Transmissivity	min/max	
Minimum	6.09600E-12	[m^2/sec]
Maximum	6.09600E-02	[m^2/sec]
Storativity	min/max	
Minimum	6.09600E-08	[]
Maximum	6.09600E-02	[]
Diffusivity	min/max	
Minimum	1.00000E-10	[m^2/sec]
Maximum	1.00000E+06	[m^2/sec]

Skin Zone

Transmissivity	f(t)	
Storativity	min/max	
Minimum	6.09600E-12	[]
Maximum	6.09600E-02	[]
Diffusivity	f(t)	
Skin factor	f(t)	

Test Zone

Open hole well-bore storage	min/max	
Minimum	7.76294E-09	[m^3/Pa]
Maximum	3.10518E-06	[m^3/Pa]

Grid Properties

Grid increment delta	min/max	
Minimum	0.04628	[]

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Maximum	0.08402	[]
First grid increment	min/max	
Minimum	4.73939E+00	[m]
Maximum	4.79878E-03	[m]
Skin grid increment delta	min/max	
Minimum	0.00000	[]
Maximum	0.15328	[]
Skin first grid increment	min/max	
Minimum	2.04063E-07	[m]
Maximum	9.06753E-03	[m]
Skin last grid increment	min/max	
Minimum	2.04100E-07	[m]
Maximum	1.42192E+01	[m]
Increment ratio	min/max	
Minimum	3.33309E-01	[]
Maximum	2.35119E+04	[]

Sequences

Sequence: H_01

Sequence type	History	
Start time	42053.802083	[day]
Duration	19.112500	[day]
Time step type	Static	
Static time step	0.010000	[day]
Type	Curve	
Wellbore storage	Open	

Sequence: F_01

Sequence type	Flow	
Start time	42072.914583	[day]
Duration	3.331945	[day]
Time step type	Log	
First log step	1.15741E-07	[day]
# of time steps	250	
Type	Fixed	
Fixed value	-0.2	[USgpm]
Wellbore storage	Open	

Sequence: F_02

Sequence type	Flow	
Start time	42076.246528	[day]
Duration	18.149305	[day]
Time step type	Log	
First log step	1.15741E-07	[day]
# of time steps	250	
Type	Fixed	
Fixed value	0.0	[USgpm]
Wellbore storage	Open	

Test Zone Curves

Curve object to use	P_Curve

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Curve type	Pressure
Start sequence	H_01
End sequence	H_01
Curve time base	Test
Curve Y data units	[psi]
Curve Y data is log 10	no

Curve object to use	Q_Curve
Curve type	Flow Rate
Start sequence	F_01
End sequence	F_01
Curve time base	Test
Curve Y data units	[USgpm]
Curve Y data is log 10	no

Simulation Results Setup

Output ID	DAT
Output type	Pressure
Pressure capture type	Test Zone
Output units	[psi]

Output ID	DAT
Output type	Flow Rate
Flow rate output type	Well
Output units	[USgpm]

OutputFiles

XY Forward Output

Write file ? yes
C:\SANDIA_PROJECTS\WIPP_wells\Culebra\AEC-7R\AEC-7R_tvary-skin2.nXYSim

Run ID	Perts
If file exists	Update
Output data	AutoSimData

Optimization Output

Write file ? yes
C:\SANDIA_PROJECTS\WIPP_wells\Culebra\AEC-7R\AEC-7R_tvary-skin2.nOpt

Run ID	Perts
If file exists	Update
Write residuals ?	no
Write Jacobian ?	no
Write covariance matrices?	no

Optimization Setup

Algorithm	Simplex
Calculate confidence limits ?	yes
Covariance matrix calculations	1st Order
Fixed derivative span ?	no

Information Only

```
Fit tolerance                                       1.0000E-05
Parameter tolerance                                   not used
# of optimized variables                                    11
Formation conductivity                                      OK
K_s.T[02]                                                   OK
K_s.T[03]                                                   OK
K_s.V[01]                                                   OK
K_s.V[02]                                                   OK
K_s.V[03]                                                   OK
Static formation pressure                                   OK
Tubing string radius                                        OK
Formation spec. storage                                     OK
Skin zone spec. storage                                     OK
Radial thickness of skin                                    OK
```

Fits to Optimize

```
CompositeFit                                                OK
```

Calculated Parameters Included

```
# of calculated variables included                           0
```

Suite/Range Setup

```
# of suite/range variables                                   0
```

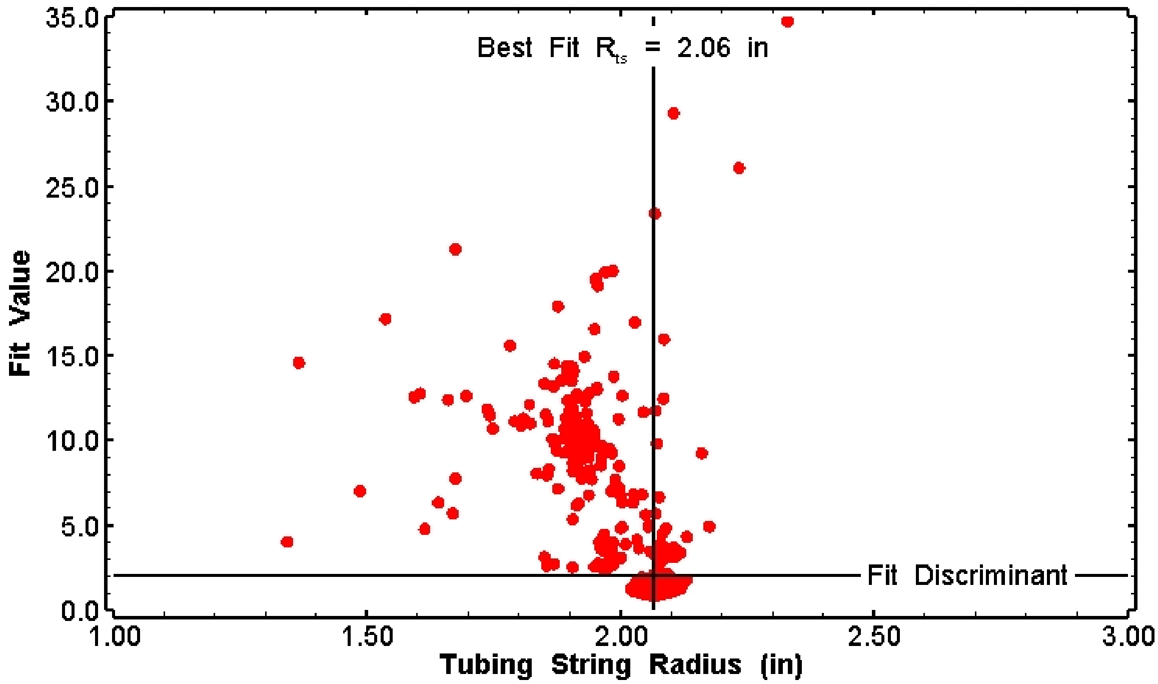

Figure B-1. X-Y scatter plot showing the tubing string radius parameter space derived from the AEC-7R perturbation analysis with the fit discriminant and best fit values.

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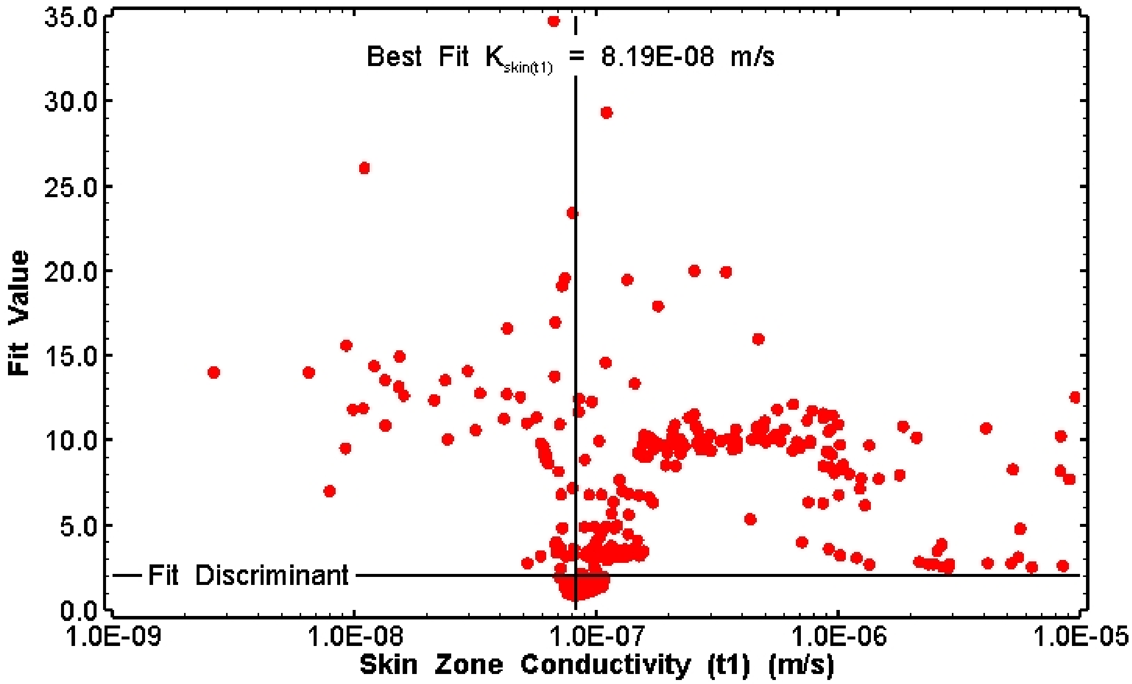

Figure B-2. X-Y scatter plot showing the skin conductivity parameter space for the first time span derived from AEC-7R perturbation analysis with the fit discriminant and best fit values.

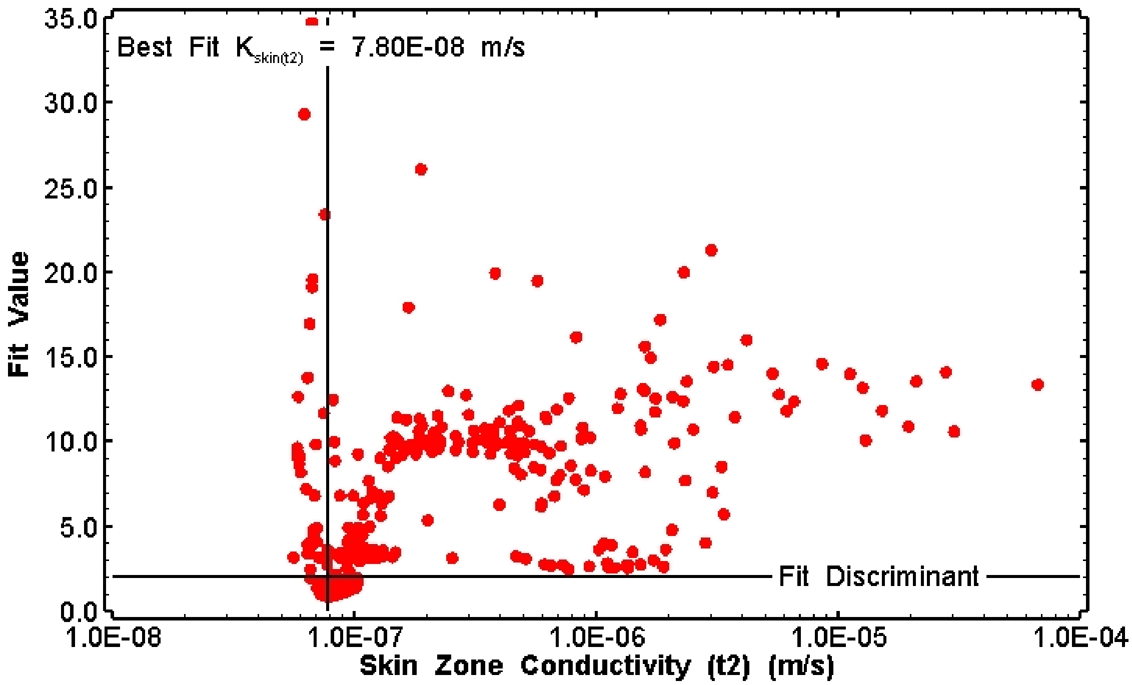

Figure B-3. X-Y scatter plot showing the skin conductivity parameter space for the second time span derived from AEC-7R perturbation analysis with the fit discriminant and best fit values.

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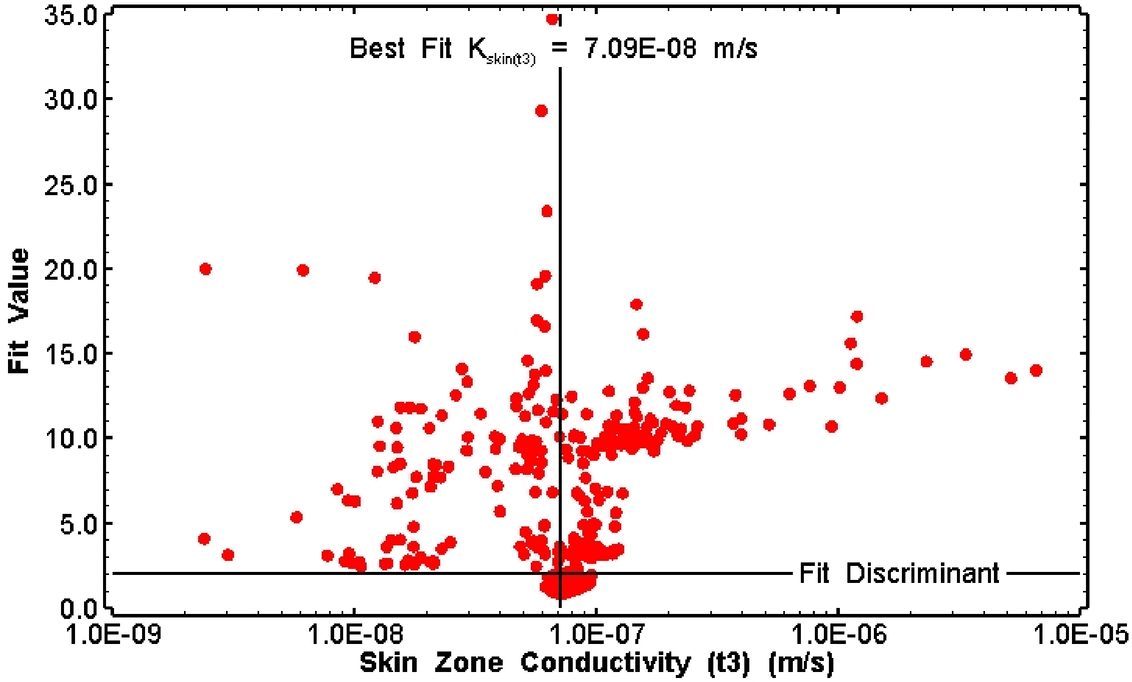

Figure B-4. X-Y scatter plot showing the skin conductivity parameter space for the third time span derived from AEC-7R perturbation analysis with the fit discriminant and best fit values.

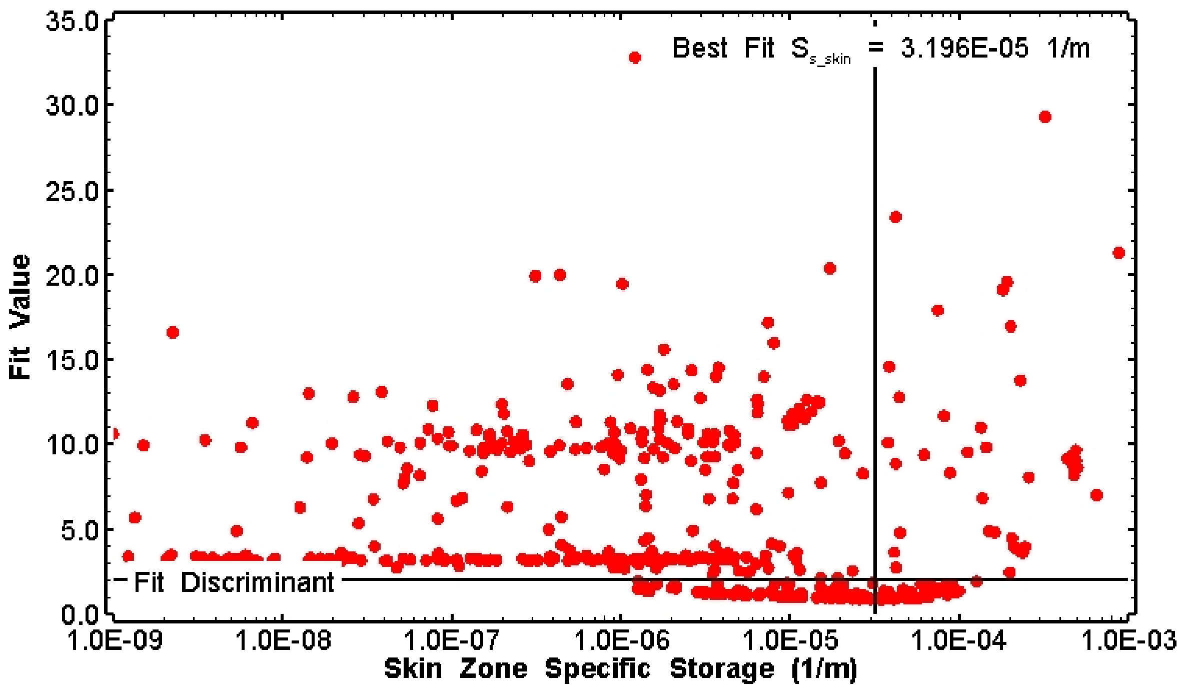

Figure B-5. X-Y scatter plot showing the skin zone specific storage parameter space derived from AEC-7R perturbation analysis with the fit discriminant and best fit values.

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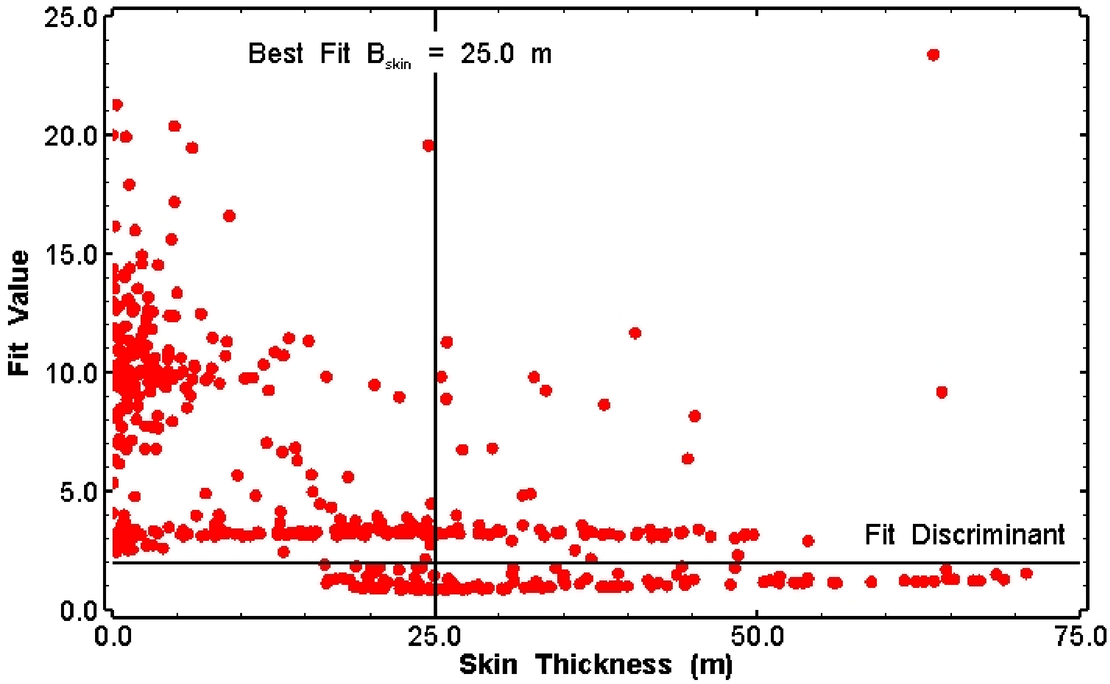


Figure B-6. X-Y scatter plot showing the skin zone thickness parameter space derived from AEC-7R perturbation analysis with the fit discriminant and best fit values.

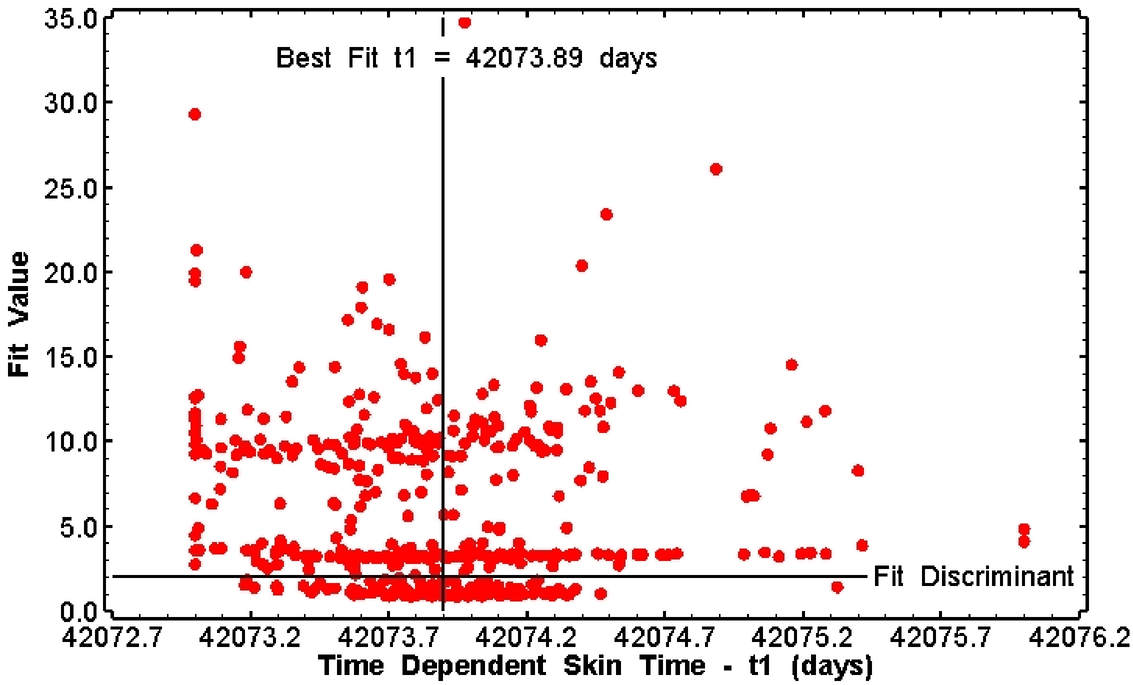


Figure B-7. X-Y scatter plot showing the first time dependent skin time parameter space derived from AEC-7R perturbation analysis with the fit discriminant and best fit values.

Information Only

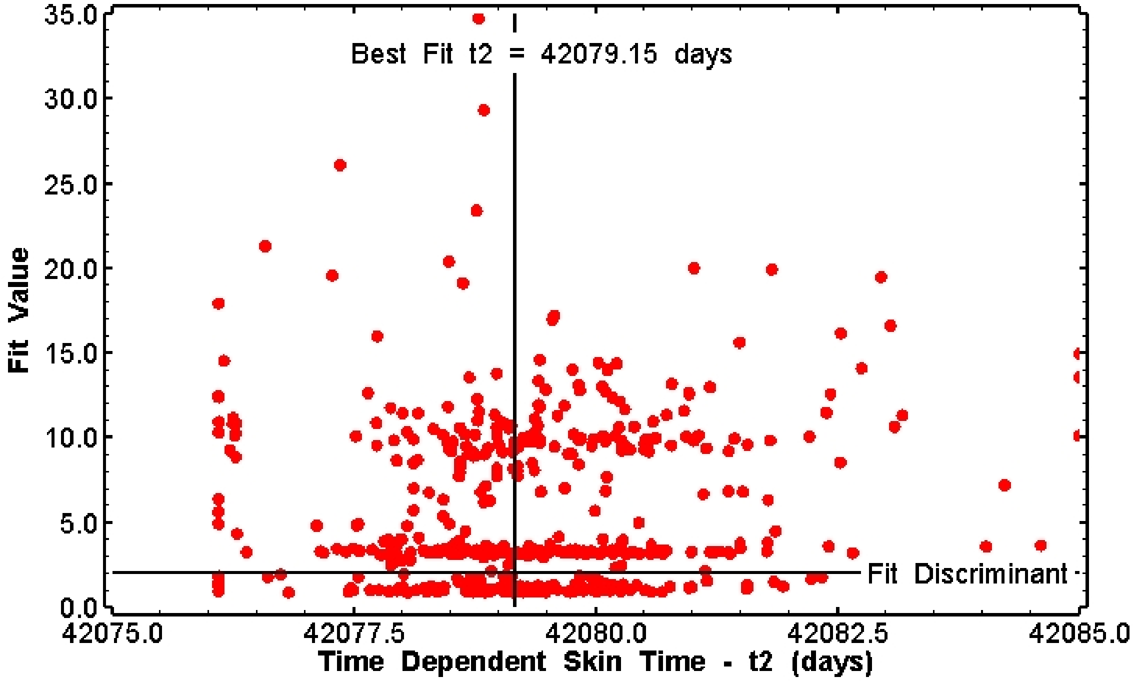


Figure B-8. X-Y scatter plot showing the second time dependent skin time parameter space derived from AEC-7R perturbation analysis with the fit discriminant and best fit values.

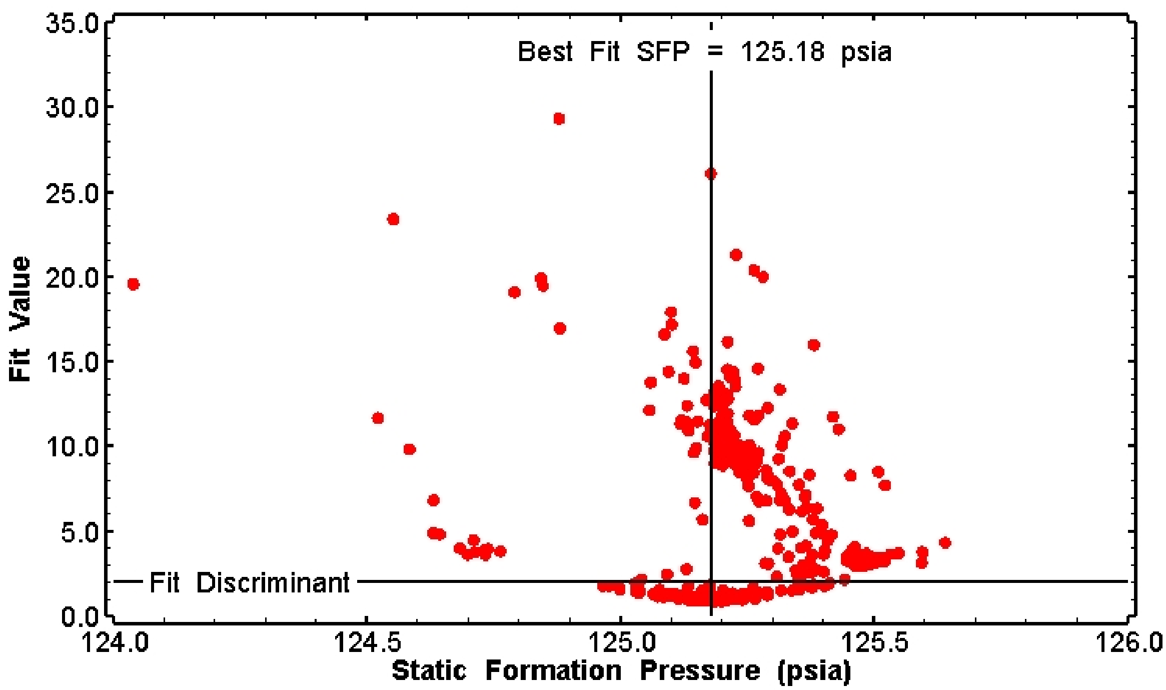


Figure B-9. X-Y scatter plot showing the static formation pressure parameter space derived from AEC-7R perturbation analysis with the fit discriminant and best fit values.

Information Only

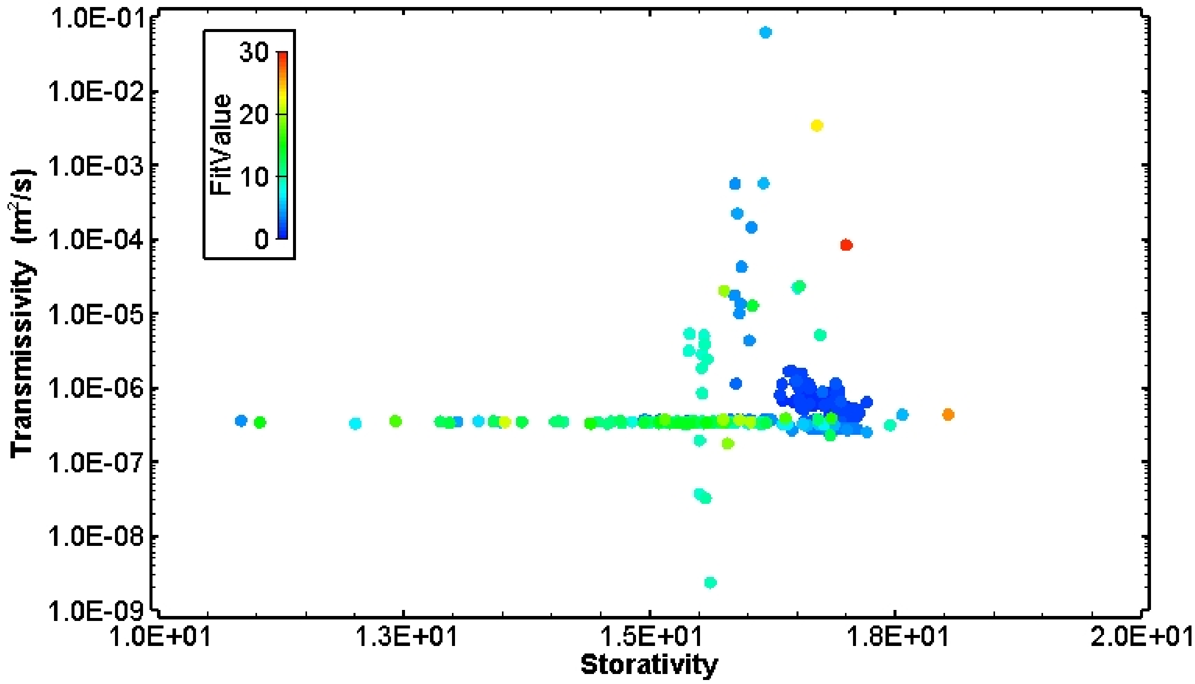


Figure B-10. Estimates of transmissivity and storativity derived from the AEC-7R perturbation analysis using no observation data.

Appendix C – File Directories

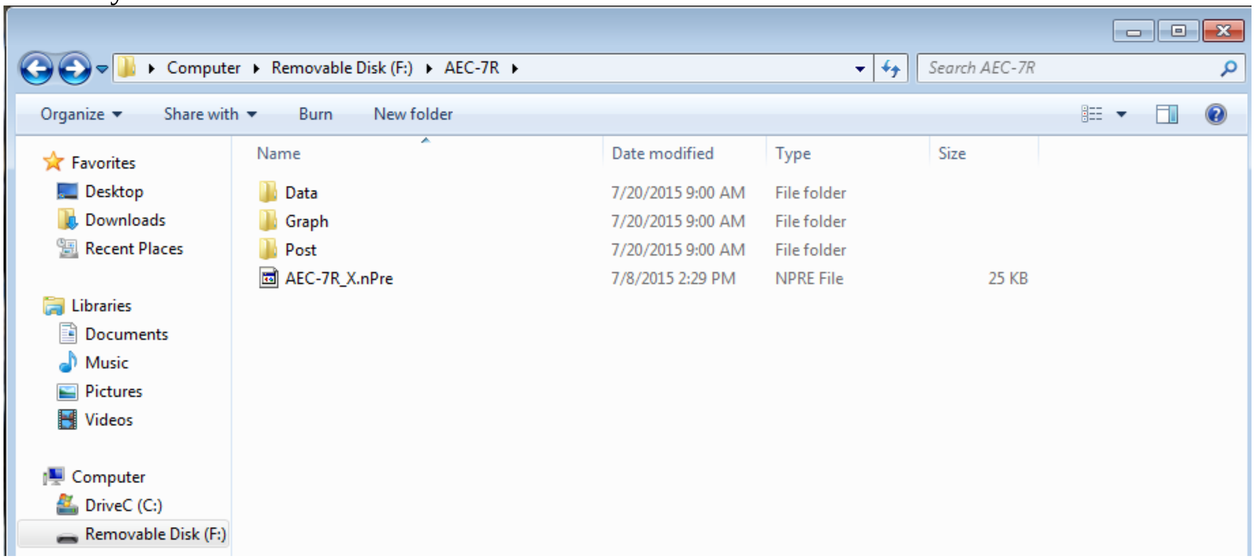
Associated files can be found in the Solaris Directory - /nfs/data/CVSLIB/WIPP_EXTERNAL/AP070.

Table C-1. File descriptions.

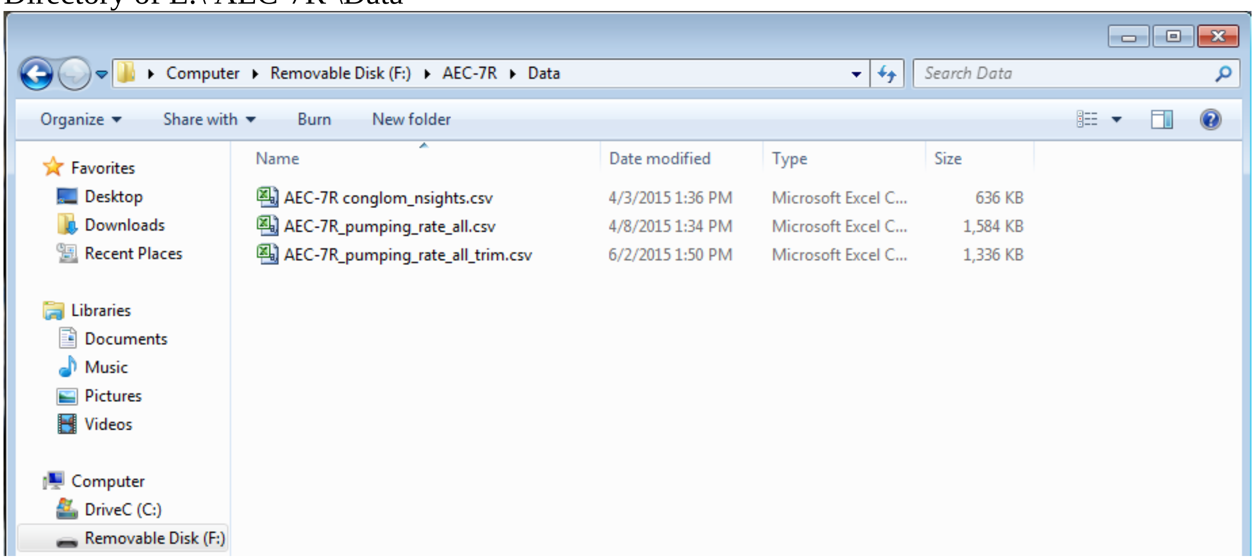
File Extension	Function/Use
<filename>.nPre	Files used for initial well test analysis.
<filename>X.nPre	Files used to generate perturbation analysis of .nPre results.
.nPost	Post-processing files used to visualize .nPre and perturbation analysis.
.nOpt	Optimization data used for post processing in .nPost files.
<filename>.nXYSim	Simulation data used for post processing in .nPost files.
<filename>FieldData.nXYSim	Field data used for post processing in .nPost files.
.jpg	Graphic output from .nPost files.
.csv,.xls, .dat	Data files used as input for .nPre files.

Information Only

Directory of E:\ AEC-7R

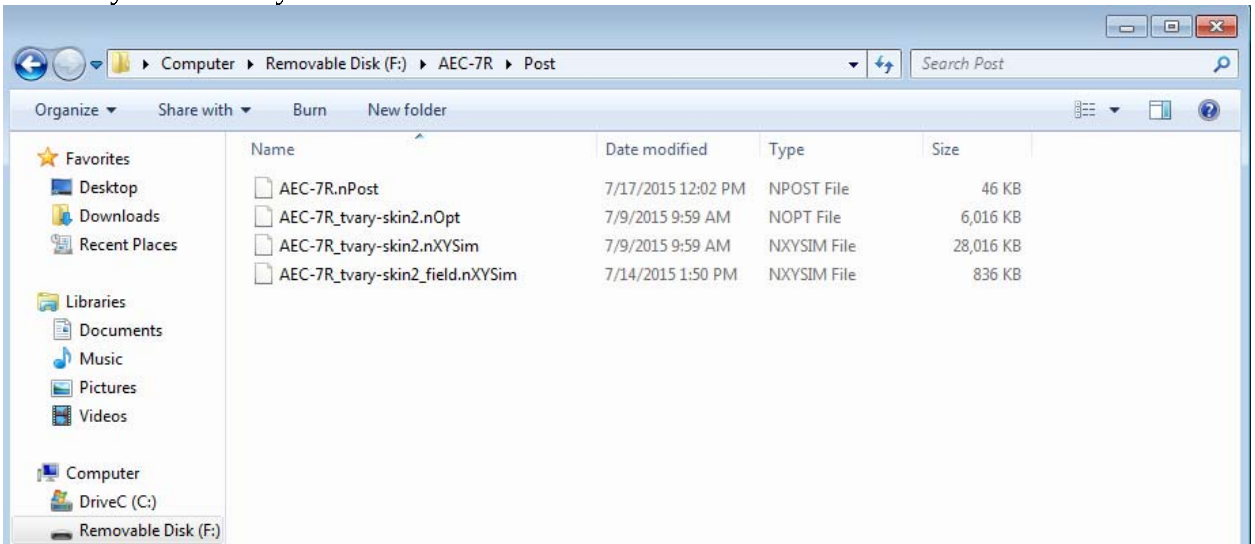


Directory of E:\ AEC-7R \Data

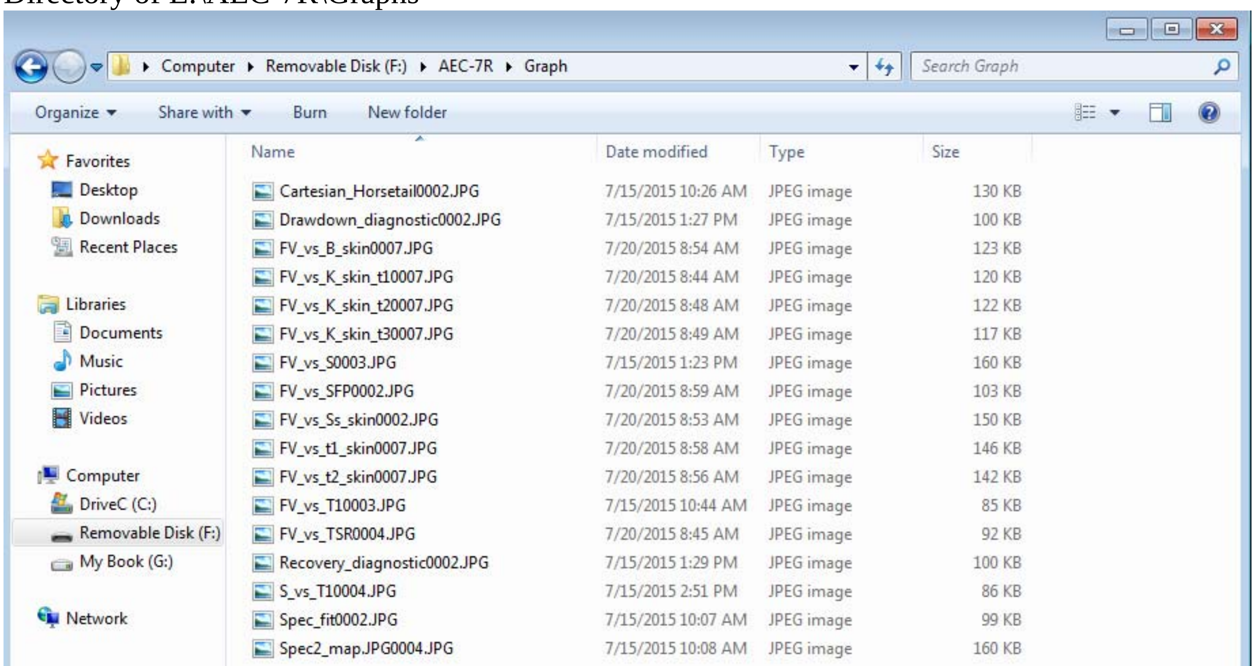


Information Only

Directory of Directory of E:\AEC-7R\Post



Directory of E:\AEC-7R\Graphs



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