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Analysis Report for AP-070

Analysis of the H-10cR Pumping Test Conducted From 7/24/17 to 7/27/17

AP-070: Analysis Plan for Hydraulic-Test Interpretations

Task Number 4.4.2.3.1

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WIPP:4.4.2.3.1:TD:QA-L:RECERT:PKG# 539221

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1. Introduction

This report discusses the analyses of hydraulic tests performed in the Culebra Dolomite Member (Culebra) of the Rustler Formation (Figure 1) at the Waste Isolation Pilot Plant (WIPP) site at the H-10 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).

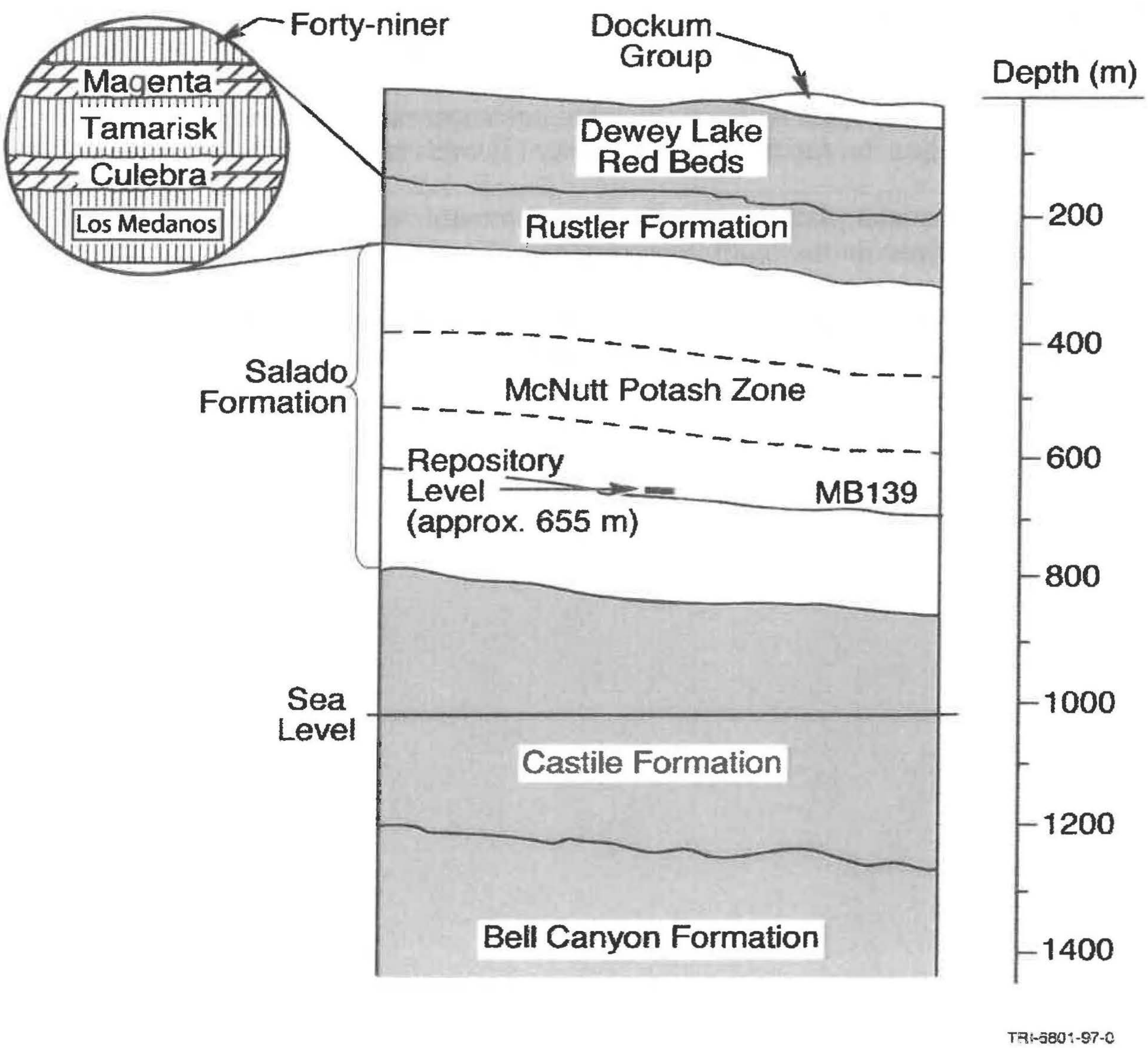

Figure 1. WIPP stratigraphy.

2. Test and Analysis Procedures

A 72-hour constant rate pumping test was performed on well H-10cR from July 24 to 27, 2017. The location of the H-10cR well pad in the WIPP well network is shown in Figure 2. The well had been subject to approximately a year of development prior to this test through 14 separate purges. The test produced 1525 gallons of brine.

The main objective of this analysis is to estimate formation transmissivity (*T*) for subsequent use in *T*-field generation and WIPP performance assessment calculations. 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 pumping test and its subsequent recovery period. The nSIGHTS test simulation incorporated pre-test pressure records as "history" periods where the observed pressures were specified in the simulations. In addition to the formation properties of interest (principally *T* and storativity (*S*)), wellbore skin was also included as a fitting parameter in the pumping-test analyses so that nSIGHTS could better match the early pressure response observed during the test.

The uncertainty quantification method applied to the analyses in this report is an informal process referred to as *perturbation analysis*. In this process, preliminary analyses are performed in which a reasonable model-data fit (i.e., a reasonably small value of the objective function) 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 range for further guesses in parameter space surrounding the analyst-provided baseline solution set. These parameter ranges are listed in Appendix B. Starting at the baseline value, the model parameters are randomly perturbed within their assigned ranges and a simplex optimization is performed from each of these random starting points. The objective of perturbation analysis is to sample the parameter space surrounding the analyst-provided baseline solution set to better understand the nature of model-data fit in this portion of the parameter space. The minimum in the explored parameter space that provides the best fit to the data, measured in terms of the smallest sum of squared errors (SSE), is assumed to be the *global minimum* for the current conceptual model, and other minima are referred to as *local minima*. Local minima are effectively localized depressions in the objective function "topography" that trap the simplex algorithm during its attempt to find the global minimum – the smallest SSE. If multiple data types with different physical units are included in the match (e.g., if pressures and pressure derivatives are matched simultaneously), then the SSE values for each component are weighted and combined and the overall objective function 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

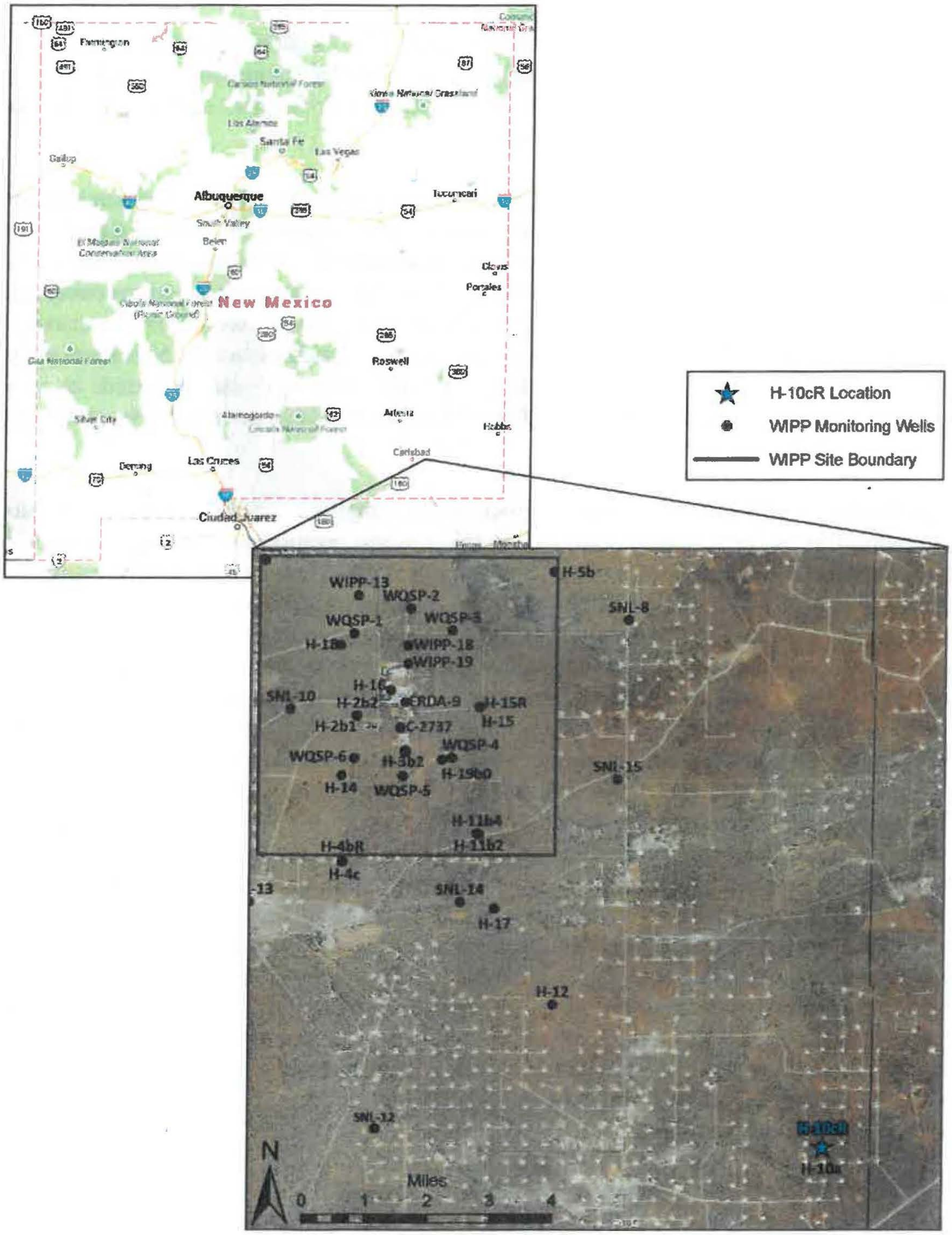

Figure 2. Location of the H-10cR Culebra well on the H-10 wellpad designated by a blue star.

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 3 figure captions.

3. H-10cR Analysis Results

Discussions of H-10cR and associated test analyses are given below. A summary of the best *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.

T_t	Mean *S* (-)	Geometric Mean *T* (m^2/s)	Log_{10} Geo. Mean *T* (m^2/s)	Log_{10} Min. *T* (m^2/s)	Log_{10} Max. *T* (m^2/s)	Variance $(m^2/s)^2$
T_1	3.52E-06	7.41E-08	-7.15	-7.54	-6.78	4.12E-16
T_2		9.57E-08	-7.03	-7.35	-6.74	4.54E-16
T_3		9.90E-08	-7.01	-7.31	-6.74	4.55E-16
T_4		1.19E-07	-6.93	-7.24	-6.66	6.42E-16
T_5		3.03E-07	-6.52	-6.57	-6.45	2.09E-16

3.1. H-10cR

A physical description of the H-10cR well is detailed in Figure 3. The well is a 11" reamed bore hole with a 5.5" OD (5.125" ID) casing slotted in the Culebra. The constant-rate pumping test of the well was made possible using a 3-phase pump, a variable frequency drive, and a DAS system aboard the testing trailer. This system enacted and maintained a constant pumping rate in the well.

Fourteen purges were previously conducted in H-10cR between March 1, 2016 and May 3, 2017. Hydraulic testing of the Culebra at H-10cR was conducted over three days from July 24 to 27, 2017 using a constant flowrate of 0.35 gpm. Pressure changes were logged using two pressure transducers; one polling at 15-minute intervals and one polling at 1-minute intervals. Flow rate was recorded by the DAS at 5-second intervals. We experienced transducer-based problems with the transducer poling at 1-minute intervals. Subsequently, we did not get good testing coverage during intermittent portions of the test. Data from both transducers was integrated into a single pressure profile to represent and subsequently model pressure change in the well during testing.

The H-10cR nSIGHTS constant-rate pumping test and recovery simulations consisted of a history sequence, a drawdown sequence, and a recovery sequence chronologically in that order. Pressure-derivative diagnostics of the drawdown and Bourdet-derivative diagnostics of the recovery were used to better fit and understand the data. The details of each sequence (i.e., start/end time, pressure, etc.) are specified in the H-10cR.nPre files and are listed in Appendix B.1.

Investigation of the drawdown response showed distinctive rate changes we assume are attributed to the incomplete development of the well. Subsequently, transmissivity changed over time as, presumably, sediment or filter pack material was loosed from the formation and/or screened portion of the well. The initial models used to fit the data considered a simple system of single *T* and *S* with and without skin effects. These models did not adequately fit the data. Secondary attempts to model the data to account for changing transmissivity (T_t) included changing skin transmissivity as a function of time or pressure. Skin transmissivity proved to be a very sensitive parameter when a single value was used; using multiple values produced a model that would not converge.

To model the changing *T*, a model that used an infinite-acting, radial systems with a variable *T* values as a function of time, wellbore storage, and a negative skin. The *T(t)* values of the model were designated T_1 to T_5, chronologically. The specified H-10cR conceptual model was chosen because it was the simplest model consistent with the available information that produced an acceptable fit to the data; acceptable by consensus of the modeler. A comparison of the model fit of the T_t model and simplest, single *T* model are shown in Figure 3. Table 2 describes the time ranges for each T_t value. The resulting model parameter estimates required only subtle changes in the *T* estimate to adequately fit the data. A sand pack surrounding the screened portion of the well, and the possible presence of a fractured or damaged zone in the formation surrounding the well still warranted the inclusion of skin effects into the model especially given the low *T* of the well.

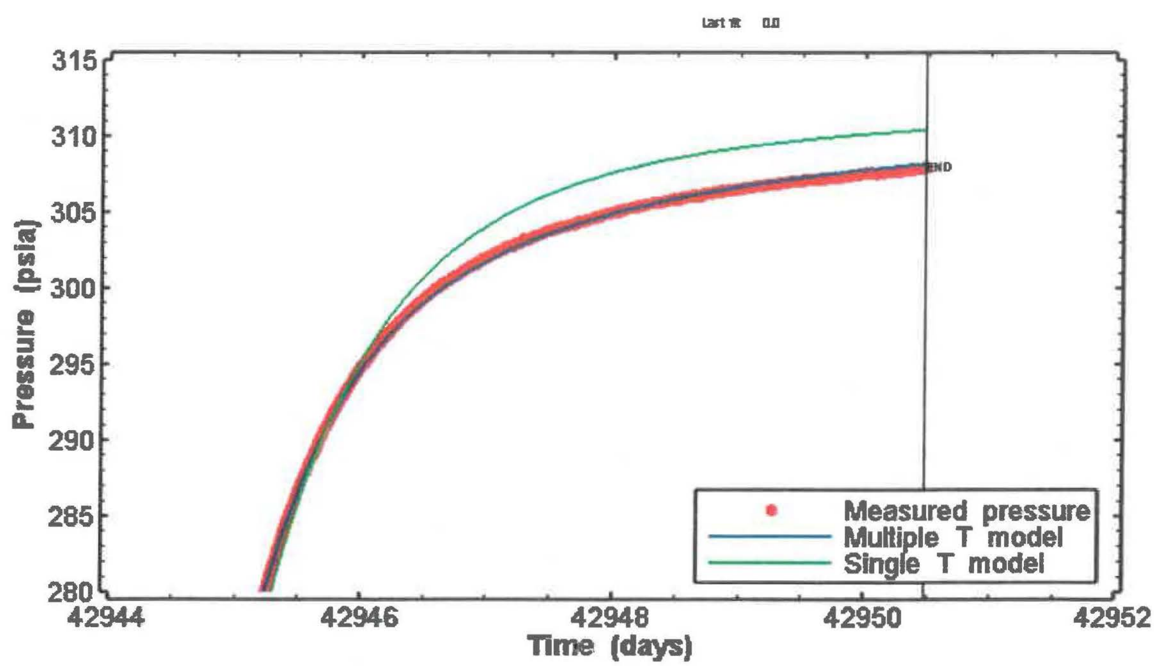

Figure 3. H-10cR model comparison.

Table 2. Variable Transmissivity Time Intervals.

T_t	Time range minimum	Time range maximum
T_1	7/24/17 10:48	7/26/17 17:31
T_2	7/26/17 17:31	7/27/17 7:40
T_3	7/27/17 7:40	7/27/17 11:16
T_4	7/27/17 11:16	7/29/17 5:16
T_5	7/29/17 5:16	8/3/17 11:31

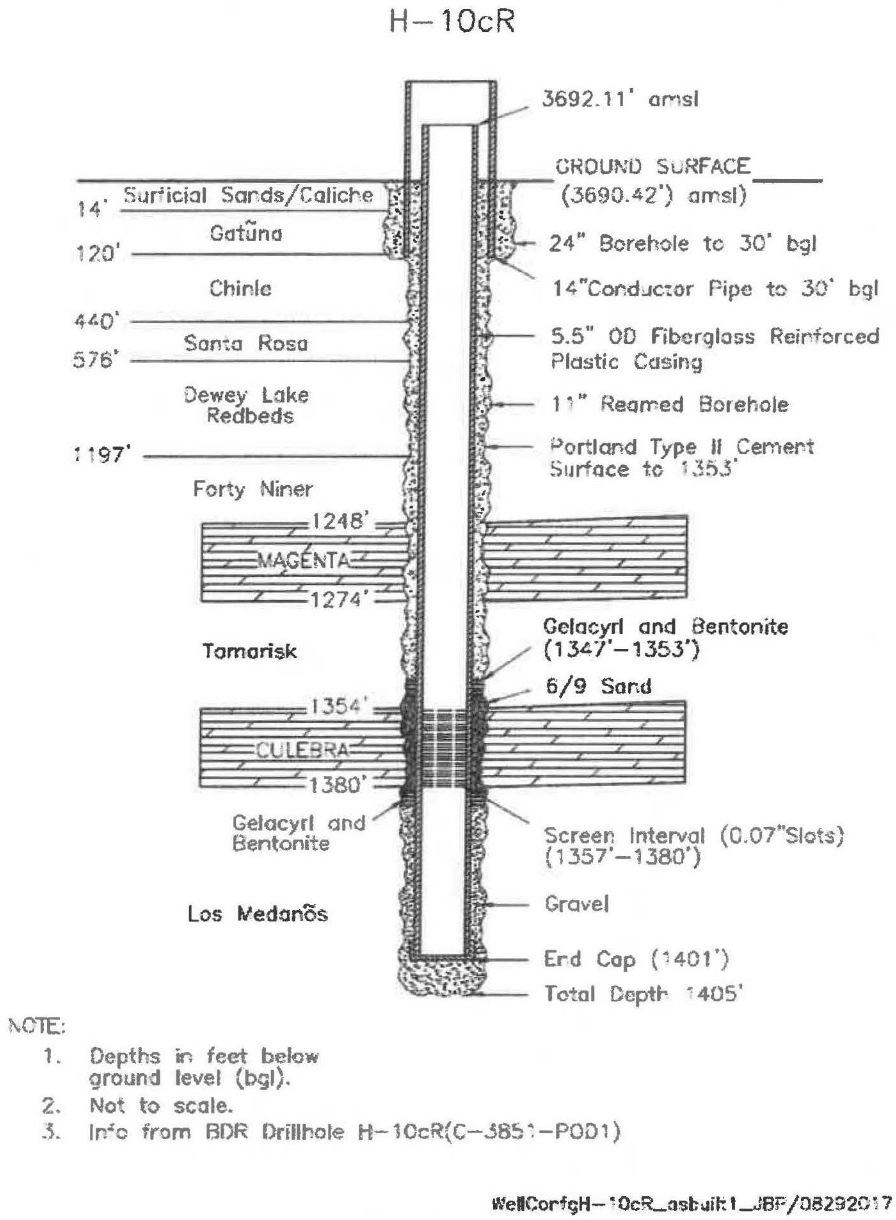

Figure 4. H-10cR well configuration during testing.

3.1.1 Pumping Test Analysis

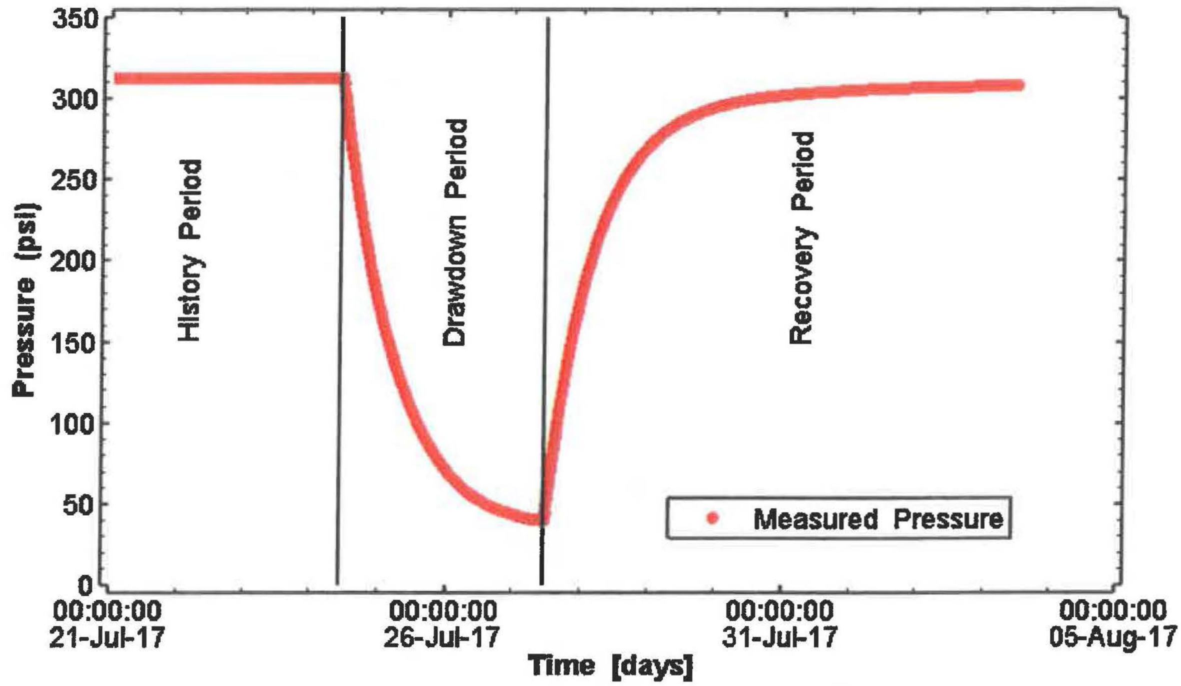

Figure 5. The 72-hour pumping test at H-10cR.

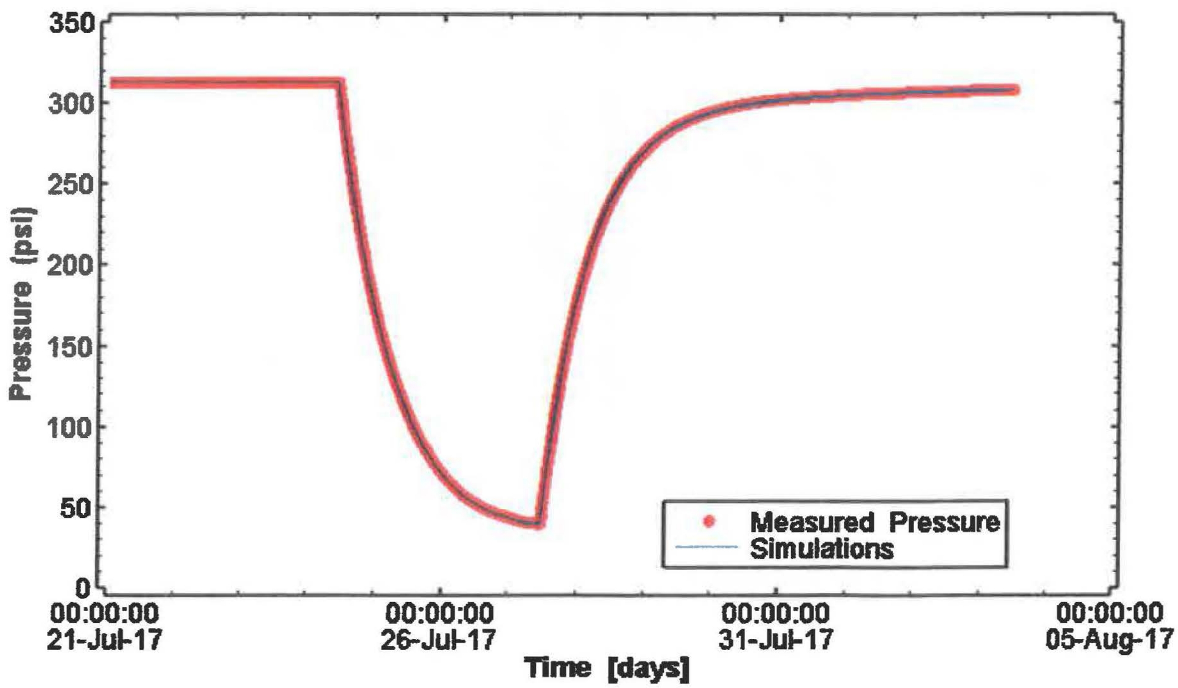

Figure 6. Pressure data and 359 model fits of the H-10cR pumping test.

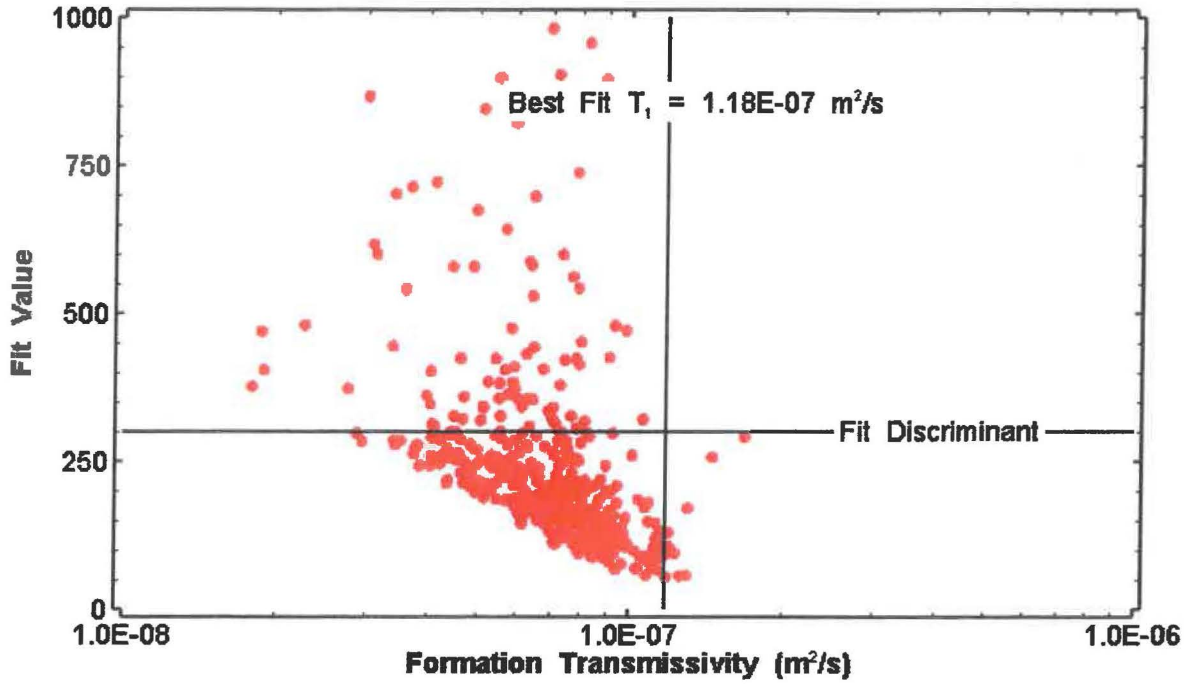

Figure 7. X-Y scatter plot showing the transmissivity (T_1) parameter space derived from the H-10cR test perturbation analysis with fit discriminant and best fit values.

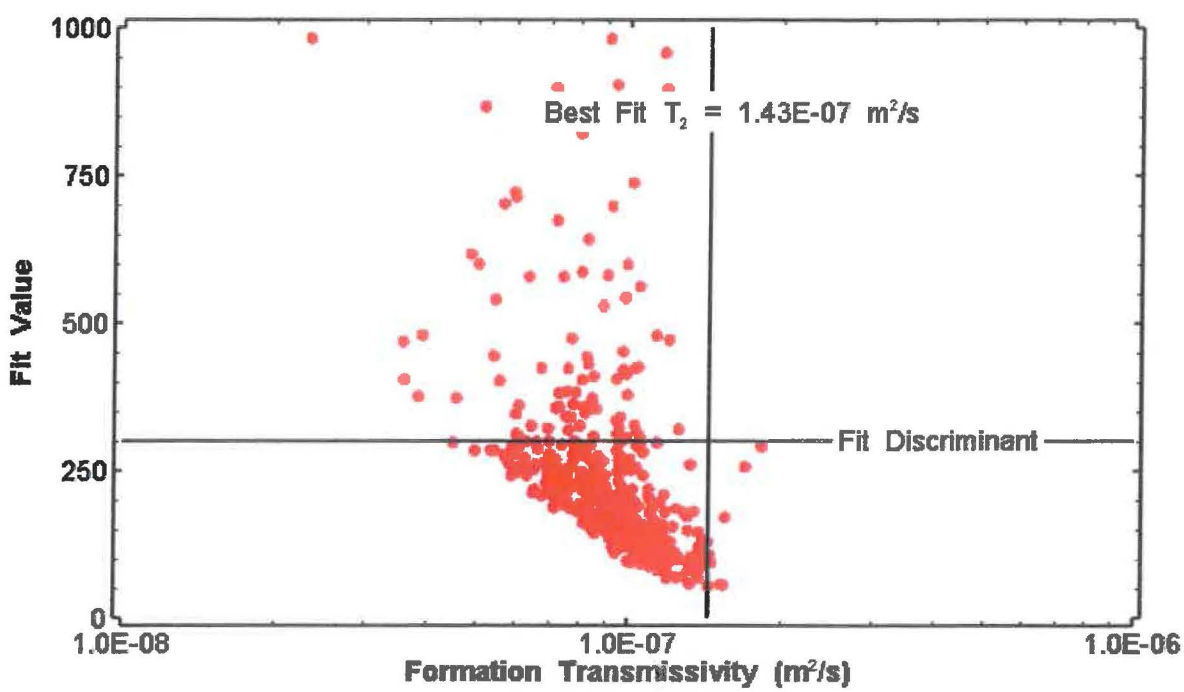

Figure 8. X-Y scatter plot showing the transmissivity (T_2) parameter space derived from the H-10cR test perturbation analysis with fit discriminant and best fit values.

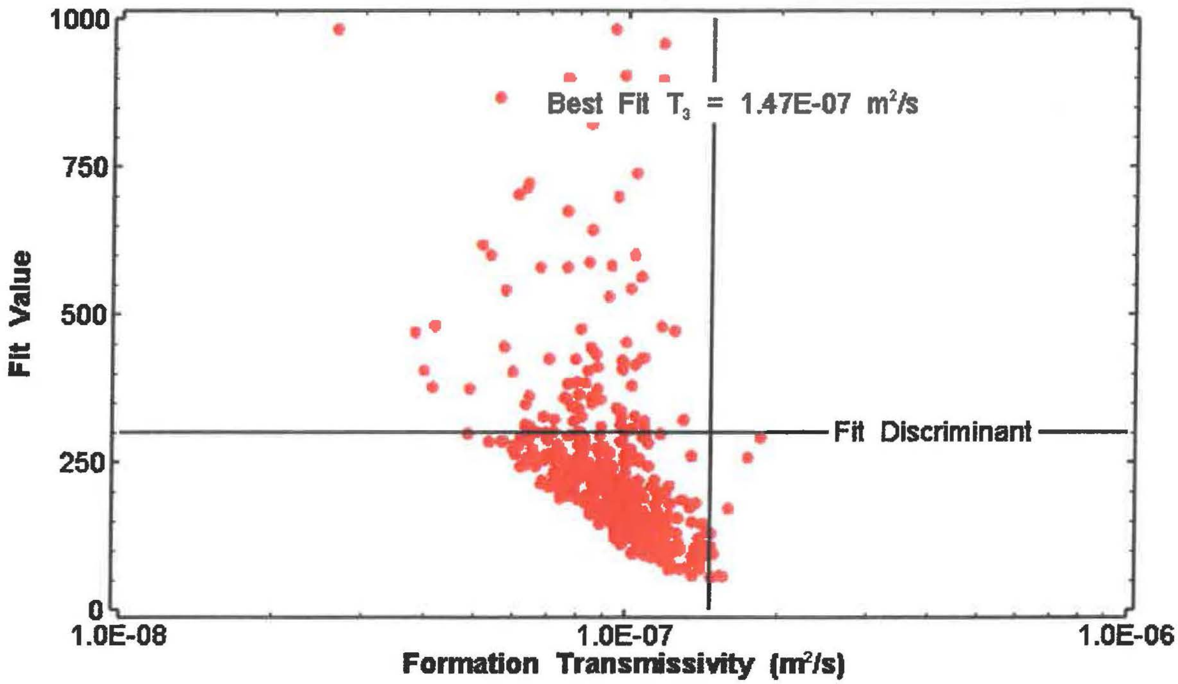

Figure 9. X-Y scatter plot showing the transmissivity (T_3) parameter space derived from the H-10cR test perturbation analysis with fit discriminant and best fit values.

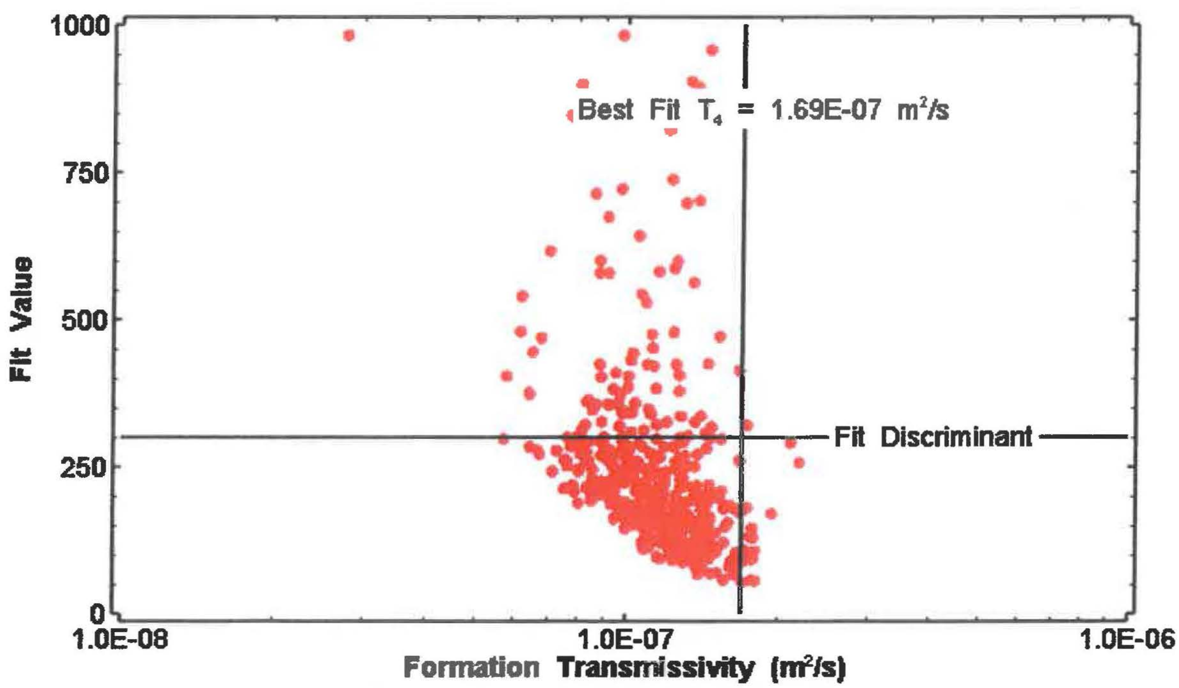

Figure 10. X-Y scatter plot showing the transmissivity (T_4) parameter space derived from the H-10cR test perturbation analysis with fit discriminant and best fit values.

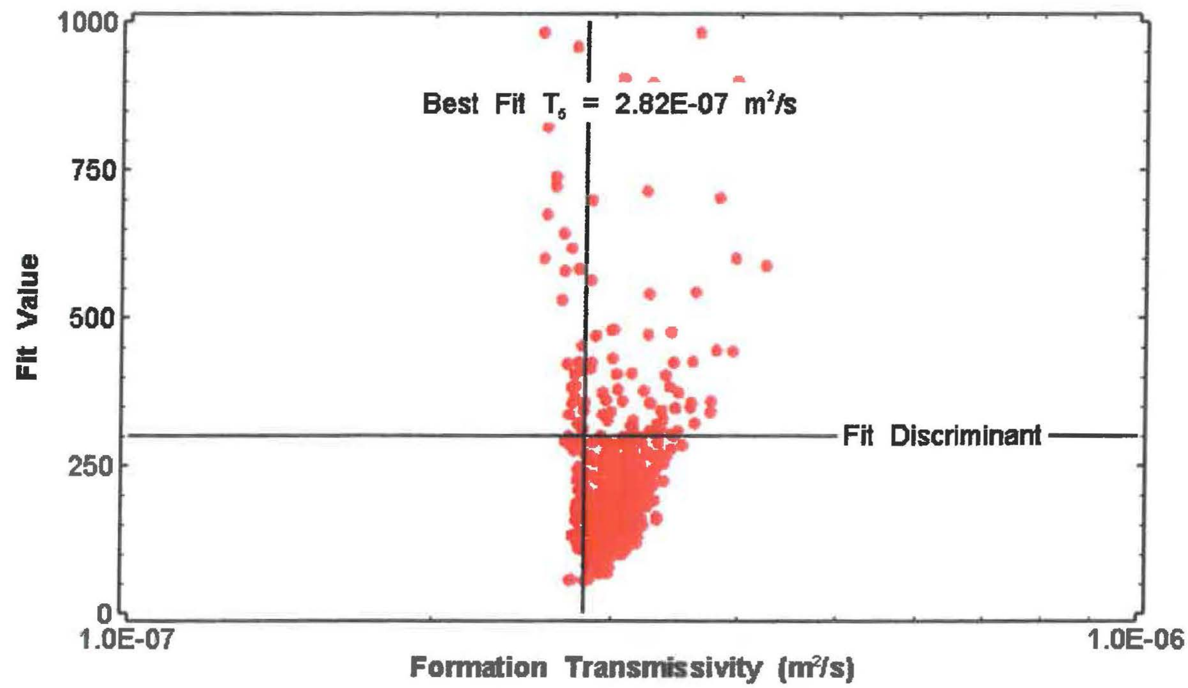

Figure 11. X-Y scatter plot showing the transmissivity (T_5) parameter space derived from the H-10cR test perturbation analysis with fit discriminant and best fit values.

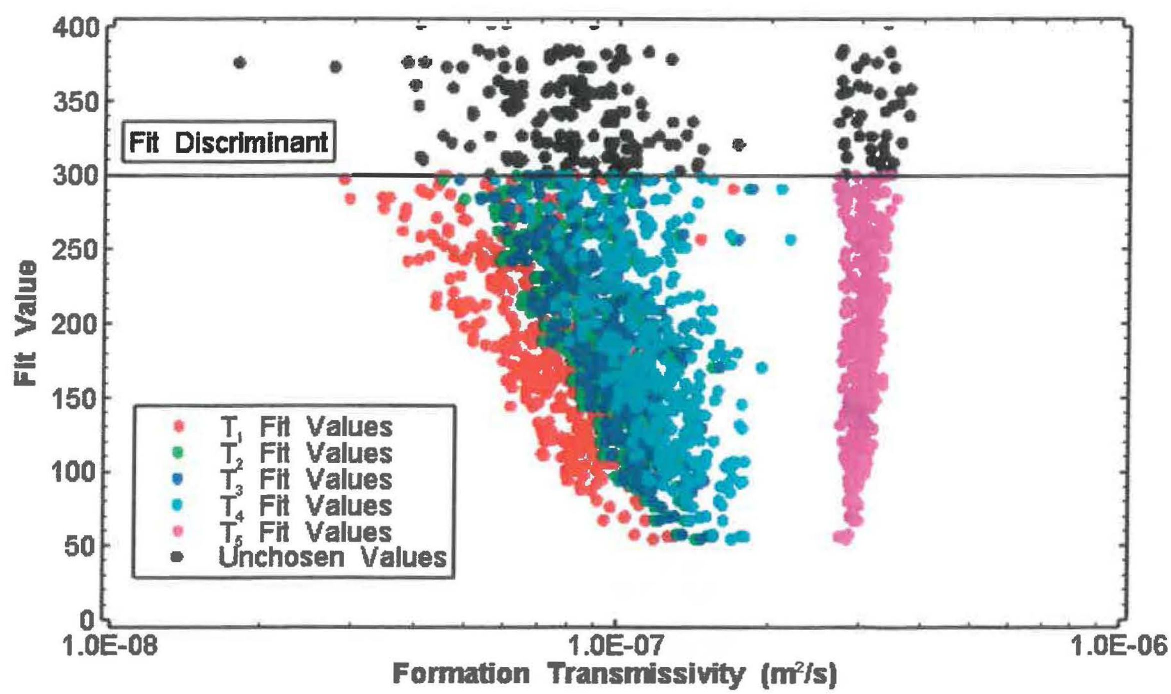

Figure 12. X-Y scatter plot showing the all estimated transmissivities in parameter space derived from the H-10cR test perturbation analysis with fit discriminant.

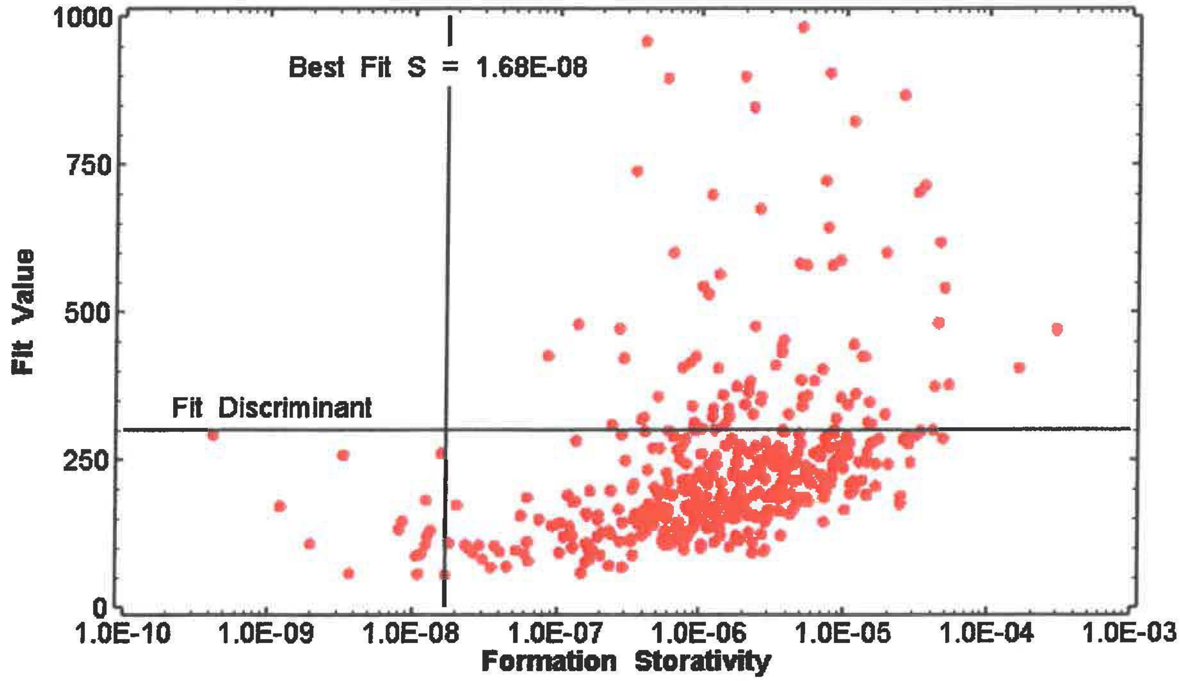

Figure 13. X-Y scatter plot showing the storativity parameter space derived from the H-10cR test perturbation analysis with fit discriminant and best fit values.

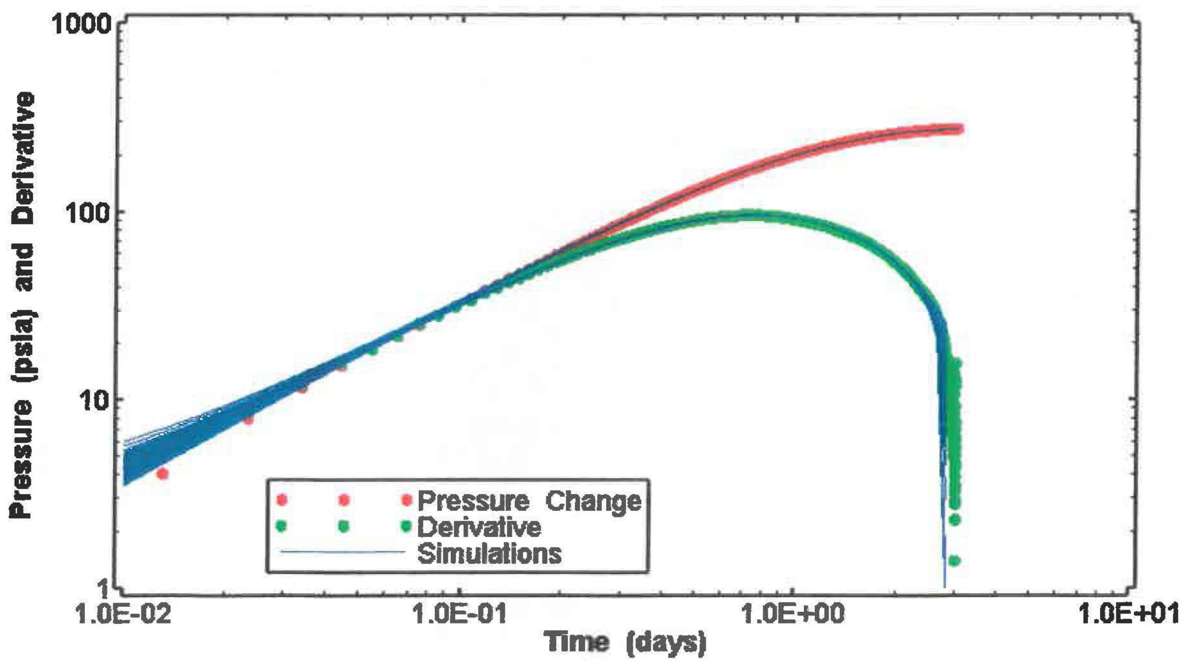

Figure 14. Log-log plot showing 359 simulations of the H-10cR drawdown period pressure change and derivative response.

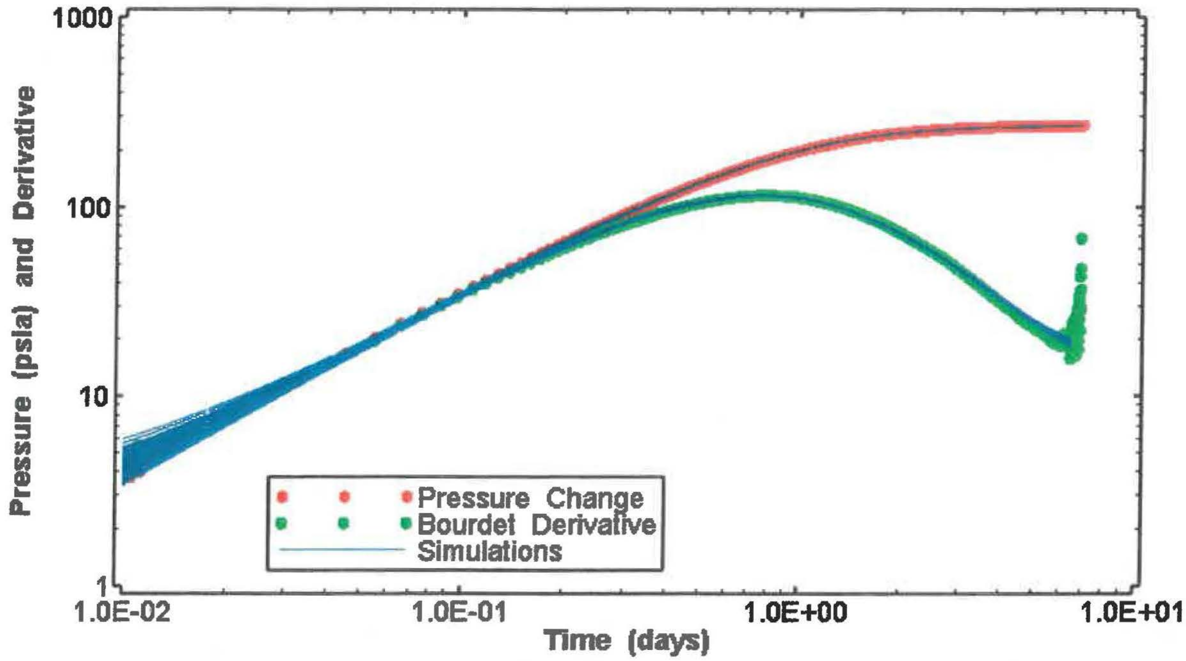

Figure 15. Log-log plot showing 359 simulations of the H-10cR recovery period pressure change and derivative response.

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Appendix A – H-10cR Pumping Test – 7/24/17 to 7/27/17

Well	Borehole Diameter (in)	Inside Tubing or Casing Diameter (in)	Culebra Interval (ft bgs)	Fluid Density (g/cm^3)	Data Source Report(s)	Field Notebook
H-10cR	5.125	1.913	1354-1380	1.100	Basic Data Report for H-10cR (C-3851) (WIPP)	WSWT#19 Scientific Notebook

Start Test Time	Stop Test Time
7/24/17	7/27/17
9:43	10:11

Appendix B – nSIGHTS Listings

B.1 H-10cR nSIGHTS Listings

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

Version date    25 June 2012
Listing date    18 Aug 2017
QA status       non-QA Open Source
Config file     C:\SANDIA_PROJECTS\WIPP_wells\Culebra\H-10cR_pumping test\H-
10cR_K_time_2.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	26.000	[ft]
Flow dimension	2.0	[]
Static formation pressure	313.000	[psi]
External boundary radius	1000000	[m]
Formation conductivity	f(t) point	
Formation spec. storage	Optimization	

Minimum value	1.00000E-10	[1/m]
Maximum value	1.00000E-02	[1/m]
Estimate value	2.39368E-06	[1/m]
Range type	Log	
Sigma	1.00000E+00	

Skin

Radial thickness of skin	Optimization	
Minimum value	0.1	[m]
Maximum value	10.0	[m]
Estimate value	0.1456165	[m]
Range type	Linear	
Sigma	1.00000E+00	
Skin zone conductivity	Optimization	
Minimum value	1.00000E-10	[m/sec]
Maximum value	1.00000E-02	[m/sec]
Estimate value	1.04738E-06	[m/sec]
Range type	Log	
Sigma	1.00000E+00	
Skin zone spec. storage	Optimization	
Minimum value	1.00000E-10	[1/m]
Maximum value	1.00000E-02	[1/m]
Estimate value	8.53711E-03	[1/m]
Range type	Log	
Sigma	1.00000E+00	

Fluid

Fluid density	1100.00	[kg/m^3]
Fluid thermal exp. coeff.	0.00000E+00	[1/C]

Test-Zone

Well radius	2.155	[in]
Tubing string radius	0.5	[in]

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

Formation conductivity

Points type	f(t)	
Time #1	Optimized	
Minimum	3710054469.600000	[day]
Estimat	3710074643.825000	[day]
Maximum	3710251674.144000	[day]
Y value#1	Optimized	
Time #2	Optimized	
Minimum	3710251674.230000	[day]

Estimat	3710251818.445000	[day]
Maximum	3710302803.936000	[day]
Y value#2	Optimized	
Time #3	Optimized	
Minimum	3710302804.022000	[day]
Estimat	3710315310.396000	[day]
Maximum	3710315403.648000	[day]
Y value#3	Optimized	
Time #4	Optimized	
Minimum	3710315403.734000	[day]
Estimat	3710315957.414001	[day]
Maximum	3710466902.592000	[day]
Y value#4	Optimized	
Time #5	Optimized	
Minimum	3710466902.678000	[day]
Estimat	3710532996.835000	[day]
Maximum	3710921400.288000	[day]
Y value#5	Optimized	
X opt range type	Linear	
X opt sigma	1.00000E+00	
Y opt minimum value	1.00000E-10	[m/sec]
Y opt maximum value	1.00000E-05	[m/sec]
Y opt range type	Log	
Y opt sigma	1.00000E+00	
Parameter curve type	Linear	

Calculated Parameters

Formation

Transmissivity	f(t)	
Storativity	min/max	
Minimum	7.92480E-10	[]
Maximum	7.92480E-02	[]
Diffusivity	f(t)	

Skin Zone

Transmissivity	min/max	
Minimum	7.92480E-10	[m^2/sec]
Maximum	7.92480E-02	[m^2/sec]
Storativity	min/max	
Minimum	7.92480E-10	[]
Maximum	7.92480E-02	[]
Diffusivity	min/max	
Minimum	1.00000E-08	[m^2/sec]
Maximum	1.00000E+08	[m^2/sec]
Skin factor	f(t)	

Test Zone

Open hole well-bore storage	4.69746E-08	[m^3/Pa]

Grid Properties

Grid increment delta	min/max	
Minimum	0.05783	[]
Maximum	0.07880	[]
First grid increment	min/max	
Minimum	5.98570E-01	[m]
Maximum	1.26868E-02	[m]
Skin grid increment delta	min/max	
Minimum	0.02121	[]
Maximum	0.10639	[]
Skin first grid increment	min/max	
Minimum	1.17325E-03	[m]
Maximum	6.14472E-03	[m]
Skin last grid increment	min/max	
Minimum	3.24709E-03	[m]
Maximum	1.01481E+00	[m]
Increment ratio	min/max	
Minimum	5.89833E-01	[]
Maximum	3.90714E+00	[]

Sequences

Sequence: H_01

Sequence type	History	
Start time	42934.500000	[day]
Duration	5.945250	[day]
Time step type	Log	
First log step	1.15741E-07	[day]
# of time steps	250	
Type	Curve	
Wellbore storage	Open	

Sequence: F_01

Sequence type	Flow	
Start time	42940.445250	[day]
Duration	3.020070	[day]
Time step type	Log	
First log step	1.15741E-07	[day]
# of time steps	250	
Type	Fixed	
Fixed value	-0.35	[USgpm]
Wellbore storage	Open	

Sequence: F_02

Sequence type	Flow	
Start time	42943.465320	[day]
Duration	7.013850	[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
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

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 ?	no

Optimization Output

Write file ?	no

Optimization Setup

Algorithm	Simplex
Calculate confidence limits ?	yes
Covariance matrix calculations	1st Order
Fixed derivative span ?	no
Fit tolerance	1.0000E-05
Parameter tolerance	not used
# of optimized variables	14
K_fm.T[01]	OK
K_fm.T[02]	OK
K_fm.T[03]	OK
K_fm.T[04]	OK
K_fm.T[05]	OK
K_fm.V[01]	OK
K_fm.V[02]	OK
K_fm.V[03]	OK
K_fm.V[04]	OK
K_fm.V[05]	OK
Skin zone conductivity	OK

Formation spec. storage	OK
Skin zone spec. storage	OK
Radial thickness of skin	OK

Fits to Optimize

Cart_DAT_P	OK

Calculated Parameters Included

# of calculated variables included	0

Suite/Range Setup

# of suite/range variables	0

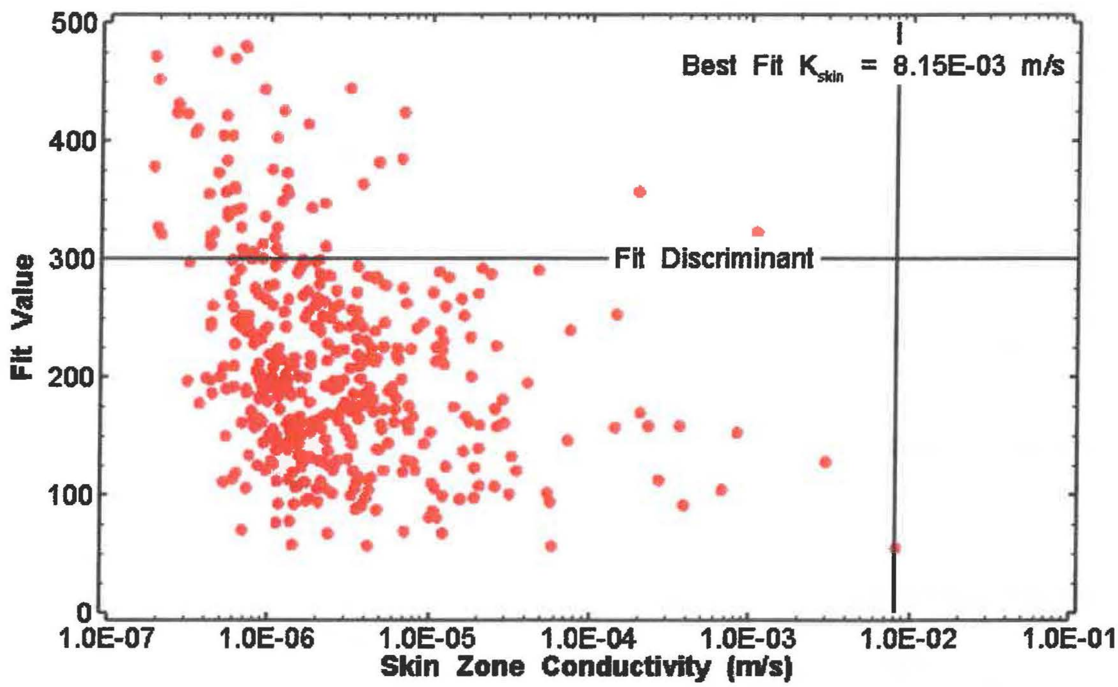


Figure B-1. X-Y scatter plot showing the skin zone conductivity parameter space derived from H-10cR perturbation analysis with the fit discriminant and best fit values.

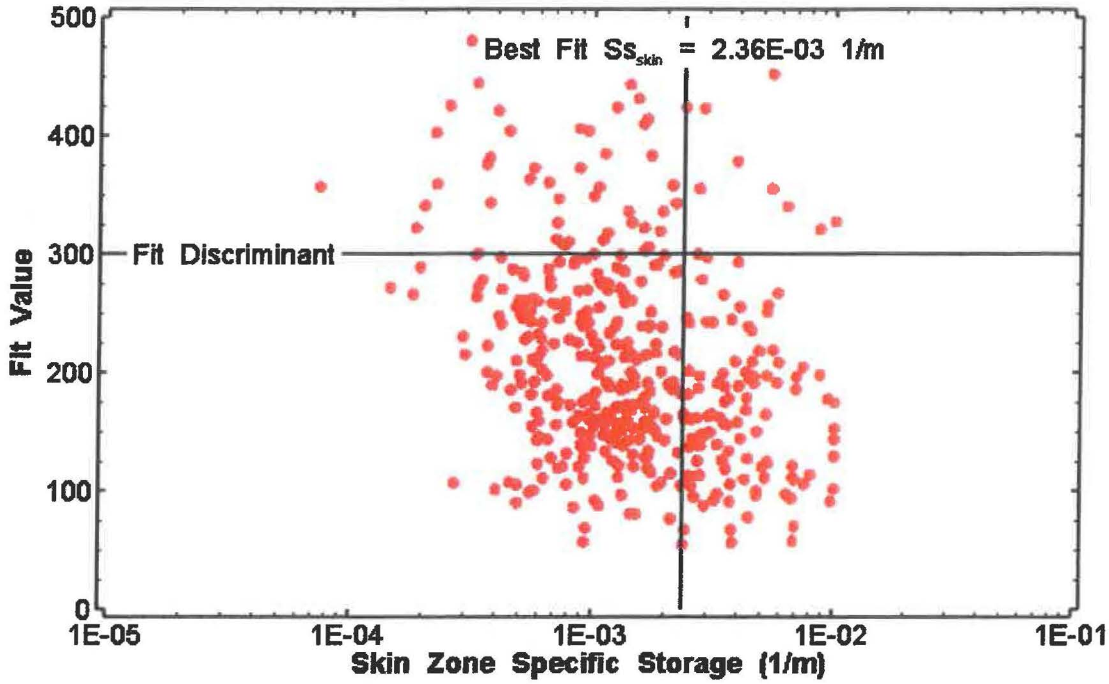


Figure B-2. X-Y scatter plot showing the skin zone specific storage parameter space derived from H-10cR perturbation analysis with the fit discriminant and best fit values.

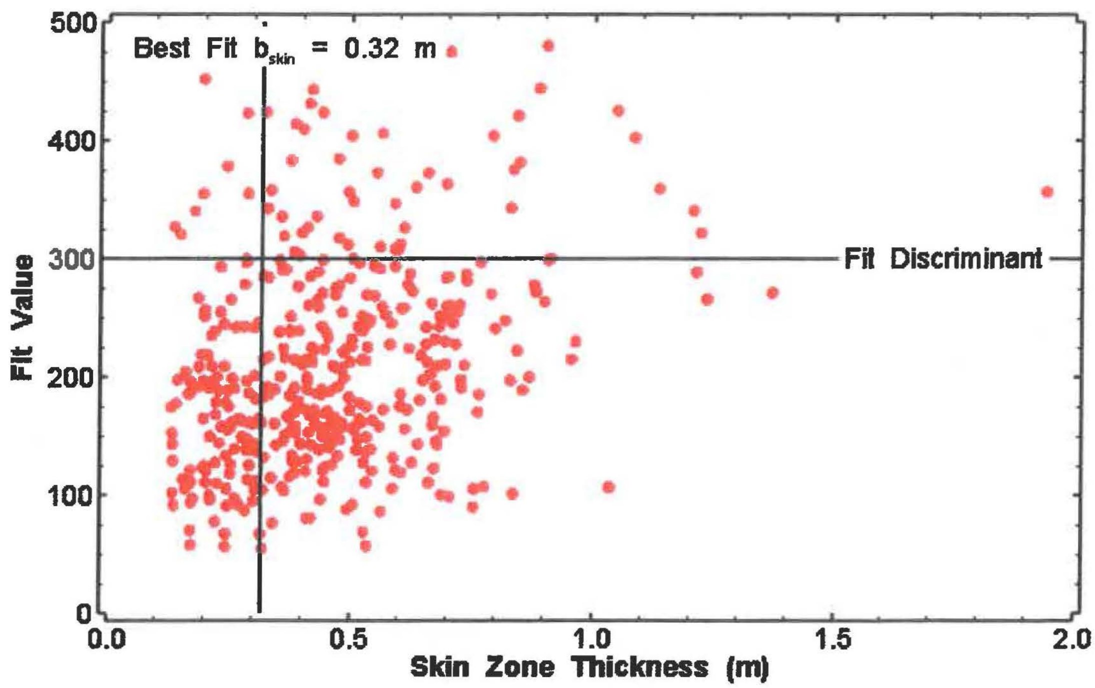


Figure B-3. X-Y scatter plot showing the skin zone thickness parameter space derived from H-10cR perturbation analysis with the fit discriminant and best fit values.

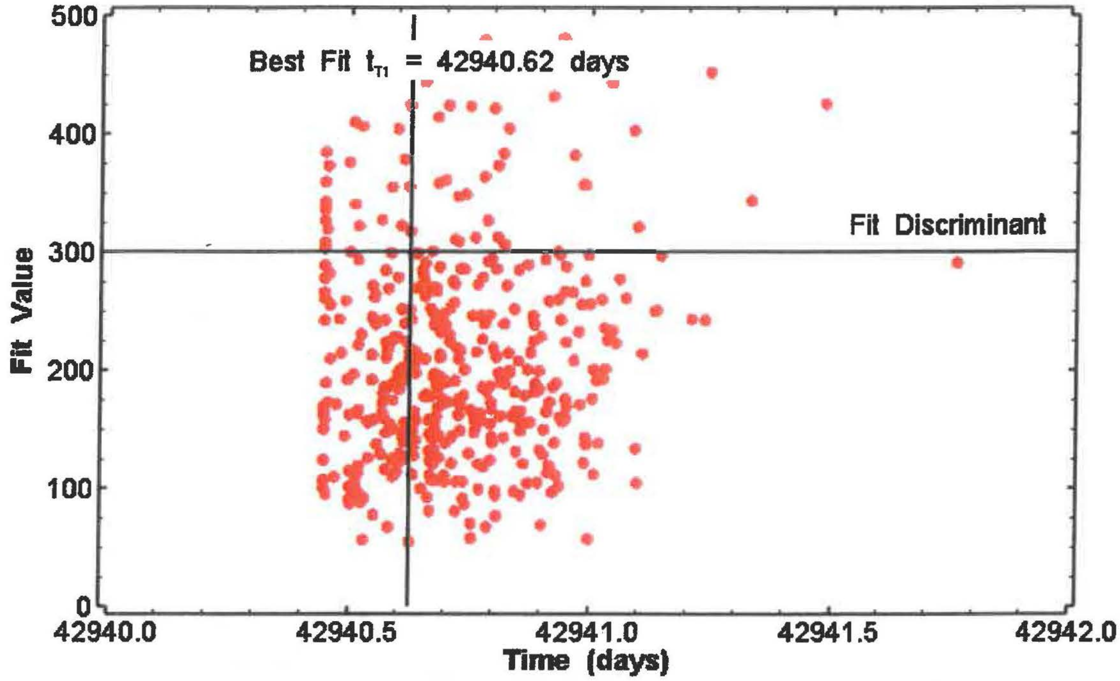


Figure B-4. X-Y scatter plot showing the time parameter space derived from H-10cR perturbation analysis for the first transmissivity (T_1) with the fit discriminant and best fit values.

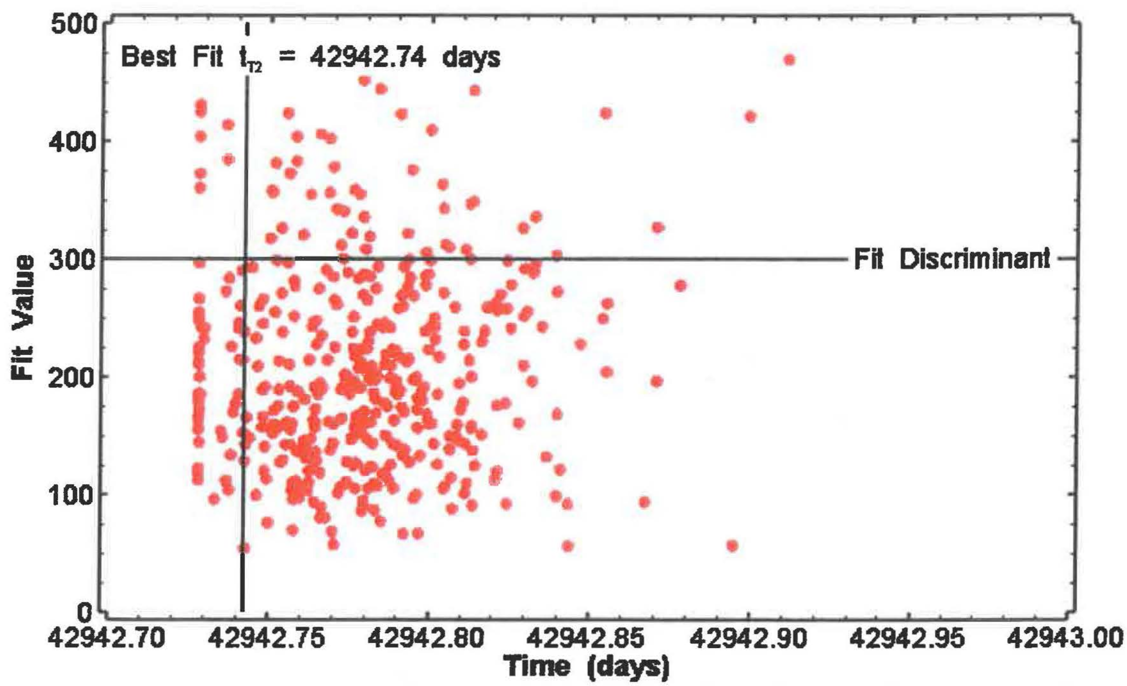


Figure B-5. X-Y scatter plot showing the time parameter space derived from H-10cR perturbation analysis for the second transmissivity (T_2) with the fit discriminant and best fit values.

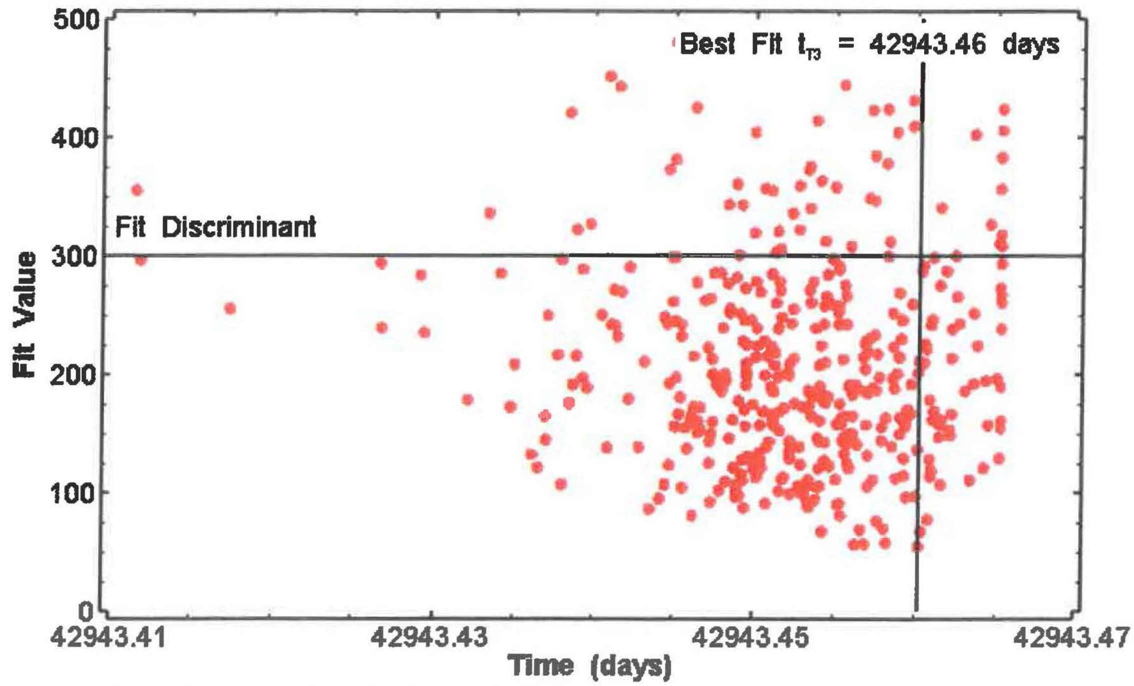


Figure B-6. X-Y scatter plot showing the time parameter space derived from H-10cR perturbation analysis for the third transmissivity (T_3) with the fit discriminant and best fit values.

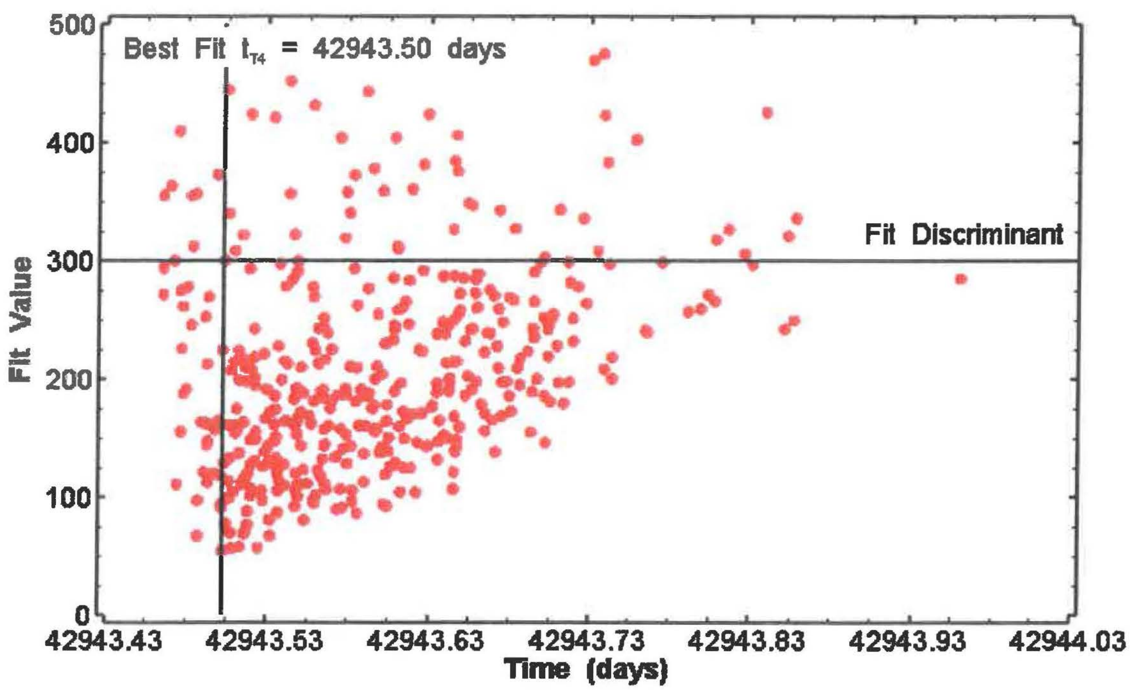


Figure B-7. X-Y scatter plot showing the time parameter space derived from H-10cR perturbation analysis for the fourth transmissivity (T_4) with the fit discriminant and best fit values.

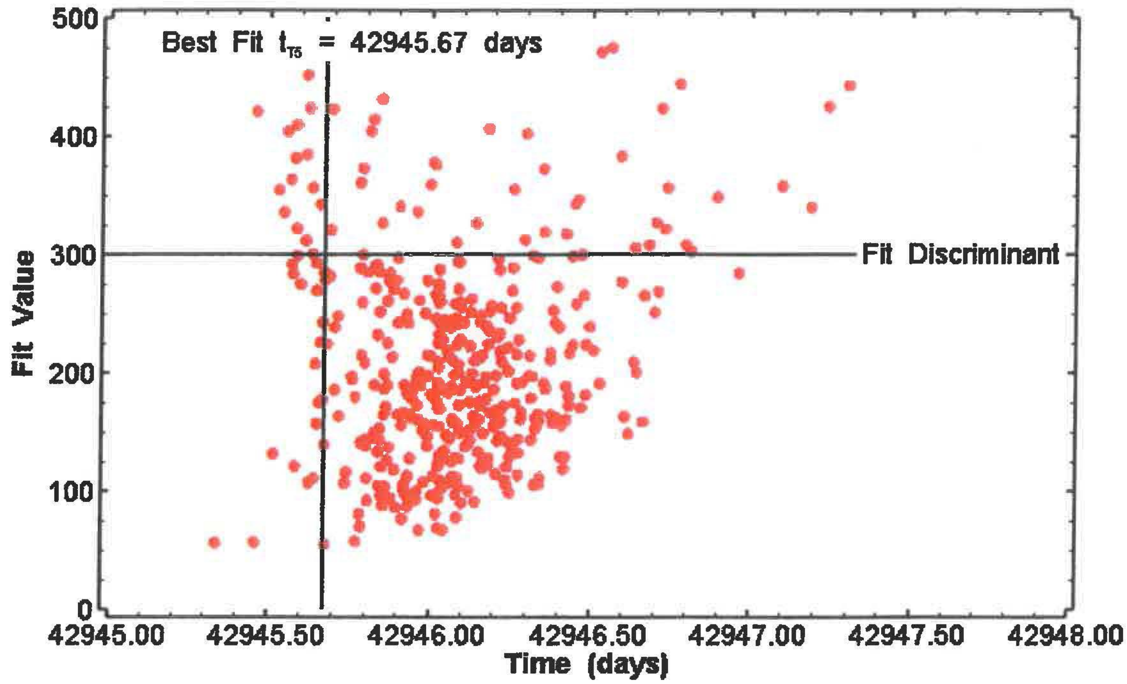


Figure B-8. X-Y scatter plot showing the time parameter space derived from H-10cR perturbation analysis for the fifth transmissivity (*T_5*) with the fit discriminant and best fit values.

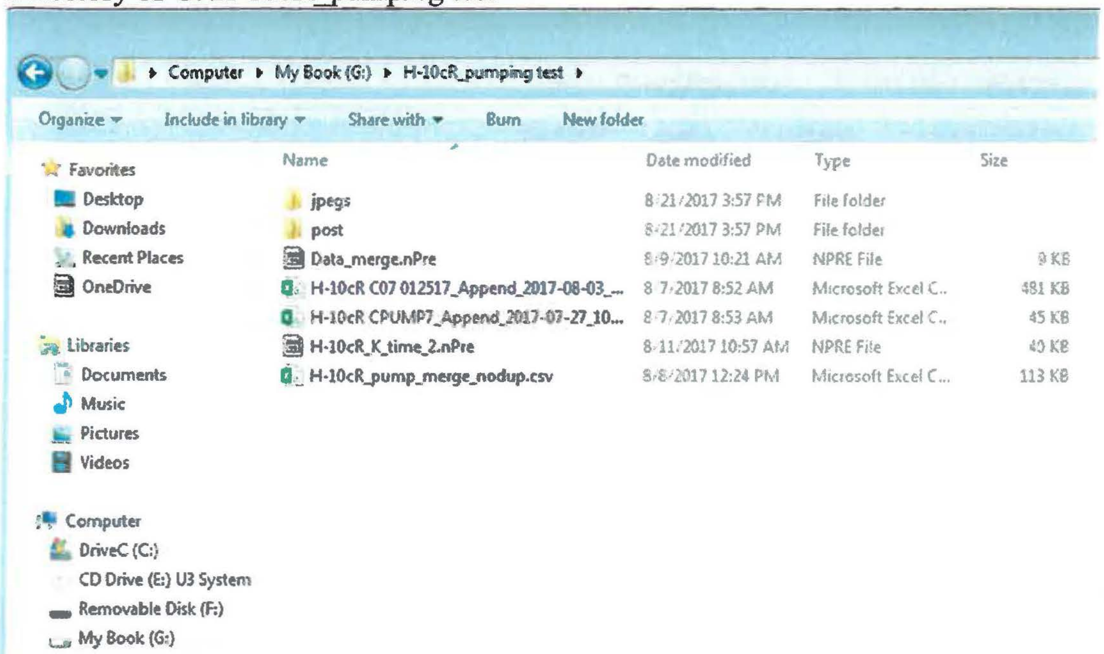
Appendix C – File Directories

These files are located in server file-path: /nfs/data/CVSLIB/WIPP_EXTERNAL/ap070

Table C-1. File descriptions.

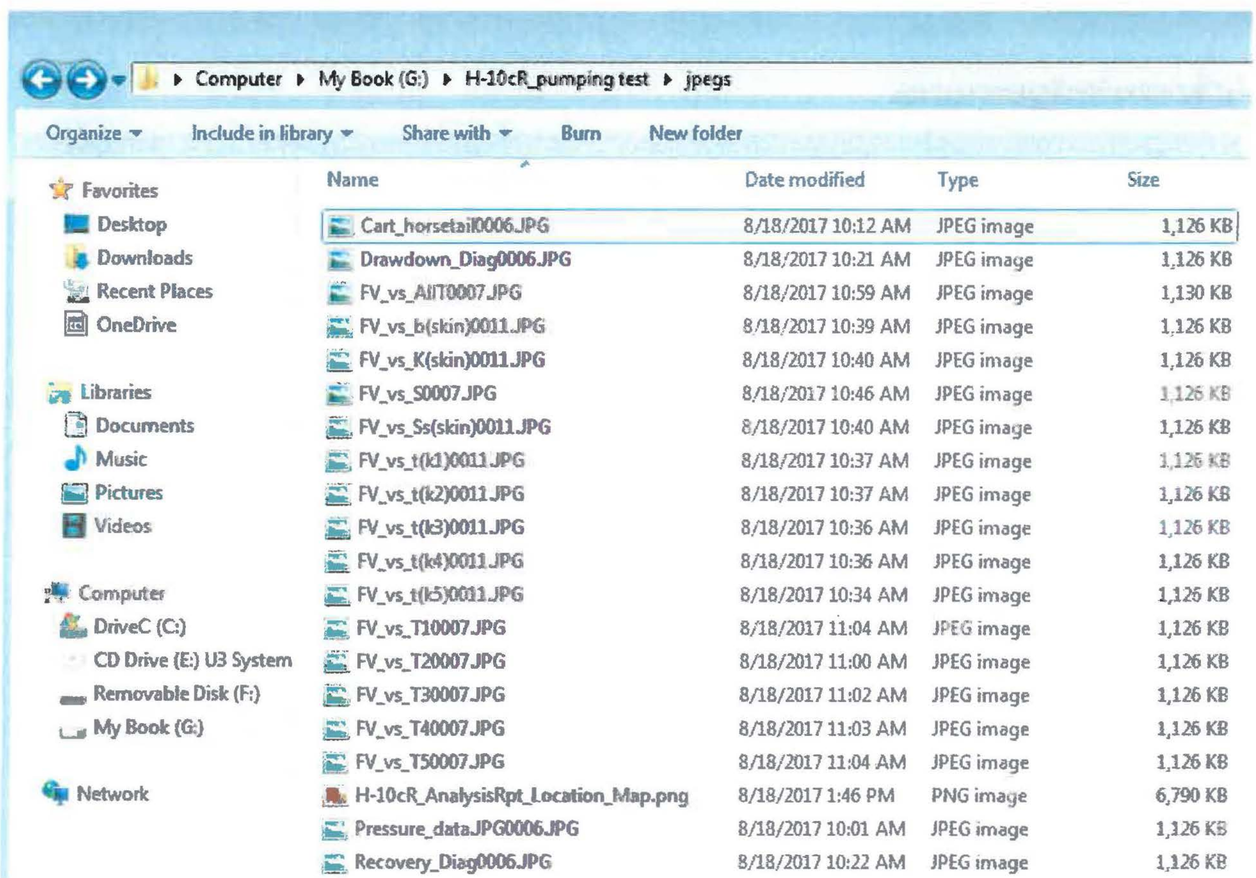
File Extension	Function/Use
<filename>.nPre	Files used for initial well test analysis.
<filename>X.nPre	Files used to generate perturbation analysis of .nPre results.
.nPost	Post-processing files used to visualize .nPre and perturbation analysis.
.nOpt	Optimization data used for post processing in .nPost 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.

Directory of G:\H-10cR_pumping test



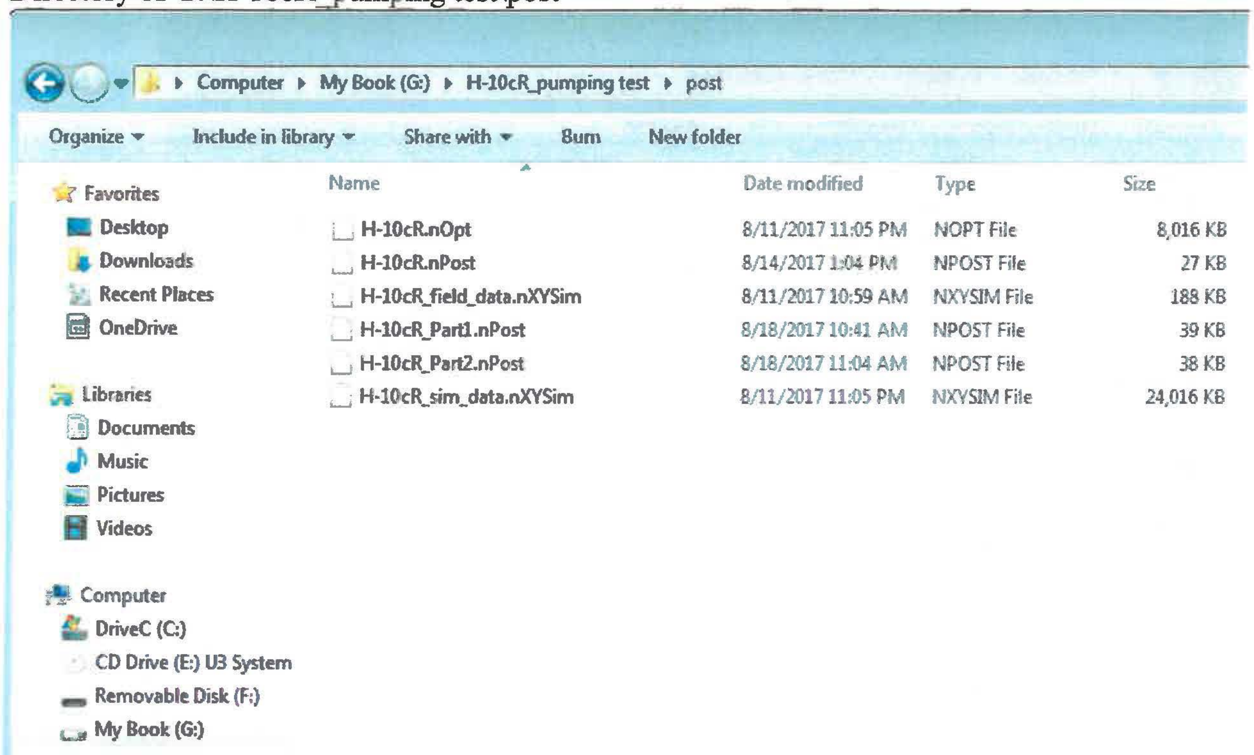
Name	Date modified	Type	Size
jpegs	8/21/2017 3:57 PM	File folder	
post	8/21/2017 3:57 PM	File folder	
Data_merge.nPre	8/9/2017 10:21 AM	NPRE File	9 KB
H-10cR C07 012517_Append_2017-08-03_...	8/7/2017 8:52 AM	Microsoft Excel C...	481 KB
H-10cR CPUMP7_Append_2017-07-27_10...	8/7/2017 8:53 AM	Microsoft Excel C...	45 KB
H-10cR_K_time_2.nPre	8/11/2017 10:57 AM	NPRE File	40 KB
H-10cR_pump_merge_nodup.csv	8/8/2017 12:24 PM	Microsoft Excel C...	113 KB

Directory of G:\H-10cR_pumping test\jpegs



Name	Date modified	Type	Size
Cart_horsetail0006.JPG	8/18/2017 10:12 AM	JPEG image	1,126 KB
Drawdown_Diag0006.JPG	8/18/2017 10:21 AM	JPEG image	1,126 KB
FV_vs_AllT0007.JPG	8/18/2017 10:59 AM	JPEG image	1,130 KB
FV_vs_b(skin)0011.JPG	8/18/2017 10:39 AM	JPEG image	1,126 KB
FV_vs_K(skin)0011.JPG	8/18/2017 10:40 AM	JPEG image	1,126 KB
FV_vs_S0007.JPG	8/18/2017 10:46 AM	JPEG image	1,126 KB
FV_vs_Ss(skin)0011.JPG	8/18/2017 10:40 AM	JPEG image	1,126 KB
FV_vs_t(k1)0011.JPG	8/18/2017 10:37 AM	JPEG image	1,126 KB
FV_vs_t(k2)0011.JPG	8/18/2017 10:37 AM	JPEG image	1,126 KB
FV_vs_t(k3)0011.JPG	8/18/2017 10:36 AM	JPEG image	1,126 KB
FV_vs_t(k4)0011.JPG	8/18/2017 10:36 AM	JPEG image	1,126 KB
FV_vs_t(k5)0011.JPG	8/18/2017 10:34 AM	JPEG image	1,126 KB
FV_vs_T10007.JPG	8/18/2017 11:04 AM	JPEG image	1,126 KB
FV_vs_T20007.JPG	8/18/2017 11:00 AM	JPEG image	1,126 KB
FV_vs_T30007.JPG	8/18/2017 11:02 AM	JPEG image	1,126 KB
FV_vs_T40007.JPG	8/18/2017 11:03 AM	JPEG image	1,126 KB
FV_vs_T50007.JPG	8/18/2017 11:04 AM	JPEG image	1,126 KB
H-10cR_AnalysisRpt_Location_Map.png	8/18/2017 1:46 PM	PNG image	6,790 KB
Pressure_data.JPG0006.JPG	8/18/2017 10:01 AM	JPEG image	1,126 KB
Recovery_Diag0006.JPG	8/18/2017 10:22 AM	JPEG image	1,126 KB

Directory of G:\H-10cR_pumping test\post



Acknowledgements

The author of this report would like to acknowledge Jeff Palmer and Patricia Johnson of Intera, Inc. for contributing the well configuration plot and well location map to this report.