Analysis Report for AP-070

Analysis of the H-11b4R Pumping Test Conducted
From 6/11/12 to 6/14/12

AP-070: Analysis Plan for Hydraulic-Test Interpretations

Task Number 1.4.2.3

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Information Only
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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-11 well pad. 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 2.41a. 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).

![WIPP stratigraphy diagram](image-url)

**Figure 1. WIPP stratigraphy.**
2. Test and Analysis Procedures

Three constant rate pumping tests were performed in the H-11b4R replacement well in 2012. The first two tests were purge tests performed to develop the well and obtain water samples for chemical analysis. These two purge tests used pumping rates of 10 gallons per minute (gpm) for approximately 5 hours and 12 gpm for approximately 4 hours. The third constant rate test used a pumping rate of approximately 12 gpm for 72 hours. The location of the H-11 wellpad 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).
Figure 2. Location of the H-11b wellpad, which includes H-11b2 (Magenta) and H-11b4R (Culebra).
All the nSIGHTS test simulations incorporated pre-test pressure records of various durations as "history" periods where the associated pressures were simply 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 was also included as a fitting parameter 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 previous Culebra wells on the H-11 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 \textit{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 \textit{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 \textit{global minimum} (assumed true solution), and the other minima are referred to as \textit{local minima}. Local minima are effectively localized depressions in the 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 \textit{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. H-11b4R Analysis Results

Discussions of H-11b4R 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 Estimates.

<table>
<thead>
<tr>
<th>H-11b4R Test</th>
<th>Geometric Mean (m$^2$/s)</th>
<th>Log Geometric Mean (m$^2$/s)</th>
<th>Log Minimum (m$^2$/s)</th>
<th>Log Maximum (m$^2$/s)</th>
<th>Variance</th>
</tr>
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<tbody>
<tr>
<td>Purge 1</td>
<td>7.45x10$^{-5}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Purge 2</td>
<td>6.29x10$^{-5}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>2012 Pumping Test:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1(@ 46.58 m)*</td>
<td>3.25x10$^{-5}$</td>
<td>-4.488</td>
<td>-4.786</td>
<td>-4.389</td>
<td>1.67x10$^{-13}$</td>
</tr>
<tr>
<td>T2(@ 165.68 m)*</td>
<td>1.14x10$^{-5}$</td>
<td>-4.943</td>
<td>-5.196</td>
<td>-4.303</td>
<td>5.19x10$^{-14}$</td>
</tr>
<tr>
<td><strong>Past Tests:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H-11 pad avg. (1987)$^1$</td>
<td>2.60x10$^{-5}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H-11b4 (1988)$^2$</td>
<td>4.50x10$^{-5}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H-11b1 (1988)$^3$</td>
<td>2.90x10$^{-5}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H-11 pad avg. (1996)$^3$</td>
<td>4.70x10$^{-5}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*In cases where multiple transmissivities (typically called a Composite Model) were used to fit the data, each progressive $T$ value was assigned a distance from the borehole.

$^1$ Saulnier (1987)
$^2$ Beauheim (1989)
$^3$ Beauheim and Ruskauff (1998)
3.1. **H-11b4R**

The Culebra interval of well H-11b4R was drilled between 11/1/2011 and 11/18/2011 (DOE 2013). The well was drilled to a depth of 755 ft with the Culebra interval screened from 720 ft to 746 ft. At the Culebra, the inner diameter (ID) of the well is 4.44-in and the pump is hanging on 3.18-in ID tubing. The siting and creation of the H-11b4R well was based on the need to replace the previous H-11b4 well. A physical description of the well is detailed in Figure 3.

Two purge tests were initiated in the Culebra at H-11b4R on 4/24/12 and 5/8/12. Both purge tests concluded on the days they were initiated. These tests were analyzed to gain insight on the hydraulic parameters associated with the well to better frame the pumping rate and duration for the later 72-hour test. The simulations for the purge tests both consisted of a history period prior to drawdown, a drawdown period while purging was active, and a recovery period once purging concluded. The data and model used in each analysis are shown in Figures 4 and 5.

A 72-hour pumping test was initiated in the Culebra at H-11b4R from 6/11/12 to 6/14/12. 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 history period concluded after pumping started due to a generator malfunction approximately 3 hours into the test. The point at which the generator power was permanently established marked the beginning of the drawdown period. The recovery period simply began once pumping was stopped, but the period was concluded prior to full recovery due to changes in water level caused by a later test conducted at H-9bR. The data acquired for the test is shown in Figure 6.

The H-11b4R nSIGHTS simulation consisted of three sequences. The details of each sequence, i.e., start/end time, pressure, etc., are specified in the H-11b4R.nPre file and are listed in Appendix B.1.

The specified H-11b4R conceptual model, chosen because it was the simplest model consistent with the available information that produced an acceptable fit to the data, was an infinite-acting radial system with a variable $T$ with respect to distance from the well, a negative skin and wellbore storage. Gravel pack around the well and localized Culebra fracturing due to drilling likely account for the negative skin. The $T$ variations required for an adequate model were thought to be due to either a non-constant $T$ in the system or double porosity effects. A variable $T$ with respect to distance model was chose as the double porosity model did not provide as good of a fit as the for both the Cartesian form of the test data or the log-log diagnostic plots of the data. The range of $T$ values derived from perturbation analysis is shown in Figure 7. The geometric mean $T$ estimate derived from this analysis was $1.90 \times 10^{-5}$ m$^2$/s. The Cartesian, log-log drawdown diagnostic, and log-log recovery diagnostic simulations corresponding to these $T$ values are shown in Figures 9-11, respectively.

The $T$ estimates gained through this analysis are similar to those of past tests and are compared in the preceding Table 1. Previously the wells had large positive skins (i.e., a low-permeability zone surrounding the well), which led to very high drawdown due to low pumping rates. Two
large-scale tracer tests have been performed on the H-11 wellpad; summaries of hydraulic and tracer testing are found in Meigs et al. (2000), section E.6.

1. Depths in feet below ground level (BGL).
2. Not to scale.

Figure 3. H-11b4R well configuration during testing.
Figure 4. Pressure data from and model fit of the first Culebra purge test in H-11b4R.

Figure 5. Pressure data from and model fit of the second Culebra purge test in H-11b4R.
Figure 6. Pressure data from the Culebra pumping test in H-11b4R.

Figure 7. X-Y scatter plot showing the transmissivity parameter space derived from the H-11b4R perturbation analysis of the drawdown period along with the fit discriminant and best fit values.
Figure 8. X-Y scatter plot showing the transmissivity parameter space derived from the H-11b4R perturbation analysis of the recovery period along with the fit discriminant and best fit values.

Figure 9. Linear plot showing 213 simulations of the H-11b4R pressure response.
Figure 10. Log-log plot showing 213 simulations of the H-11b4R drawdown period pressure change and derivative response.

Figure 11. Log-log plot showing 213 simulations of the H-11b4R recovery period pressure change and derivative response.
4. References


Information Only
# Appendix A – H-11b4R Hydraulic Test – 6/11/12 to 6/14/12

<table>
<thead>
<tr>
<th>Well</th>
<th>Date and Time Start DAS</th>
<th>Date and Time Stop DAS</th>
<th>Date and Time Start Test</th>
<th>Date and Time Stop Test</th>
<th>Borehole Diameter (in)</th>
</tr>
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<tr>
<td>H-11b4R</td>
<td>4/10/12 14:00</td>
<td>1/30/13 11:00</td>
<td>6/11/12 13:05</td>
<td>6/14/12 13:09</td>
<td>8.62</td>
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<table>
<thead>
<tr>
<th>Inside Tubing or Casing Diameter (in)</th>
<th>Culebra Interval (ft bgs)</th>
<th>Fluid Density (g/cm³)</th>
<th>Field Notebook</th>
<th>Data Source Report(s)</th>
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</thead>
<tbody>
<tr>
<td>3.18</td>
<td>720 - 746</td>
<td>1.073</td>
<td>WSWT-15</td>
<td>BDR (C-2769-POD2)</td>
</tr>
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</table>
Appendix B – nSIGHTS Listings

B.1 H-11b4R nSIGHTS Listings

*************
nPre/32 2.41a
*************

Version date  1 April 2011
Listing date  18 Aug 2013
QA status QA: Approved
Config file E:\SANDIA_PROJECTS\WIPP_wells\Culebra\H-11b4R\H-11b4R_pumping_test_longhis.nPre

Control Settings

Main Settings

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

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 155.000 [psi]
External boundary radius 1000000 [m]
<table>
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<td>Formation conductivity</td>
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</tr>
<tr>
<td>Formation spec. storage</td>
<td>Optimization</td>
</tr>
<tr>
<td>Minimum value</td>
<td>0.0001 [m]</td>
</tr>
<tr>
<td>Maximum value</td>
<td>10.0 [m]</td>
</tr>
<tr>
<td>Estimate value</td>
<td>0.0625197 [m]</td>
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<td>Range type</td>
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<tr>
<td>Sigma</td>
<td>1.00E+00</td>
</tr>
<tr>
<td>Skin</td>
<td></td>
</tr>
<tr>
<td>Radial thickness of skin</td>
<td>0.00002 [m]</td>
</tr>
<tr>
<td>Minimum value</td>
<td>0.00002 [m]</td>
</tr>
<tr>
<td>Maximum value</td>
<td>10.0 [m/sec]</td>
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<tr>
<td>Estimate value</td>
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<tr>
<td>Range type</td>
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<tr>
<td>Sigma</td>
<td>1.00E+00</td>
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<tr>
<td>Skin zone conductivity</td>
<td>1.00E-10 [m/sec]</td>
</tr>
<tr>
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<td>0.00002 [m/sec]</td>
</tr>
<tr>
<td>Maximum value</td>
<td>10.0 [m/sec]</td>
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<tr>
<td>Estimate value</td>
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<td>Sigma</td>
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<tr>
<td>Maximum value</td>
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<td>Estimate value</td>
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<td>Sigma</td>
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<td>Fluid</td>
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<td>Fluid density</td>
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<td>Fluid thermal exp. coeff.</td>
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</tr>
<tr>
<td>Test-Zone</td>
<td></td>
</tr>
<tr>
<td>Well radius</td>
<td>8.0 [in]</td>
</tr>
<tr>
<td>Tubing string radius</td>
<td>1.59 [in]</td>
</tr>
<tr>
<td>Numeric</td>
<td></td>
</tr>
<tr>
<td># of radial nodes</td>
<td>250 []</td>
</tr>
<tr>
<td># of skin nodes</td>
<td>50 []</td>
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<tr>
<td>Pressure solution tolerance</td>
<td>1.45038E-11 [psi]</td>
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<td>STP flow solution tolerance</td>
<td>1.58503E-11 [USgpm]</td>
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**f(x) Points Parameters**

**Formation conductivity**

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<th>f(r)</th>
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<td>Optimized</td>
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</table>
Calculated Parameters

Formation

Transmissivity

Storativity

Minimum

Maximum

Diffusivity

Skin Zone

Transmissivity

Storativity

Minimum

Maximum

Diffusivity

Minimum

Maximum

Skin factor

Test Zone

Open hole well-bore storage

Grid Properties

Grid increment delta

Minimum

Maximum

First grid increment
<table>
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<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
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<tr>
<td>Skin grid increment delta</td>
<td>6.06612E-01</td>
<td>1.63670E-02</td>
</tr>
<tr>
<td>Skin first grid increment</td>
<td>0.00001</td>
<td>0.07992</td>
</tr>
<tr>
<td>Skin last grid increment</td>
<td>2.04032E-06</td>
<td>1.69072E-02</td>
</tr>
<tr>
<td>Increment ratio</td>
<td>2.04131E-06</td>
<td>7.83742E-01</td>
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<tr>
<td></td>
<td>7.73995E-01</td>
<td>8.01790E+03</td>
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### Sequences

**Sequence: H_01**

- **Sequence type**: History
- **Start time**: 41009.583330 [day]
- **Duration**: 61.961810 [day]
- **Time step type**: Log
- **First log step**: 1.15741E-07 [day]
- **# of time steps**: 250
- **Type**: Curve
- **Wellbore storage**: Open

**Sequence: H_02**

- **Sequence type**: History
- **Start time**: 41071.545140 [day]
- **Duration**: 0.130562 [day]
- **Time step type**: Log
- **First log step**: 1.15741E-07 [day]
- **# of time steps**: 250
- **Type**: Curve
- **Wellbore storage**: Open

**Sequence: H_03**

- **Sequence type**: History
- **Start time**: 41071.675701 [day]
- **Duration**: 0.001728 [day]
- **Time step type**: Log
- **First log step**: 1.15741E-07 [day]
- **# of time steps**: 250
- **Type**: Curve
- **Wellbore storage**: Open

**Sequence: H_04**

- **Sequence type**: History

---

**Information Only**
Start time 41071.677430 [day]
Duration 0.001620 [day]
Time step type Log
First log step 1.15741E-07 [day]
# of time steps 250
Type Curve
Wellbore storage Open

Sequence: H_05

Sequence type History
Start time 41071.679050 [day]
Duration 0.004019 [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 41071.683069 [day]
Duration 2.861371 [day]
Time step type Log
First log step 1.15741E-07 [day]
# of time steps 250
Type Fixed
Fixed value -12.0 [USgpm]
Wellbore storage Open

Sequence: F_02

Sequence type Flow
Start time 41074.544440 [day]
Duration 54.330560 [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_05
Curve time base Test
Curve Y data units [psi]
Curve Y data is log 10 no
Simulation Results Setup

Output ID | Output type | DAT | Pressure Test Zone
---|---|---|---
Output type | Pressure capture type | Pressure [psi]
Output units | Flow rate output type | Flow Rate [USgpm]

Optimization Setup

Algorithm | Simplex
Simplex algorithm | NR
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 | 8
K_fm.R[01] | OK
K_fm.R[02] | OK
K_fm.V[01] | OK
K_fm.V[02] | OK
Skin zone conductivity | 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 storativity parameter space derived from the H-11b4R perturbation analysis with the fit discriminant and best fit values.

Figure B-2. X-Y scatter plot showing the skin conductivity parameter space derived from H-11b4R perturbation analysis with the fit discriminant and best fit values.
Figure B-3. X-Y scatter plot showing the skin zone specific storage parameter space derived from H-11b4R perturbation analysis with the fit discriminant and best fit values.

Figure B-4. Estimates of transmissivity (drawdown) and storativity derived from the H-11b4R perturbation analysis.

Information Only
Appendix C – File Directories

Table C-1. File descriptions.

<table>
<thead>
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<th>File Extension</th>
<th>Function/Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;filename&gt;.nPre</td>
<td>Files used for initial well test analysis.</td>
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<tr>
<td>&lt;filename&gt;.X.nPre</td>
<td>Files used to generate perturbation analysis of .nPre results.</td>
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<td>.nPost</td>
<td>Post-processing files used to visualize .nPre and perturbation analysis.</td>
</tr>
<tr>
<td>.nOpt</td>
<td>Optimization data used for post processing in .nPost files.</td>
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<td>Simulation data used for post processing in .nPost files.</td>
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</tr>
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<td>im</td>
<td>Graphic output from .nPost files.</td>
</tr>
<tr>
<td>.jpg</td>
<td>Data files used as input for .nPre files.</td>
</tr>
<tr>
<td>.csv, .xls, .dat</td>
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Directory of E:\SANDIA_PROJECTS\WIPP_wells\Culebra\H-11b4R_working

Directory of E:\SANDIA_PROJECTS\WIPP_wells\Culebra\H-11b4R_working\post

Information Only
Directory of E:\SANDIA_PROJECTS\WIPP_wells\Culebra\H-11b4R_working\graphs
### Acknowledgements

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