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Analysis Report for AP-070

Analysis of the H-12R Pumping Test Conducted From 4/20/15 to 4/22/15

AP-070: Analysis Plan for Hydraulic-Test Interpretations

Task Number 4.4.2.3.1

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gd 9/22/15

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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 H-12 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).

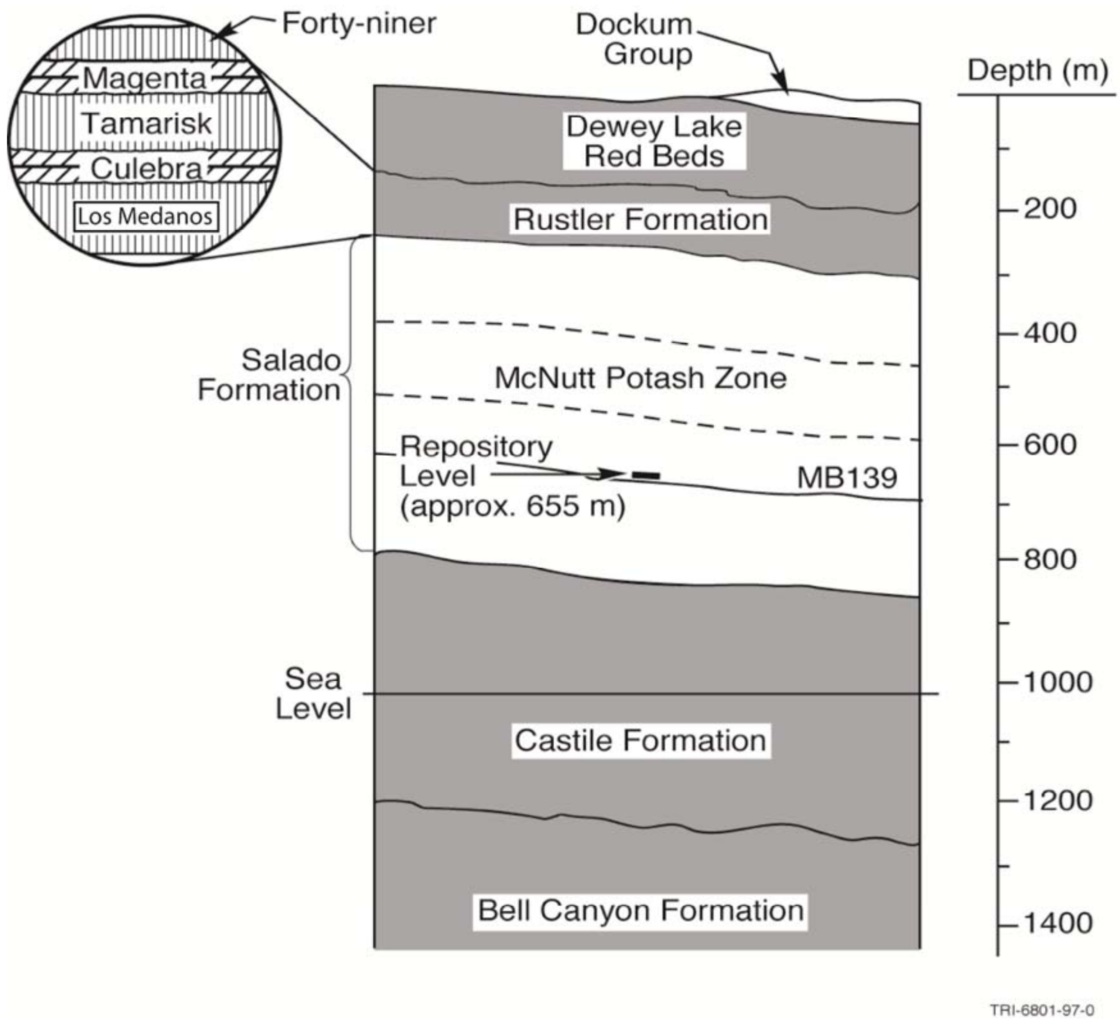

Figure 1. WIPP stratigraphy.

2. Test and Analysis Procedures

Four purge tests were performed in the H-12R replacement well on 8/28/14, 10/22/14, 12/10/14, and 2/19/15 for the purpose of removing non-formation water and obtaining water quality samples. These purges removed a total of 1014 gal. of water from the H-12R well. Analysis of the first purge indicated that the well could sustain approximately a 0.25 gpm pumping rate for a 48 hour test. 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 H-12R 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 H-12 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

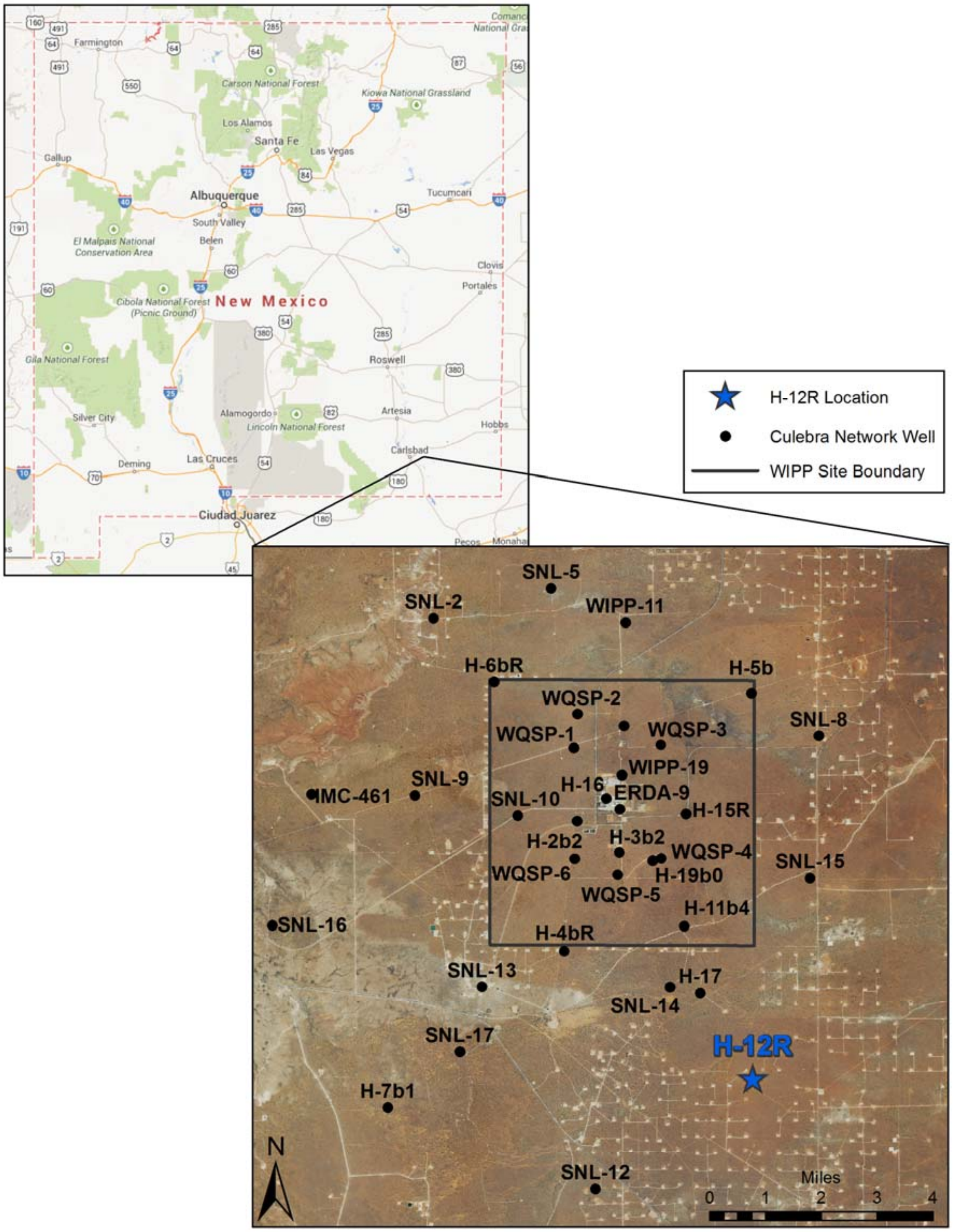

Figure 2. Location of the H-12R Culebra well located on the H-12 wellpad. The H-12R pumping well is designated by a blue star.

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 3 figure captions.

3. H-12R Analysis Results

Discussions of H-12R 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.

H-12R Test	Mean *S* *(fixed values)*	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	7.92E-06	1.11E-07	-	-	-	-
Pumping Test	7.92E-05	1.53E-07	-6.81455	-6.87282	-6.76143	1.02E-18

3.1. H-12R

The Culebra interval of well H-12R was drilled and completed between 7/12/2014 and 7/24/2014. The well was drilled to a depth of 865 ft with the Culebra interval screened from 820 ft to 846 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 H-12R well was based on the need to replace the previous H-12R 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.

Four purge tests and a pumping test were initiated in the Culebra at H-12R between 8/28/14 and 4/22/15. 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 reach stabilized water quality parameters. The simulation for the purge test consisted of a history period prior to drawdown and a recovery period once purging concluded. The data and model used in the analysis is shown in Figure 4.

A ~893 gallon pumping test was conducted in the Culebra at H-12R from 4/20/15 to 4/22/15. 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 5.

The H-12R nSIGHTS simulations each consisted of three sequences. The details of each sequence, i.e., start/end time, pressure, etc., are specified in the H-12R.nPre file and are listed in Appendix B.1.

The specified H-12R 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, two image wells, and a negative, time-dependent skin. Storativity and skin specific storage estimates were very poorly constrained so they were held as constants in the final model fit.

A gravel pack surrounding the screened portion of the well and localized fracturing likely account for the existence of negative skin with respect to *T* estimates. The skin is likely time dependent due to continued physical development of the well, blockage of the well screen, and unknown blockage in the gravel pack by the sealant in the well screen.

The static formation pressure of the well seemingly drops every time a pumping test is conducted in the Culebra. This would indicate pumping in a discreet, rather than a traditionally assumed continuous aquifer. The initial model had a close radial boundary was first attempted to fit the pumping test data with no success. The idea that boundaries were affecting the aquifer response was still sound, but a second method, implementation of no-flow boundaries, produced better model results. To apply this effect, two image wells were implemented in the model which decreased model error (fit value) by orders of magnitude. The range of *T* values derived from this analysis is shown in Figure 6. The *T* estimates gained through this analysis are described in the preceding Table 1.

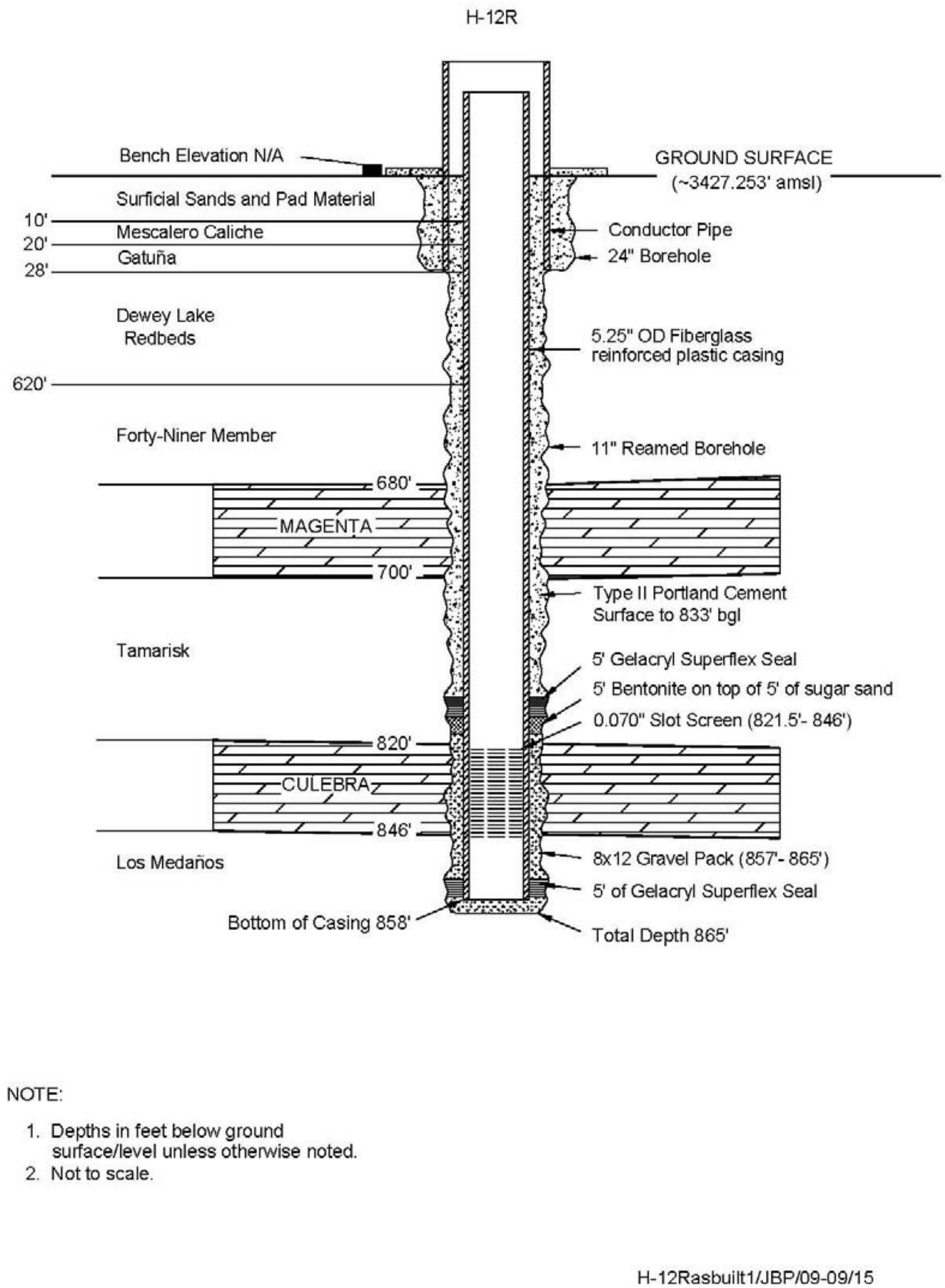

Figure 3. H-12R well configuration during testing.

3.1.1 Purge Test Analysis

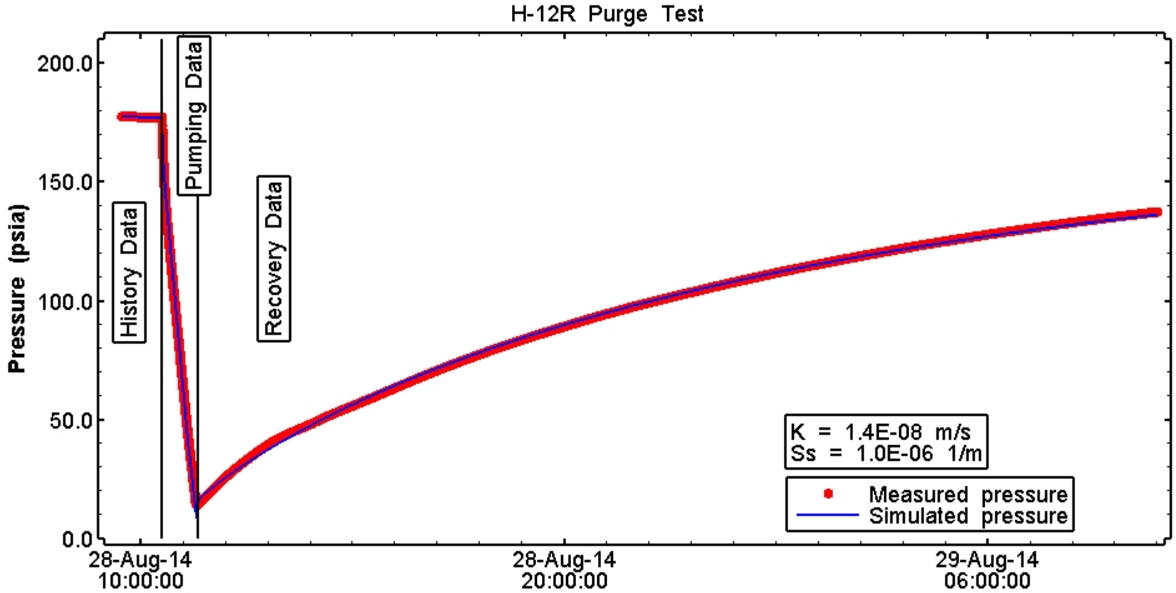

Figure 4. Pressure data and model fit of the first Culebra purge test in H-12R.

3.1.2 Pumping Test Analysis

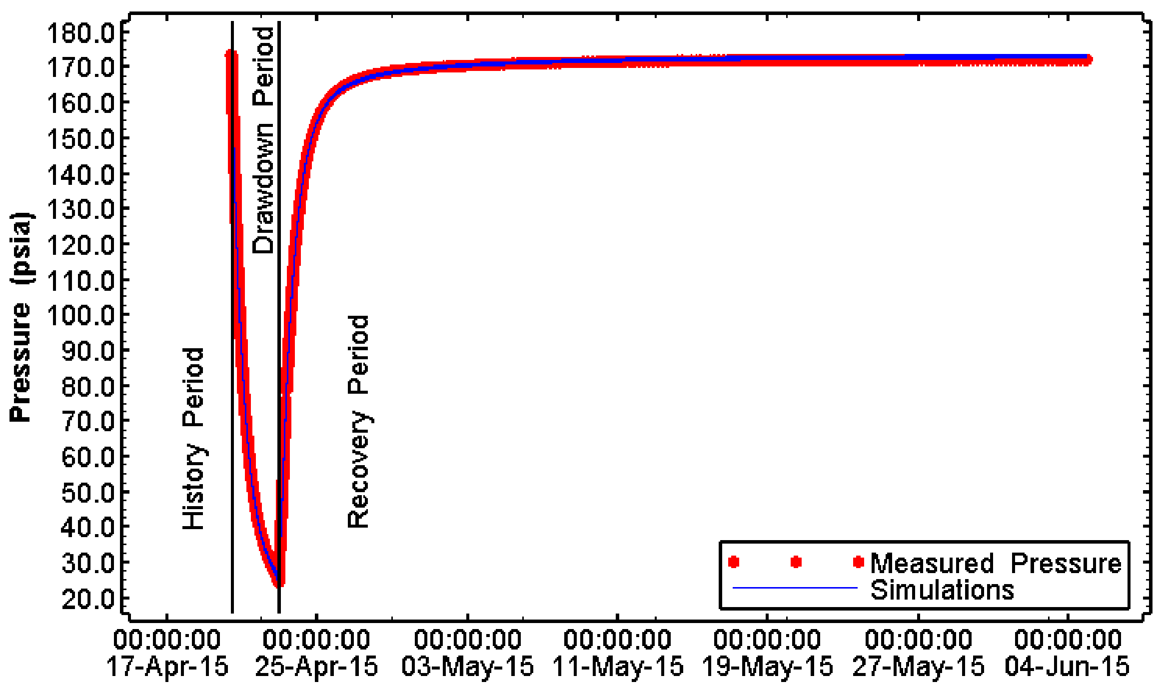

Figure 5. Pressure data and 184 model fits of the final Culebra pumping test in H-12R.

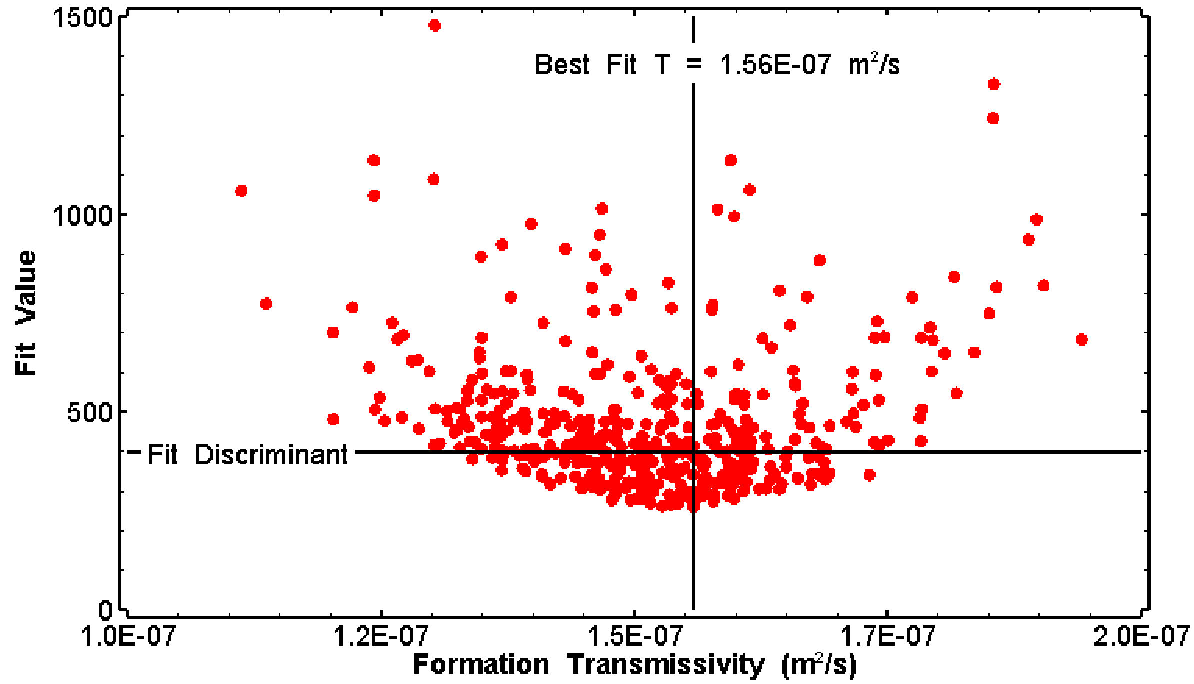

Figure 6. X-Y scatter plot showing the transmissivity parameter space derived from the H-12R perturbation analysis with fit discriminant and best fit values.

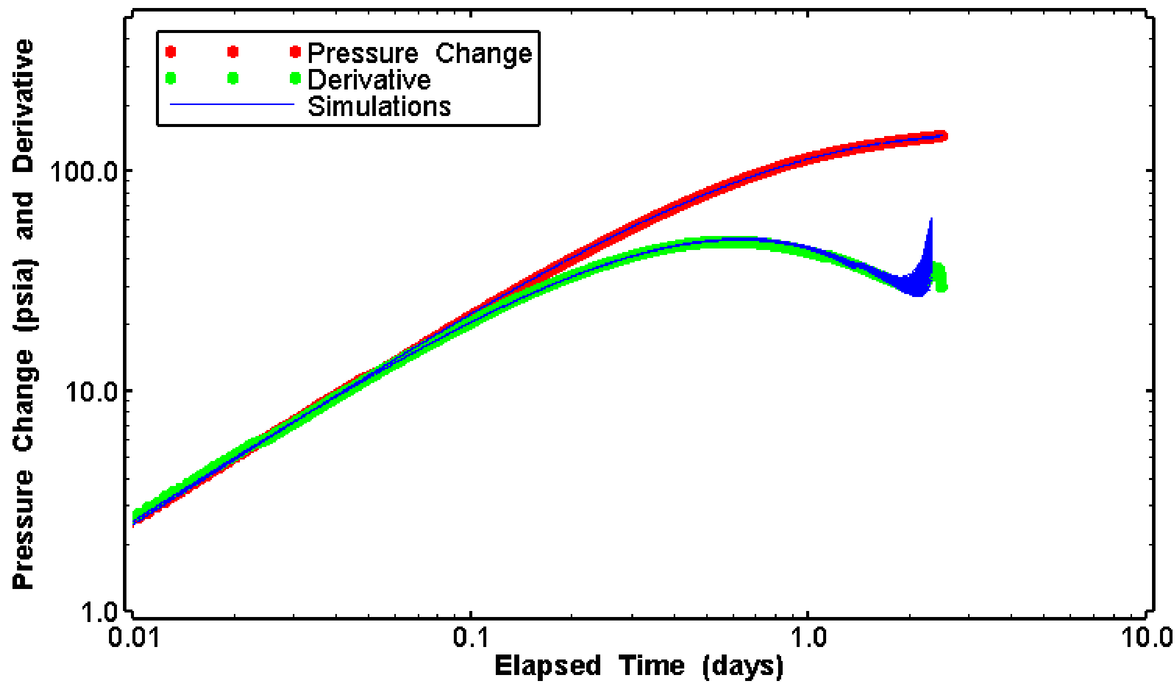

Figure 7. Log-log plot showing 184 simulations of the H-12R drawdown period pressure change and derivative response.

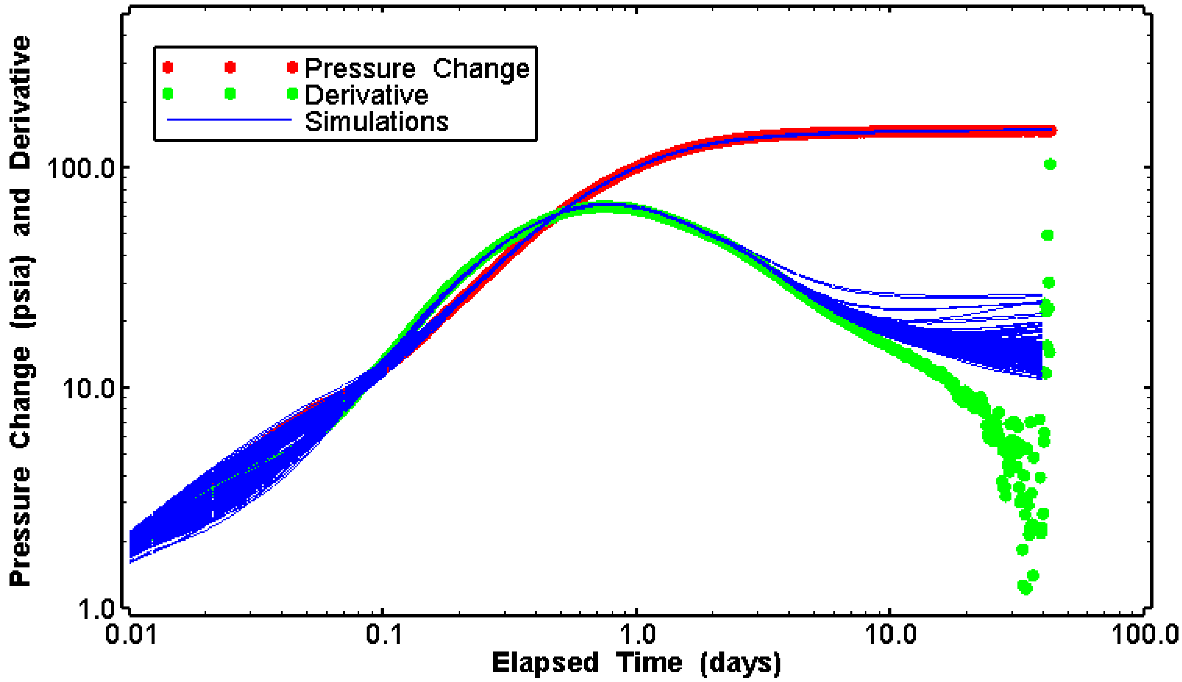

Figure 8. Log-log plot showing 184 simulations of the H-12R recovery period pressure change and derivative response.

A brief note needed to be added that the data, prior to model fitting was thinned. The purpose of the thinning was to lower the modeling run time while still retaining the pressure-change characteristics of the test. Using the full data set, the perturbation analysis contained in this report would require 52 days of processing time. By thinning the data, the processing time was reduced to approximately 7 hours. Figure 9 displays the original data and the overlying thinned data to demonstrate the reduction and the pressure characteristic retention.

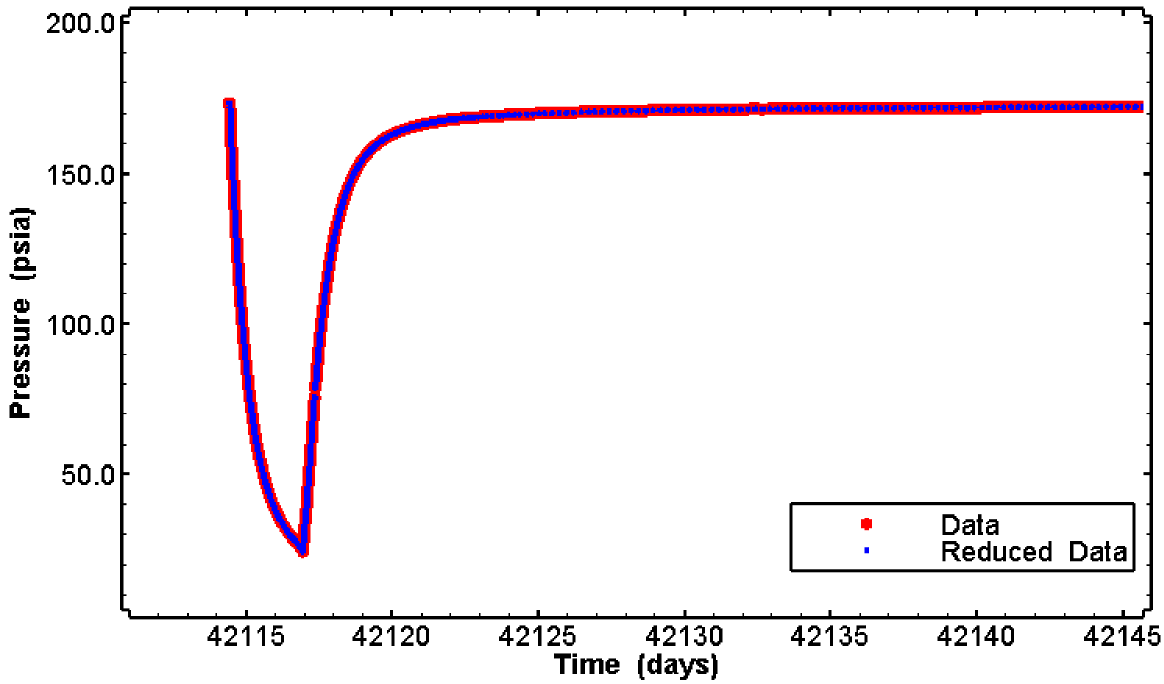

Figure 9. A plot comparing recorded pressure data and the reduced pressure data used for the modeling process.

4. References

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Appendix A – H-12R Hydraulic Test – 4/20/15 to 4/22/15

Well	Date and Time Start DAS	Date and Time Stop DAS	Date and Time Start Test	Date and Time Stop Test	Borehole Diameter (in)
H-12R	4/20/15 10:35	4/22/15 11:00	4/20/15 11:00	4/22/15 10:52	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	820-846 (26 ft)	1.104	WSWT-17	N/A

Appendix B – nSIGHTS Listings

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

Version date    25 June 2012
Listing date    08 Sep 2015
QA status       non-QA Open Source
Config file     C:\SANDIA_PROJECTS\WIPP_wells\Culebra\H-12R\H-12R_RR_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                                26.000     [ft]
Flow dimension                                        2.0     []
Static formation pressure                    Optimization
   Minimum value                                  160.000     [psi]
   Maximum value                                  180.000     [psi]
   Estimate value                                 173.791     [psi]
   Range type                                      Linear
   Sigma                                      1.00000E+00
External boundary radius                          1000000     [m]
Formation conductivity                       Optimization
```

Minimum value	1.00000E-12	[m/sec]
Maximum value	1.00000E-02	[m/sec]
Estimate value	2.12834E-08	[m/sec]
Range type	Log	
Sigma	1.00000E+00	
Formation spec. storage	1.00000E-04	[1/m]

Skin

Radial thickness of skin	Optimization	
Minimum value	1.0E-05	[m]
Maximum value	5.0	[m]
Estimate value	0.5373267	[m]
Range type	Linear	
Sigma	1.00000E+00	
Skin zone conductivity	f(t) point	
Skin zone spec. storage	1.00000E-05	[1/m]

Fluid

Fluid density	1104.00	[kg/m^3]
Fluid thermal exp. coeff.	0.00000E+00	[1/C]

Test-Zone

Well radius	2.155	[in]
Tubing string radius	2.0	[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

Skin zone conductivity

Points type	f(t)	
Time #1	Optimized	
Minimum	3638684160.000000	[day]
Estimat	3638778790.733000	[day]
Maximum	3638901024.000000	[day]
Y value#1	Optimized	
Time #2	Optimized	
Minimum	3638901024.086000	[day]
Estimat	3638904358.843000	[day]
Maximum	3638904480.000000	[day]
Y value#2	Optimized	
Time #3	Optimized	
Minimum	3638904480.086000	[day]
Estimat	3638907846.087000	[day]
Maximum	3638910441.600000	[day]
Y value#3	Optimized	
Time #4	Optimized	

Minimum	3638910441.686000	[day]
Estimat	3638935500.425000	[day]
Maximum	3638995200.000000	[day]
Y value#4	Optimized	
Time #5	Optimized	
Minimum	3638995200.863999	[day]
Estimat	3639316146.217000	[day]
Maximum	3639427200.000000	[day]
Y value#5	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-05	[m/sec]
Y opt range type	Log	
Y opt sigma	1.00000E+00	
Parameter curve type	Linear	

Calculated Parameters

Formation

Transmissivity	min/max	
Minimum	7.92480E-12	[m^2/sec]
Maximum	7.92480E-02	[m^2/sec]
Storativity	7.92480E-04	[]
Diffusivity	min/max	
Minimum	1.00000E-08	[m^2/sec]
Maximum	1.00000E+02	[m^2/sec]

Skin Zone

Transmissivity	f(t)	
Storativity	7.92480E-05	[]
Diffusivity	f(t)	
Skin factor	f(t)	

Test Zone

Open hole well-bore storage	7.48871E-07	[m^3/Pa]

Grid Properties

Grid increment delta	min/max	
Minimum	0.06128	[]
Maximum	0.08402	[]
First grid increment	min/max	
Minimum	3.19455E-01	[m]
Maximum	4.79878E-03	[m]
Skin grid increment delta	min/max	
Minimum	0.00000	[]
Maximum	0.09236	[]
Skin first grid increment	min/max	
Minimum	2.04063E-07	[m]

Maximum	5.29621E-03	[m]
Skin last grid increment	min/max	
Minimum	2.04100E-07	[m]
Maximum	4.45936E-01	[m]
Increment ratio	min/max	
Minimum	7.16369E-01	[]
Maximum	2.35119E+04	[]

Sequences

Sequence: H_01

Sequence type	History	
Start time	42114.416667	[day]
Duration	0.049303	[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	42114.465970	[day]
Duration	2.485420	[day]
Time step type	Log	
First log step	1.15741E-07	[day]
# of time steps	250	
Type	Fixed	
Fixed value	-0.247	[USgpm]
Wellbore storage	Open	

Sequence: F_02

Sequence type	Flow	
Start time	42116.951390	[day]
Duration	43.048610	[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]	
Output ID	P_S_01	
Output type	Pressure	
Pressure capture type	Superposition	
P_S_01[1] operation	+ Pressure	
Type	Constant	
Fixed radius	0.054737	[m]
P_S_01[2] operation	- Delta P	
Type	Optimized	
Optimized radius optimization ID	P_S_01[2]	
Minimum value	2.0	[m]
Maximum value	1000	[m]
Estimate value	67.1701016	[m]
Range type	Linear	
Sigma	1.00000E+00	
P_S_01[3] operation	- Delta P	
Type	Optimized	
Optimized radius optimization ID	P_S_01[3]	
Minimum value	1.0	[m]
Maximum value	1000	[m]
Estimate value	72.0335999	[m]
Range type	Linear	
Sigma	1.00000E+00	
Output units	[psi]	

OutputFiles

XY Forward Output

Write file ?	yes
C:\SANDIA_PROJECTS\WIPP_wells\Culebra\H-12R\Post\H-12R_sim.nXYSim	
Run ID	Run#1
If file exists	Overwrite
Output data	AutoSimData

Optimization Output

Write file ?	yes
C:\SANDIA_PROJECTS\WIPP_wells\Culebra\H-12R\Post\H-12R_sim.nOpt	
Run ID	Run#1
If file exists	Overwrite
Write residuals ?	no
Write Jacobian ?	no
Write covariance matrices?	yes

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	15
Formation conductivity	OK
K_s.T[01]	OK
K_s.T[02]	OK
K_s.T[03]	OK
K_s.T[04]	OK
K_s.T[05]	OK
K_s.V[01]	OK
K_s.V[02]	OK
K_s.V[03]	OK
K_s.V[04]	OK
K_s.V[05]	OK
P_S_01[2]	OK
P_S_01[3]	OK
Static formation pressure	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

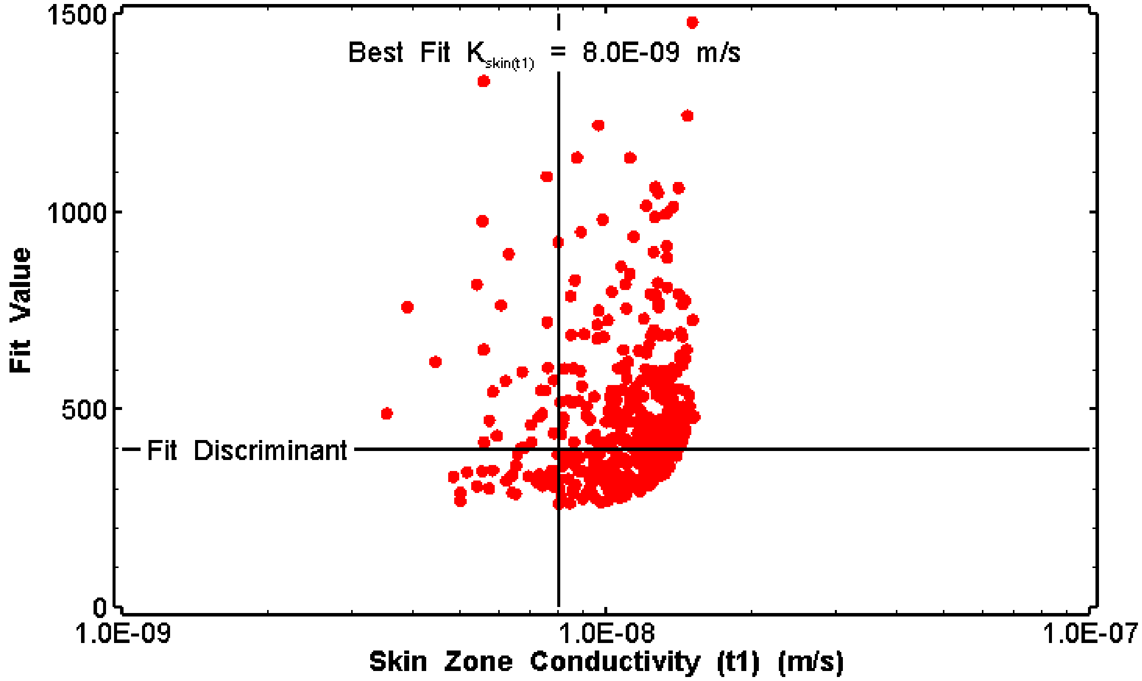


Figure B-1. X-Y scatter plot showing the skin conductivity parameter space for the first time span derived from H-12R perturbation analysis with the fit discriminant and best fit values.

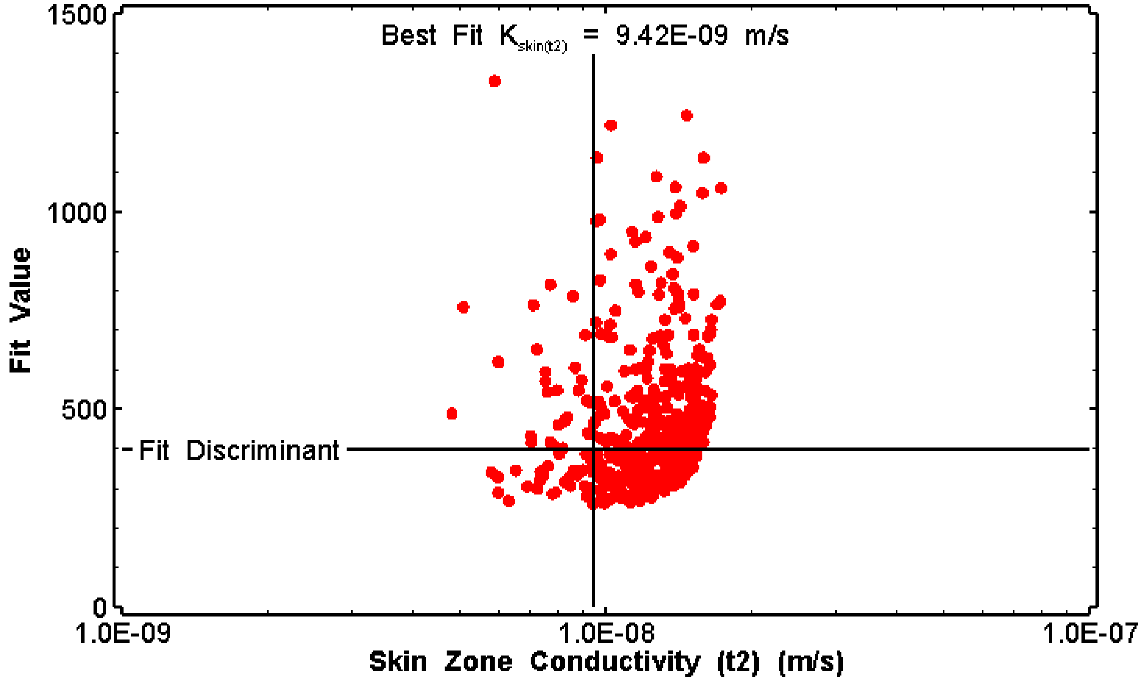


Figure B-2. X-Y scatter plot showing the skin conductivity parameter space for the second time span derived from H-12R perturbation analysis with the fit discriminant and best fit values.

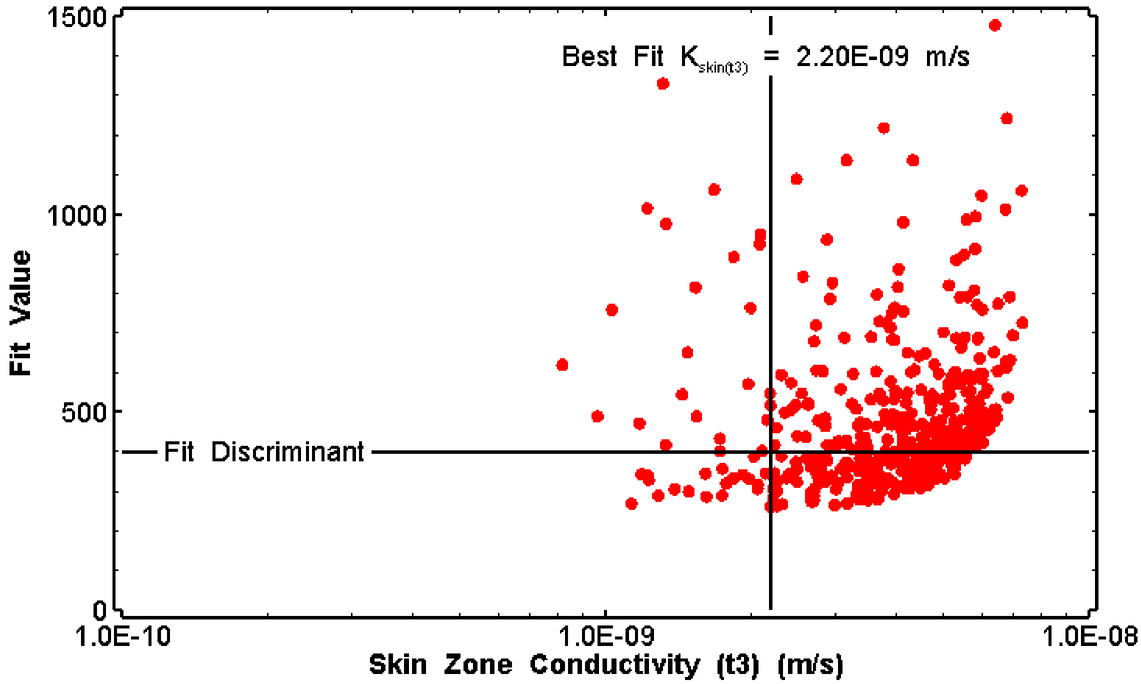


Figure B-3. X-Y scatter plot showing the skin conductivity parameter space for the third time span derived from H-12R perturbation analysis with the fit discriminant and best fit values.

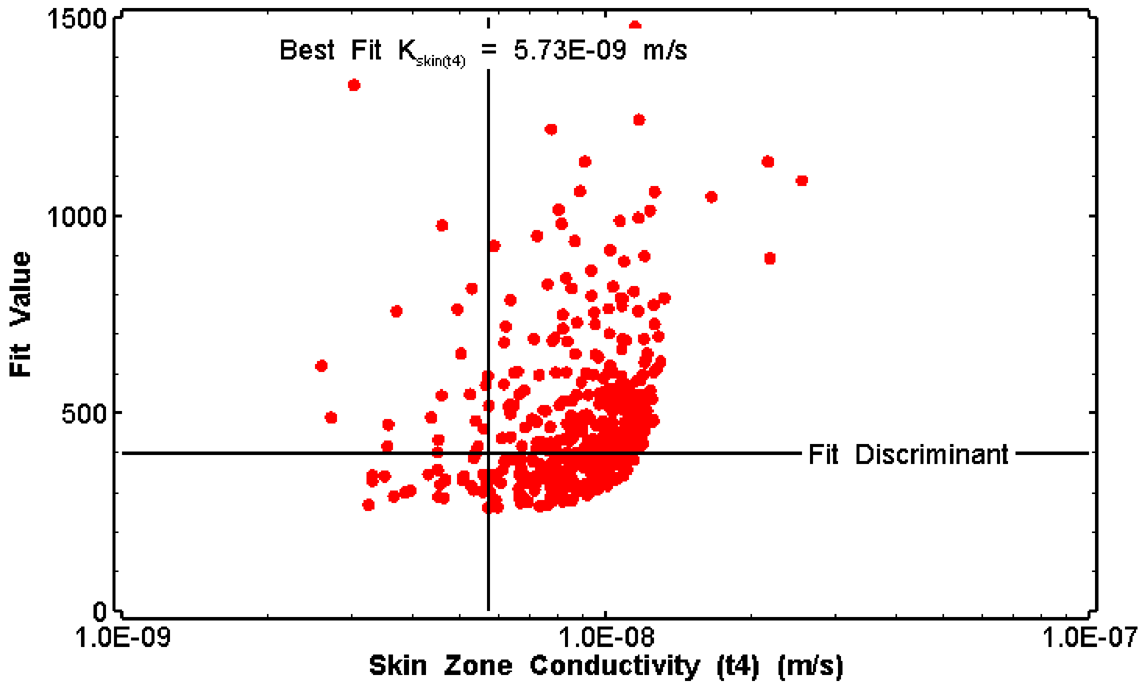


Figure B-4. X-Y scatter plot showing the skin conductivity parameter space for the fourth time span derived from H-12R perturbation analysis with the fit discriminant and best fit values.

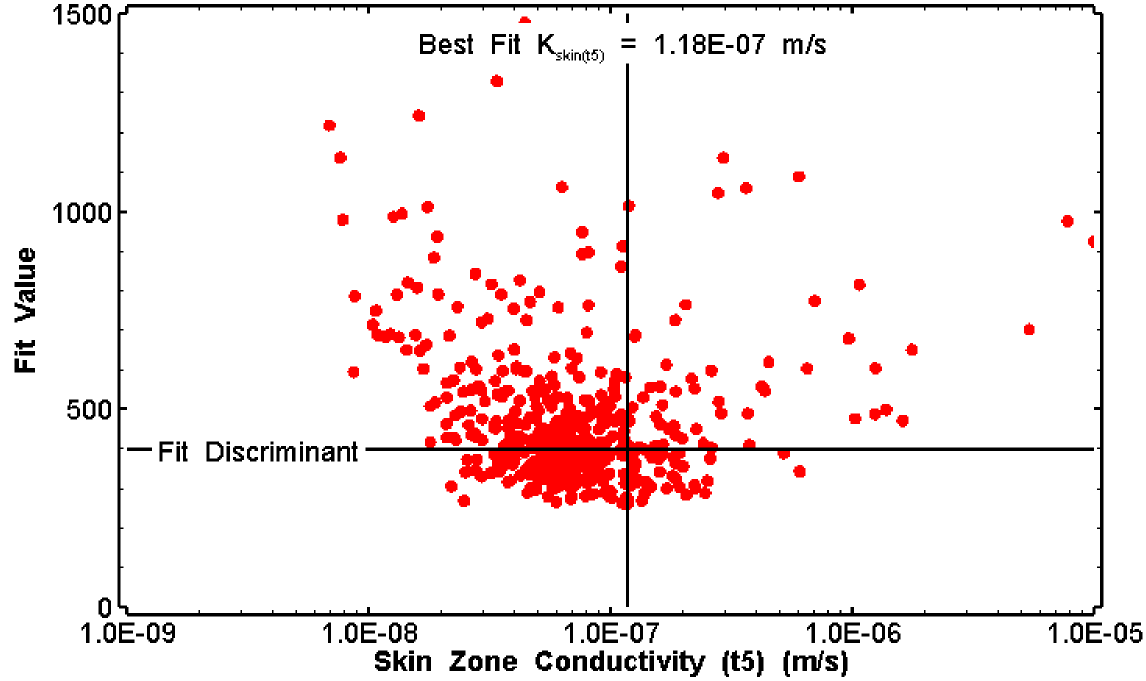


Figure B-5. X-Y scatter plot showing the skin conductivity parameter space for the fifth time span derived from H-12R perturbation analysis with the fit discriminant and best fit values.

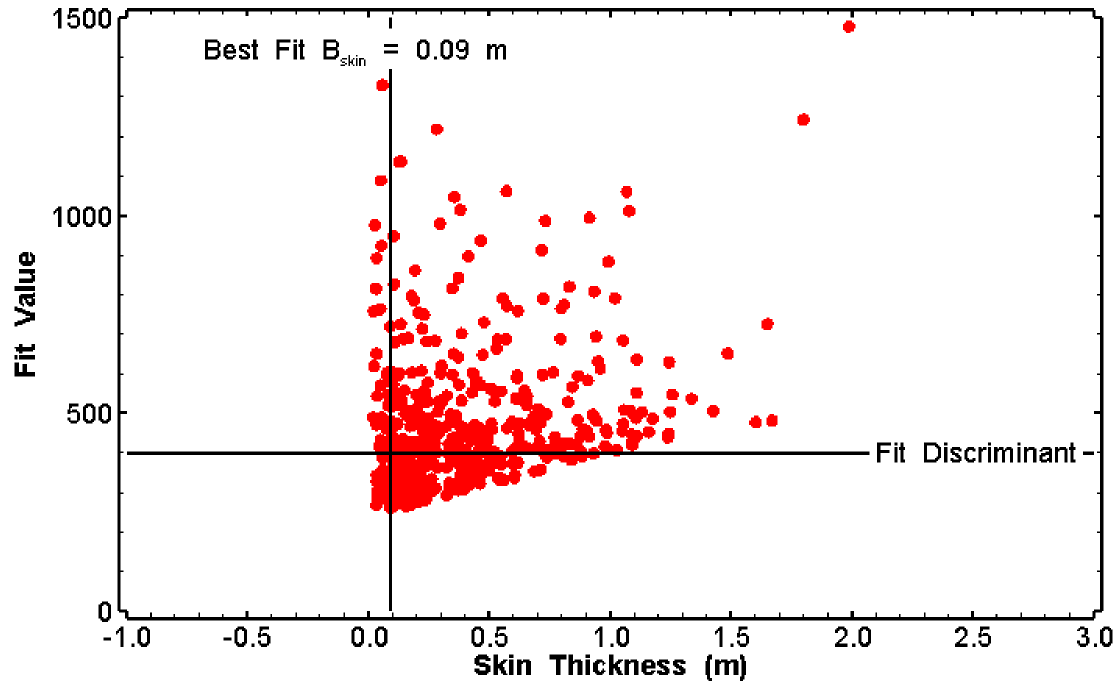


Figure B-6. X-Y scatter plot showing the skin zone thickness parameter space derived from H-12R perturbation analysis with the fit discriminant and best fit values.

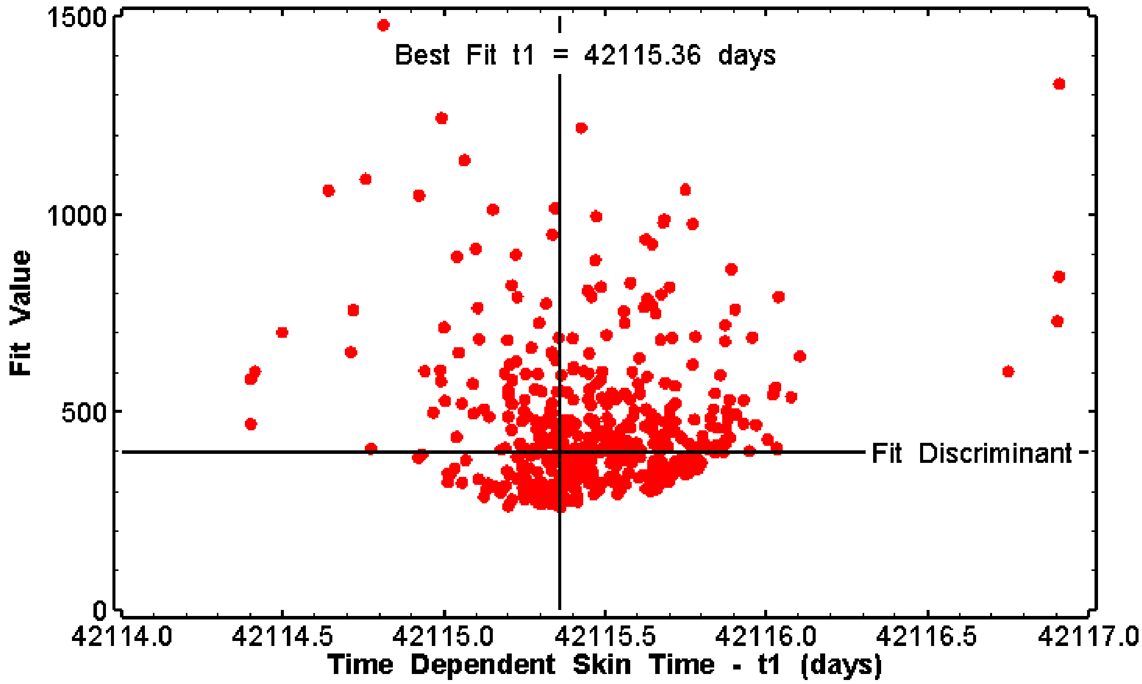


Figure B-7. X-Y scatter plot showing the first time dependent skin time parameter space derived from H-12R perturbation analysis with the fit discriminant and best fit values.

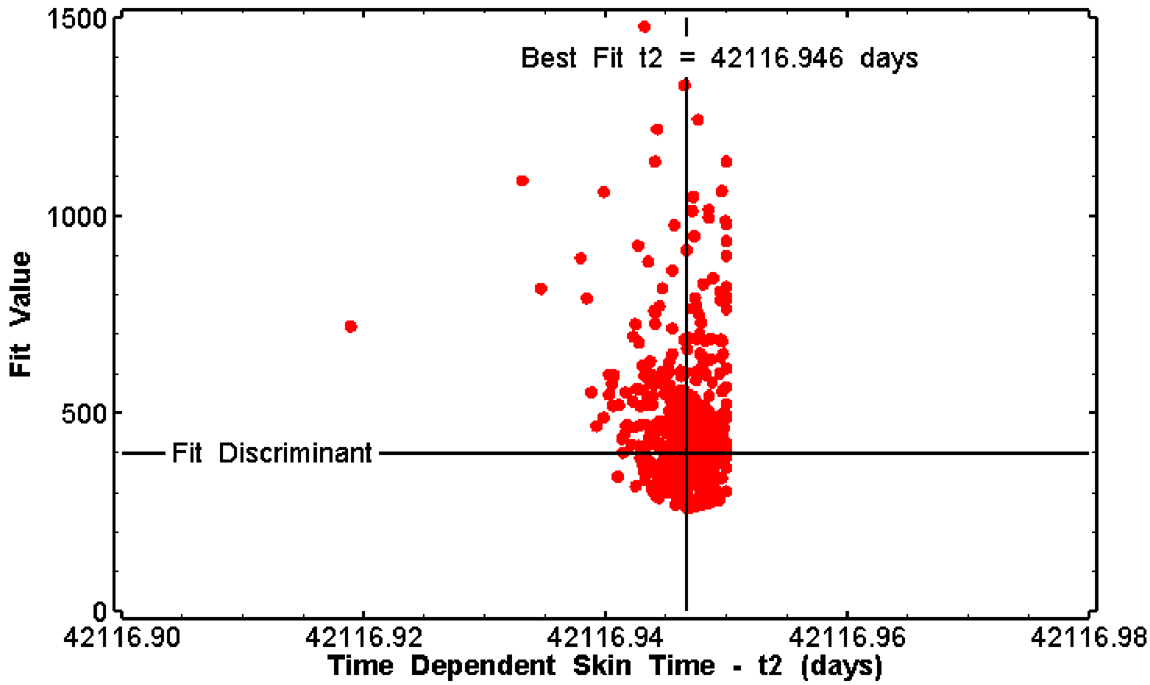


Figure B-8. X-Y scatter plot showing the second time dependent skin time parameter space derived from H-12R perturbation analysis with the fit discriminant and best fit values.

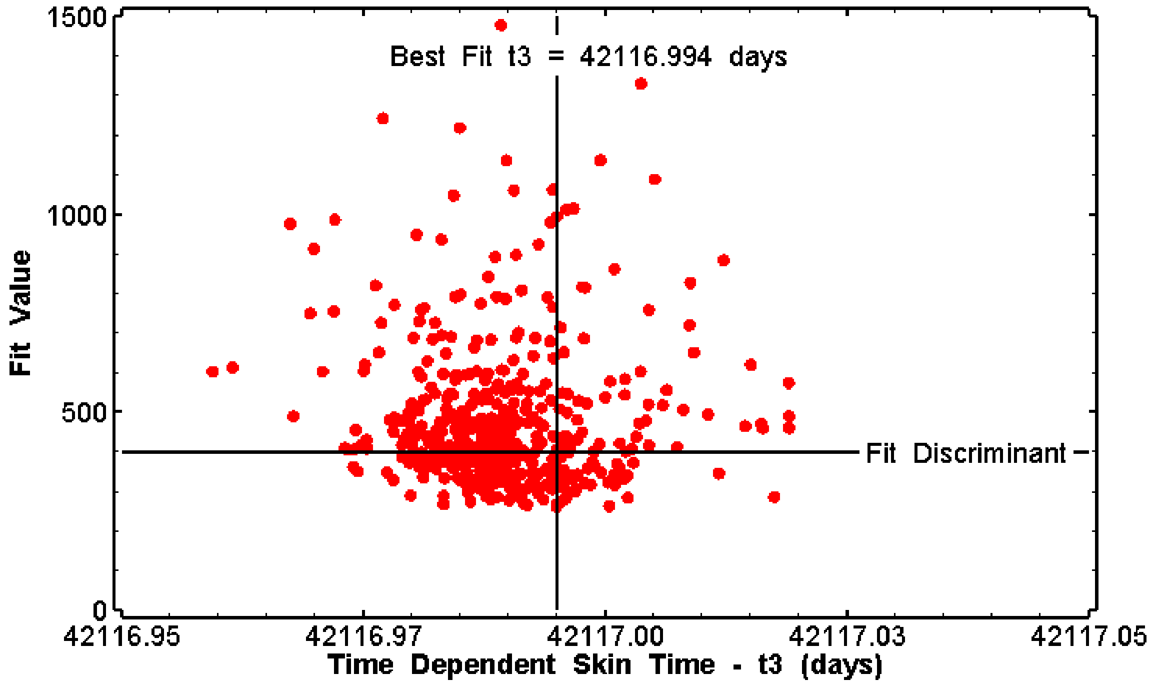


Figure B-9. X-Y scatter plot showing the third time dependent skin time parameter space derived from H-12R perturbation analysis with the fit discriminant and best fit values.

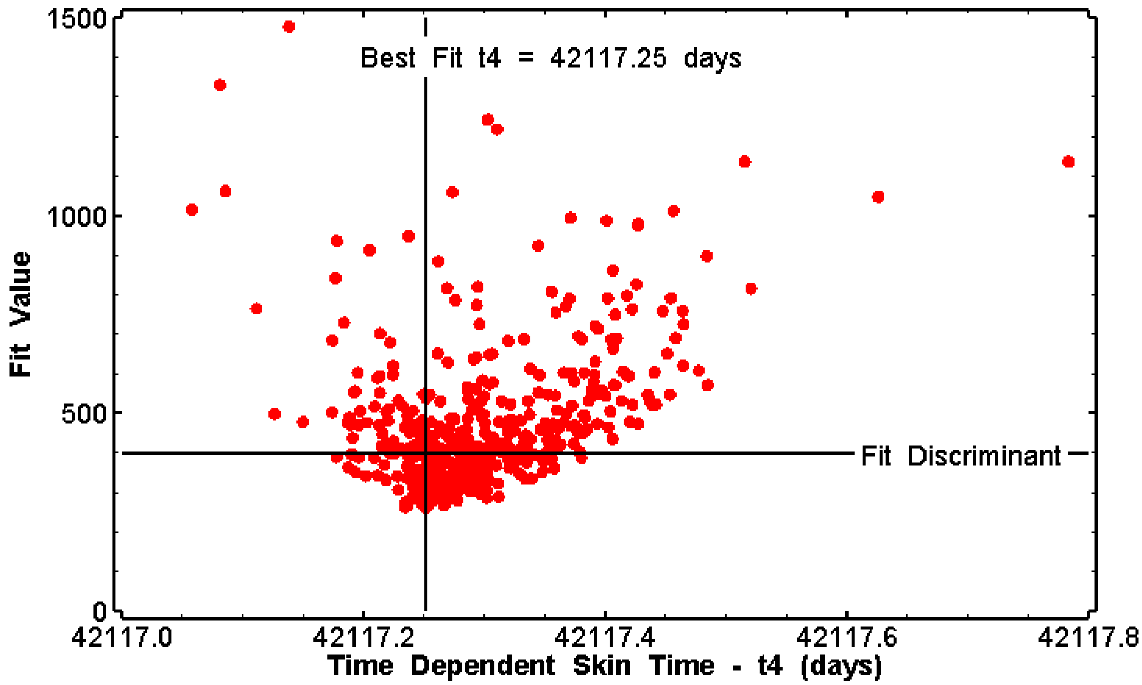


Figure B-10. X-Y scatter plot showing the fourth dependent skin time parameter space derived from H-12R perturbation analysis with the fit discriminant and best fit values.

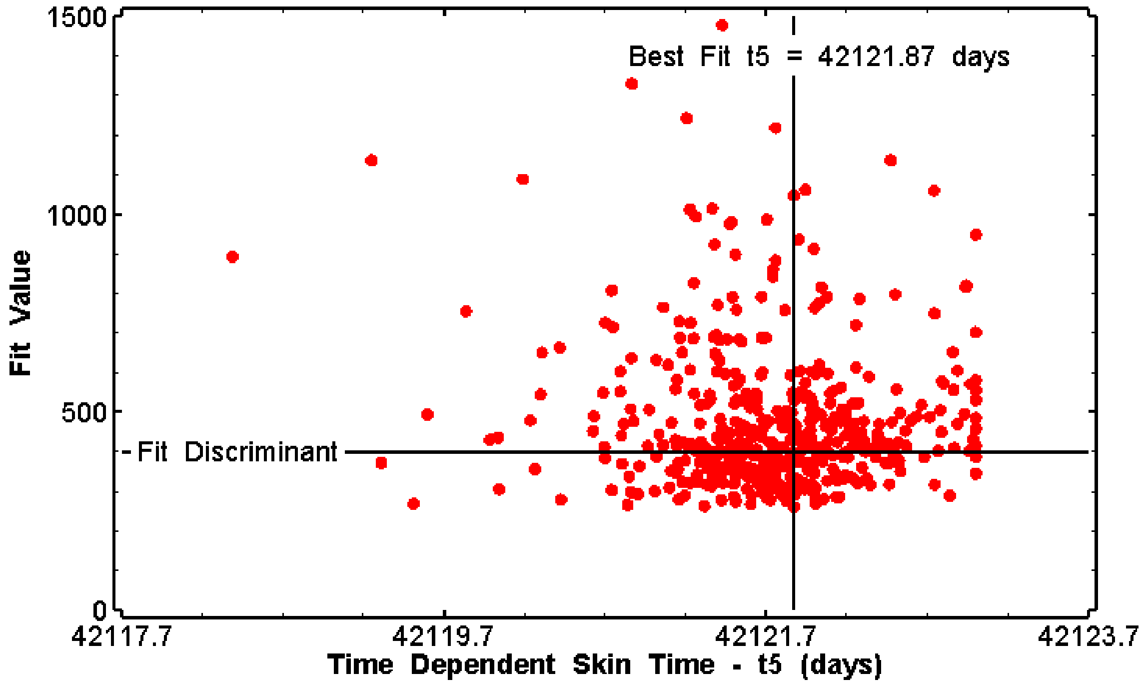


Figure B-11. X-Y scatter plot showing the fifth dependent skin time parameter space derived from H-12R perturbation analysis with the fit discriminant and best fit values.

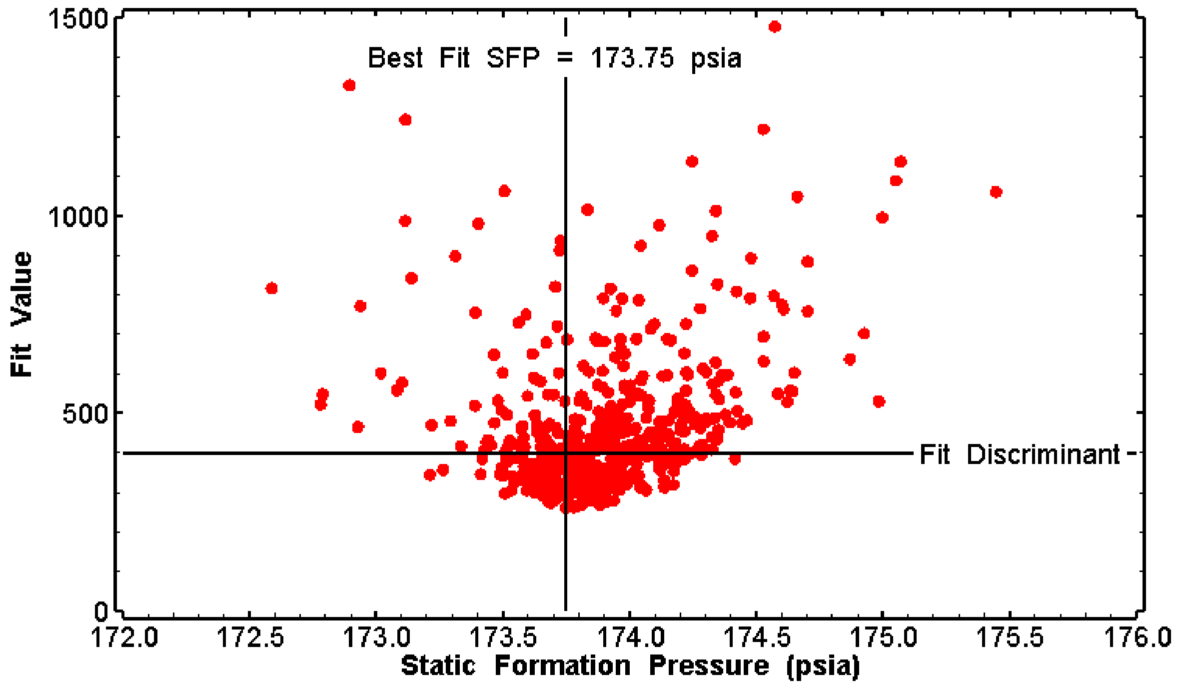


Figure B-12. X-Y scatter plot showing the static formation pressure parameter space derived from H-12R perturbation analysis with the fit discriminant and best fit values.

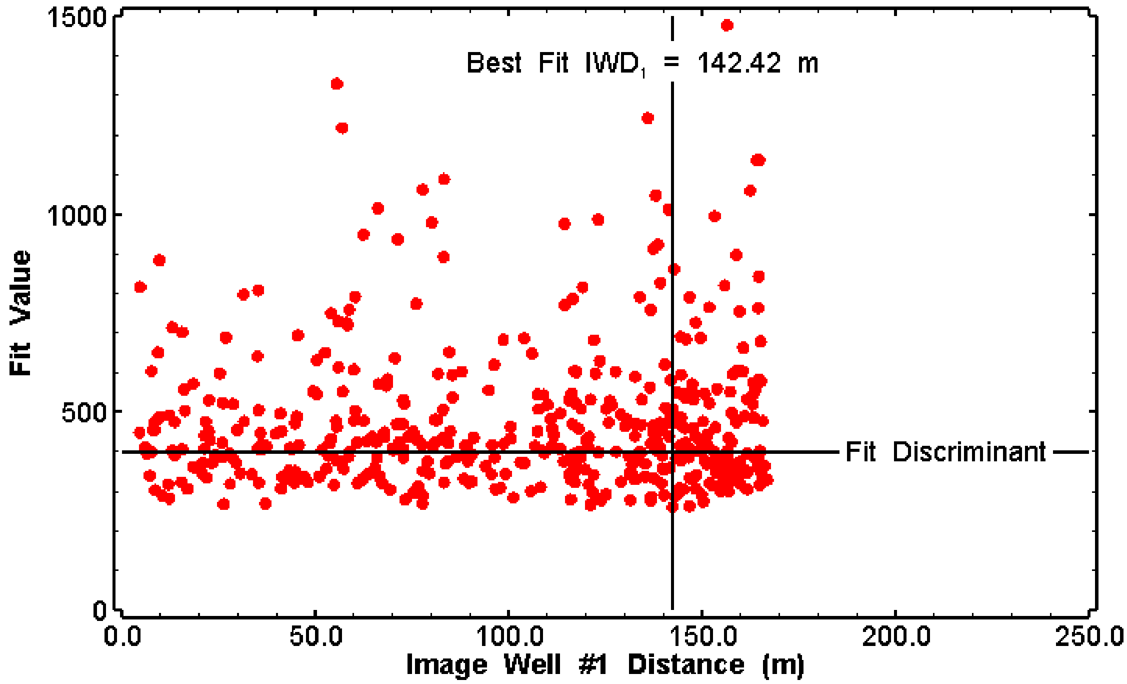


Figure B-13. X-Y scatter plot showing the image well #1 distance parameter space derived from H-12R perturbation analysis with the fit discriminant and best fit values.

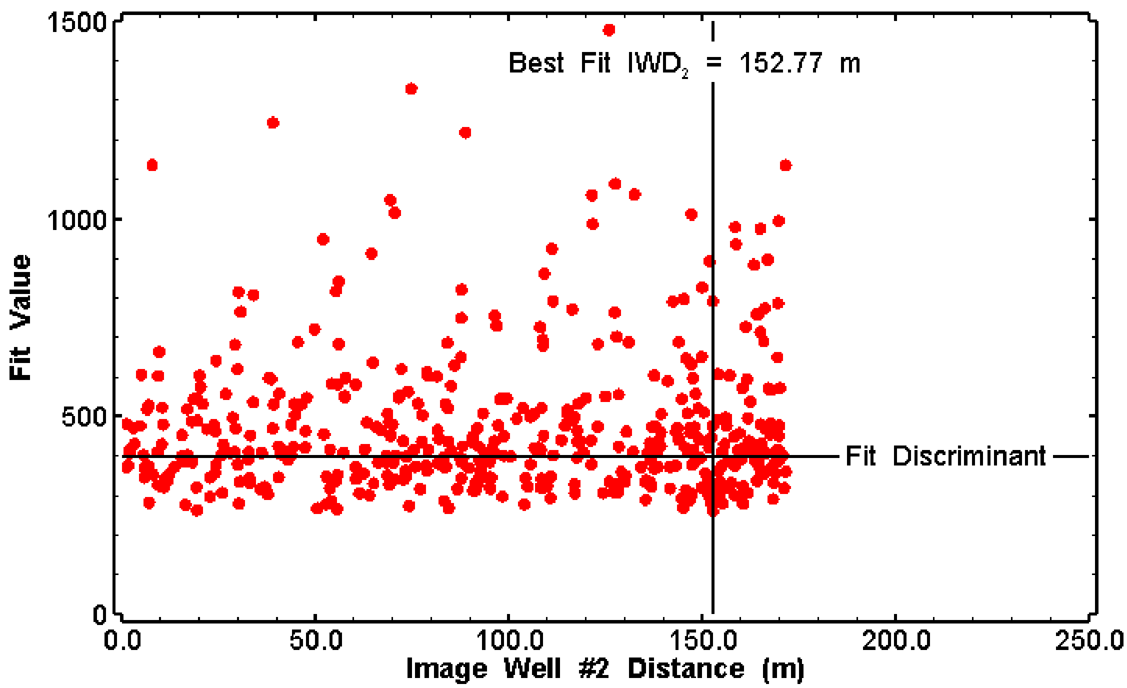


Figure B-14. X-Y scatter plot showing the image well #2 distance parameter space derived from H-12R perturbation analysis with the fit discriminant and best fit values.

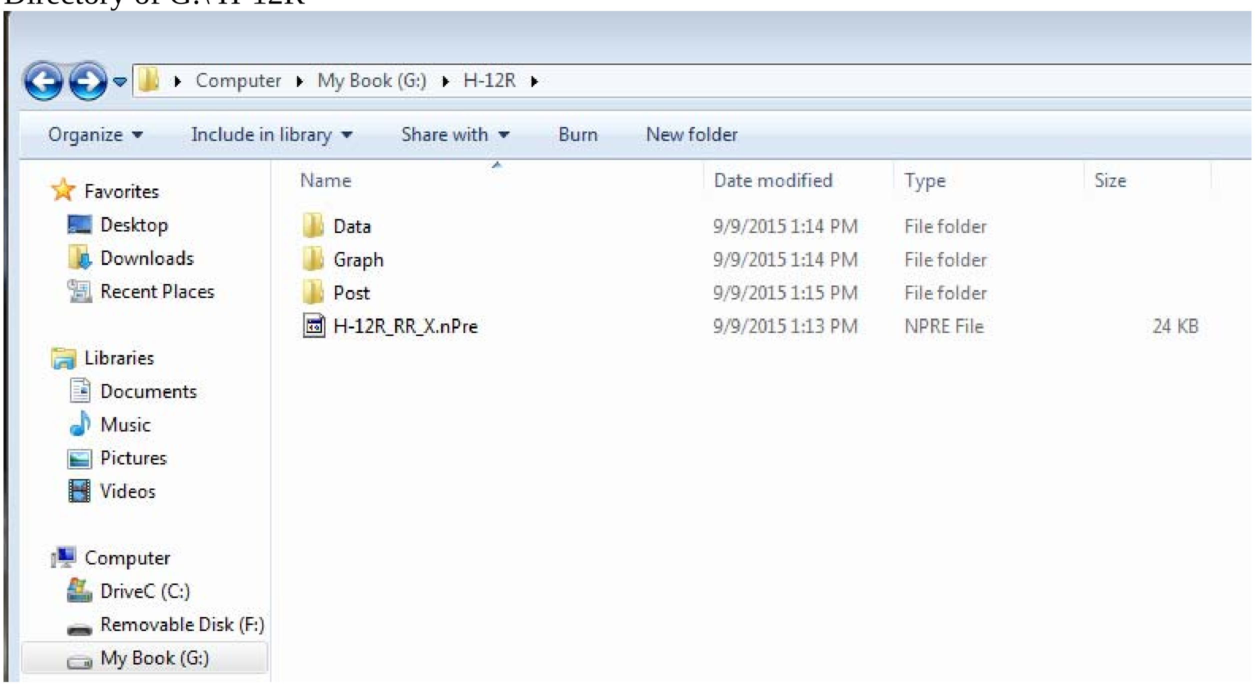
Appendix C – File Directories

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

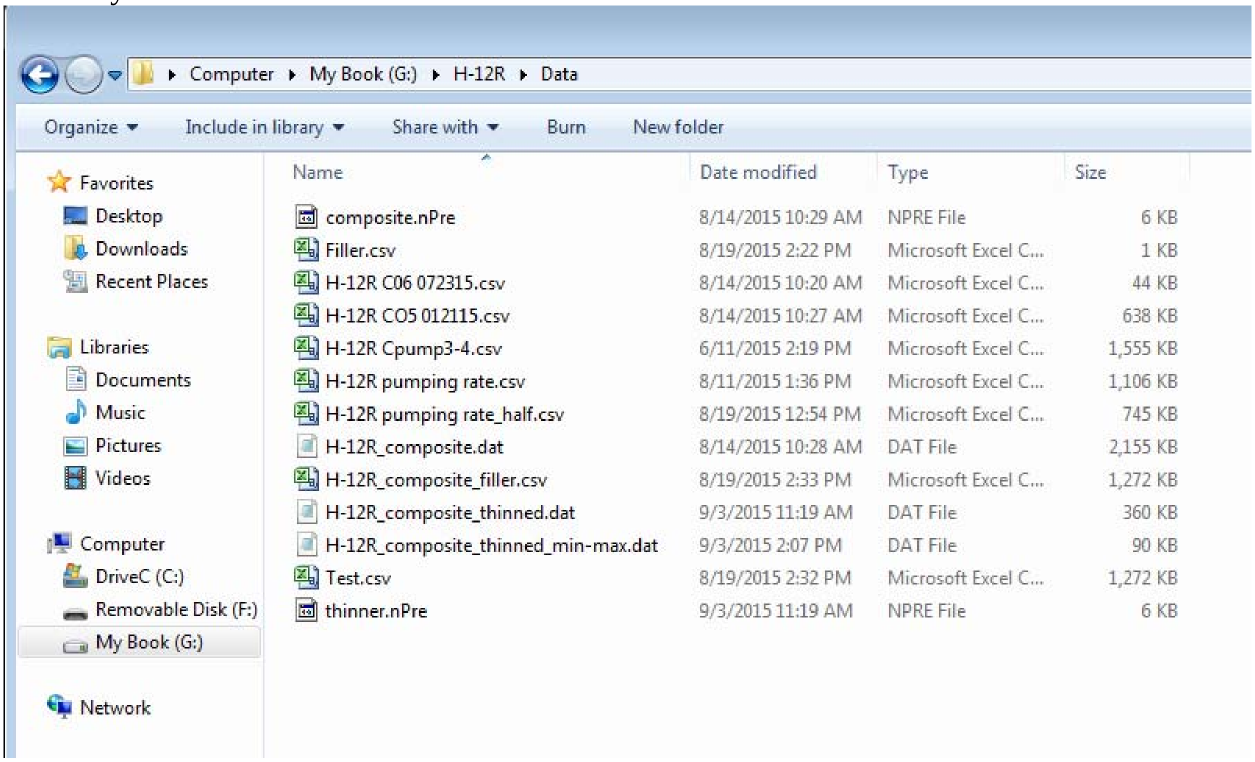
Table C-1. File descriptions.

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.

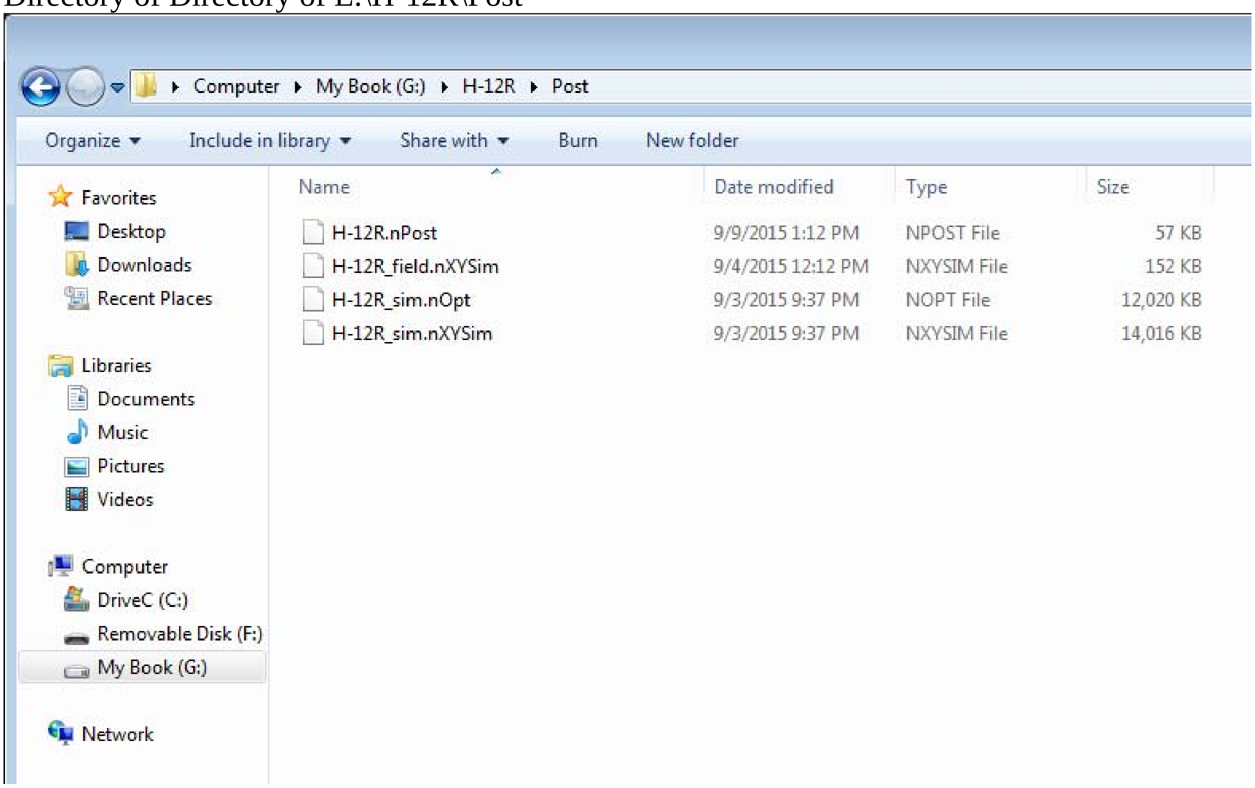
Directory of G:\ H-12R



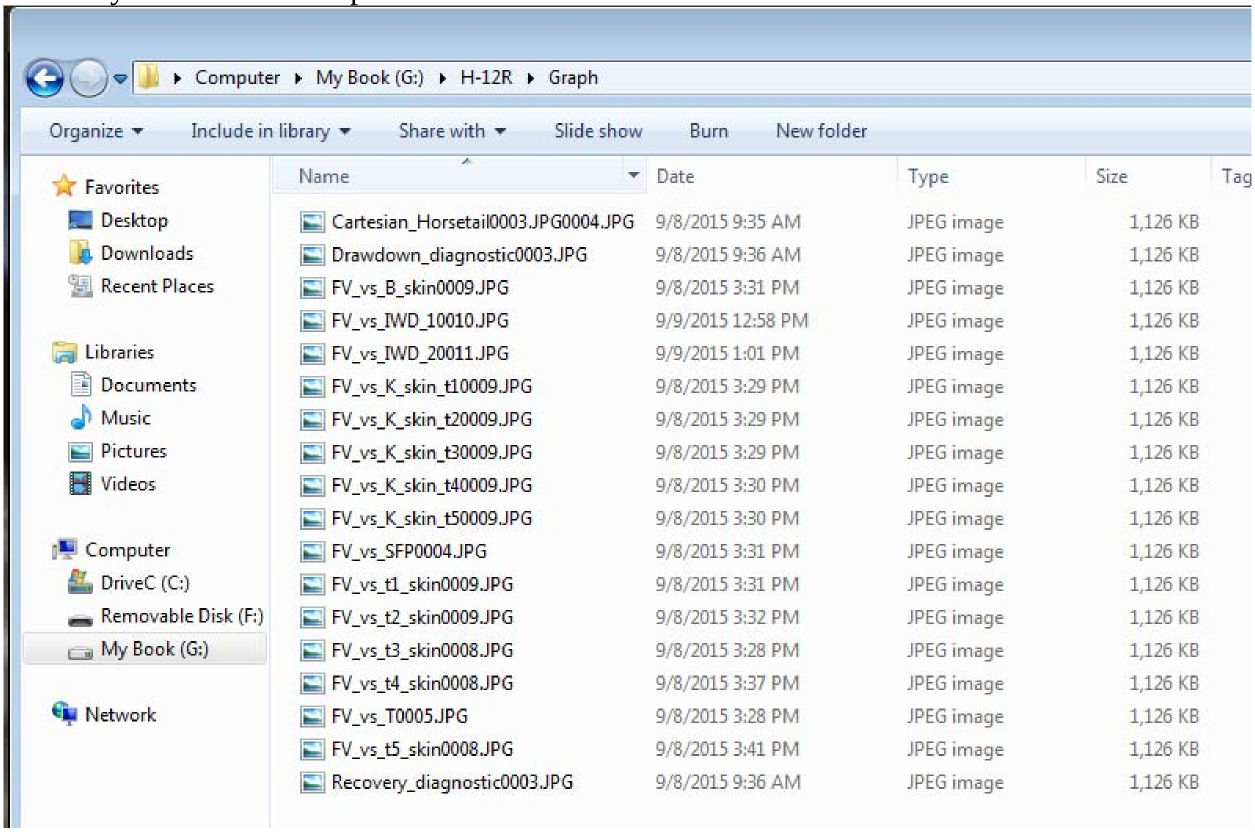
Directory of G:\ H-12R \Data



Directory of Directory of E:\H-12R\Post



Directory of E:\H-12R\Graphs



Name	Date	Type	Size
Cartesian_Horsetail0003.JPG0004.JPG	9/8/2015 9:35 AM	JPEG image	1,126 KB
Drawdown_diagnostic0003.JPG	9/8/2015 9:36 AM	JPEG image	1,126 KB
FV_vs_B_skin0009.JPG	9/8/2015 3:31 PM	JPEG image	1,126 KB
FV_vs_IWD_10010.JPG	9/9/2015 12:58 PM	JPEG image	1,126 KB
FV_vs_IWD_20011.JPG	9/9/2015 1:01 PM	JPEG image	1,126 KB
FV_vs_K_skin_t10009.JPG	9/8/2015 3:29 PM	JPEG image	1,126 KB
FV_vs_K_skin_t20009.JPG	9/8/2015 3:29 PM	JPEG image	1,126 KB
FV_vs_K_skin_t30009.JPG	9/8/2015 3:29 PM	JPEG image	1,126 KB
FV_vs_K_skin_t40009.JPG	9/8/2015 3:30 PM	JPEG image	1,126 KB
FV_vs_K_skin_t50009.JPG	9/8/2015 3:30 PM	JPEG image	1,126 KB
FV_vs_SFP0004.JPG	9/8/2015 3:31 PM	JPEG image	1,126 KB
FV_vs_t1_skin0009.JPG	9/8/2015 3:31 PM	JPEG image	1,126 KB
FV_vs_t2_skin0009.JPG	9/8/2015 3:32 PM	JPEG image	1,126 KB
FV_vs_t3_skin0008.JPG	9/8/2015 3:28 PM	JPEG image	1,126 KB
FV_vs_t4_skin0008.JPG	9/8/2015 3:37 PM	JPEG image	1,126 KB
FV_vs_T0005.JPG	9/8/2015 3:28 PM	JPEG image	1,126 KB
FV_vs_t5_skin0008.JPG	9/8/2015 3:41 PM	JPEG image	1,126 KB
Recovery_diagnostic0003.JPG	9/8/2015 9:36 AM	JPEG image	1,126 KB

Acknowledgements

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