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A User's Guide to DFNGen

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Cover Illustration: The figure shows the splash page of the DFNGen program.

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A User's Guide to DFNGen

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Acronyms and Abbreviations

Abbreviation	Description
Acronyms/Abbreviations/Symbols	
*.fgn	file with the extension ".fgn"; file for FracGen 14M
*.dat	file with the extension ".dat"; original FracGen file
1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional
DOE	U.S. Department of Energy
NETL	National Energy Technology Laboratory
NRAP	National Risk Assessment Partnership
PC	Personal computer
RAM	Random access memory
TRS	(NRAP) Technical Report Series
Units	
°F	degrees Fahrenheit
ft	feet
ft^2	square feet
GB	gigabyte
GHz	gigahertz
MB	megabyte
psia	pounds per square inch absolute
Computer Code Names	
DFNGen	Discrete Fracture Network Generator Graphical Interface
FracGen	Fracture Network Generator
NFflow	Naturally-Fractured Gas Flow Simulator
FracOut	Fracture (Network and Flow Graphics) Output Display
FARM	Fracture Aperture Reduction Modeling Ancillary Program
BHP	Bottom Hole Pressure Ancillary Program
Kappa	Center-Point Density (Kappa) Ancillary Program
logSTAT	Lognormal Statistics Ancillary Program
spa_L	Spacing Frequency of Fracture Lengths Ancillary Program
ClusDen	Intra-Cluster Fracture Density Ancillary Program
EXPmean	Exponential Mean Ancillary Program

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The user interface described in this guide implements a number of computer codes developed by other professionals at NETL as documented in *FracGen & NFflow: Naturally-Fractured Natural Gas Reservoir Simulator, User's Guide* (NETL, 2014). In particular: (1) the original version of FracGen code (version 6) was developed by Mark McKoy of the DOE, with contributions from James H. Dean, AECOM; (2) the FracOut code was originally developed by James H. Dean, AECOM, and modified by Phillip Nicoletti AECOM, and Seth King, AECOM; and (3) the programs termed "ancillary codes" were developed by Mark McKoy of the DOE, with contributions to the BHP code by Kane Gyovai, formerly with AECOM.

In addition, special thanks to Mark McKoy and Dustin Crandall of the DOE for their reviews and comments on DFNGen code and to Grant Bromhal, Technical Coordinator, DOE, NETL's Office of Research and Development for his management direction and support.

EXECUTIVE SUMMARY

This report is the user manual for the initial release of the computer code DFNGen. DFNGen (Discrete Fracture Network Generator Interface) is a graphical user interface for the computer code FracGen and several supplementary ("ancillary") programs developed at the National Energy Technology Laboratory (NETL) in Morgantown, West Virginia.

The intent of DFNGen is to facilitate use of FracGen, to increase the understanding of FracGen's input options and to reduce errors in input. DFNGen is a Windows-based interface, which allows for the generation and control of input files using specially-created forms (windows). DFNGen runs FracGen as a background process and can analyze the resulting output using a range of options. The code also allows the import of input files from prior versions of FracGen. The analysis options in DFNGen allow the user to examine fracture length, fracture orientation, scan-line spacing, and the spatial distribution of fracture center points.

DFNGen implements a special version of FracGen, termed version 14M (i.e., FracGen version 2014, modified for current application), which has a revised input format. FracGen 14M, as with other versions of FracGen, incorporates three fracture "models" (Model1, Model2, Model3) to simulate randomly located fractures, randomly-located swarms or clusters of fractures and regularly-distributed cluster zones. Another option (termed Model0) permits the input of fracture data collected along boreholes, cores or outcrop scans by the user. Of importance for flow modeling, the generated fractures of the network can be subsequently adjusted for varying connectivity by several approaches, including synthetic annealing, to facilitate flow modeling with a network with a sparse number of fractures.

This user guide provides an essential, but directed summary of DFNGen operation. For more details on FracGen, NFflow, or the ancillary codes, the user is referred to the user guide for these codes (NETL, 2014).

1. INTRODUCTION

This report provides a concise description on the use of the DFNGen interface. DFNGen is a Windows-Forms based interface[1] that facilitates the use of a set of computer codes for the generation of discrete fracture networks. In particular, DFNGen facilitates the use of the FracGen computer code by gathering and checking input values, formatting input files, running the FracGen code in different modes, and performing analyses of the generated fracture network with several tools that display and evaluate the fracture network attributes.

In the initial sections of the manual, the user is introduced to installing the DFNGen program (with a listing on system requirements and how to perform an installation), followed by a description of the startup process. The startup form (window) is then introduced with a menu system that supports the steps needed to conduct all operations. This is followed by a description of the basics of defining fracture data as well as importing and exporting input files from prior versions of FracGen.

In Section 4, the manual describes and illustrates the array of menu options that can be selected by the user. Six menu options (*File – Data – Run – Tools – Analyze – Help*) on the startup form take the user from developing input file and adding/editing data for stochastic models, to running FracGen code and then evaluating the results with several tools that display and analyze the data.

This manual then follows in Sections 5 and 6 with a more in-depth description on how to specify input data using the Layer and Fracture forms and subforms for each fracture generation option. The various tabs and options are briefly illustrated for each option, together with some elementary input requirements.

Section 7 describes how to run FracGen in both single-layer and multiple-layer modes and how to conduct multiple runs using the same stochastic input descriptions. Further, the various methods that can be used to evaluate the output from FracGen are discussed in Section 8, including basic instructions on the windows that implement these methods. These methods can: 1) provide a two-dimensional (2-D) display of the fractures; 2) evaluate fracture length distributions; 3) evaluate fracture orientation distributions; 4) count the number of intersections for each fracture; 5) compute fracture spacing distances along a user-defined scanlines across the network; and 6) display and evaluate the density of fracture center points.

Finally, a short discussion is provided in Sections 9 and 10 on running the FracOut code (which can plot FracGen and NFflow fracture network data) and running a set of supplementary codes (labeled as Ancillary Codes) that support FracGen computations or modify FracGen networks.

Appendices to the report are enclosed for background information including:

- Listing of the various forms (windows) that the user will encounter in DFNGen (Appendix A)
- Descriptions of the files and file formats used in DFNGen (Appendix B)

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[1] Specifically, DFNGen is a Microsoft© Windows Forms application using .NET Framework GDI+ graphics classes, and written in C#.

- Parameters used in FracGen 14M for model input (Appendix C)
- Notes on the specific PC facilities used to develop DFNGen (Appendix D)
- Descriptions of ancillary codes implemented with DFNGen (Appendix E)

2. INSTALLING DFNGEN

2.1 SYSTEM REQUIREMENTS

The following computer capabilities are recommended for using DFNGen:

- Personal computer (PC) with 64-bit operating system, with a dual-core, 2.66-GHz or faster processor
- Video memory of a minimum of 512 MB
- Microsoft Windows 7 operating system, Service Pack 1
- True Color or High Color display with a minimum resolution of 1680 x 1050
- A minimum of 2 GB of total installed random-access memory (RAM)[2]
- A minimum of 4 GB of total storage[2]
- Installed software for Microsoft's ".NET Framework 4.0"[3]
- Installed "OpenGL" utilities[4]

The system can operate on PC's with fewer capabilities, but the user may experience difficulties.

2.2 INSTALLATION

DFNGen file system can be installed either from a data storage device (USB flash drive, CD, etc.) or from a common network drive. The user initiates the installation by running the **setup.exe** program under the *.\DFNGen Deploy 2014* directory.

The installation process employs a step-by-step interface requiring only that the user have administrative rights to the PC for the installation process. The code can be installed anywhere on the computer system where the user has Read-Write privileges[5], but it is recommended that the code is installed under the user's *\My Documents* directory. The code will be installed in a directory, DFNGen, together with a subdirectory (*.\programs*) for FracGen and other related programs and files. Before initiating the DFNGen installation, the user should verify that the computer has at least 200 MB of free storage space for the code installation in addition to the operating requirements.

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[2] Memory and storage recommendations were estimated from code operation with typical fracture networks. DFNGen may work satisfactorily on computer systems with less memory or storage, especially if modeling is restricted to smaller networks.

[3] This software can be installed from Microsoft's download center, at URL: http://www.microsoft.com/en-us/download/details.aspx?id=17851.

[4] Most PC windows systems sold after mid-1996 will have the OpenGL utilities pre-installed.

[5] The program creates several types of files; if the user does not have Read-Write privileges on the installation directory, DFNGen will run, but FracGen-related files cannot be created, and no output or error messages are provided. This becomes problematic on network-based PCs especially when installing the software in the *C:\Program Files* or *C:\Program Files* (x86) directory.

To install DFNGen:

- Go to directory containing the installation program
- Double-click on the installation program, **setup.exe**
- Follow the installation instructions

To start the program, open the DFNGen folder under the .*programs* folder and double click on **DFNGen.exe**. (You can create a shortcut on your desktop by clicking on the DFNGen.exe label, selecting the "Create shortcut" option and dragging the shortcut icon to your desktop.)

3. GETTING STARTED

3.1 STARTUP FORM (WINDOW)

DFNGen is a Microsoft Windows-based program, and uses commands and mouse operations typical of such applications. By selecting options using the buttons shown in a window (termed here as a "form"), the user will initiate actions, which in many cases will open secondary forms to provide for additional data input. (A list of all the forms used in DFNGen is provided in Appendix A.) Data is input using both a mouse and the computer keyboard for console-based interactions.

The DFNGen program is initiated by double-clicking on the **DFNGen.exe** file in the installation directory. When running, DFNGen first displays a splash screen, which appears (hangs) for a few seconds on the console, and requires no action from the user. This splash form, which provides the code version and copyright, is then replaced by the DFNGen Startup form or window. At this point, the Startup form (shown in Figure 1) is largely blank and is hiding a number of input controls. The hidden controls are to emphasize the need for the user to first specify a working directory, or to select an existing DFNGen input file (i.e., a file with an ".fgn" extension)[6]. Upon completing this action, the hidden controls become visible (Figure 2).

Two additional categories of input are now shown on the form. If the user is starting a new analysis, all input boxes on the form will be blank and need to be completed. If starting using an existing DFNGen file (such as a provided example file), the input from the file will appear in the appropriate boxes, and the user need only complete any undesignated controls.

Across the top of this form is a set of six menu options (File – Data – Run – Tools – Analyze – Help) that allow the user to input data, run various codes and review the results. These menu options are discussed in more detail in Section 4.

3.2 DEFINING FRACTURE NETWORK DATA

To generate a fracture network using FracGen, various stochastic parameters are required depending on the fracture model used.[7] As mentioned, if the user selects an existing file as input, all values in the input file are translated into the DFNGen system. To input new values for this layer, or if the user wishes to edit or confirm the values from a prior file, the user employs the menu at the top of the Startup form, selects the "Data" option and then selects the "Define Fracturing" submenu option.

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6 This action will also specify the working directory.

7 Fracture models and their basis are discussed in more detail in NETL (2014), and only a brief discussion on the models is presented in this guide.

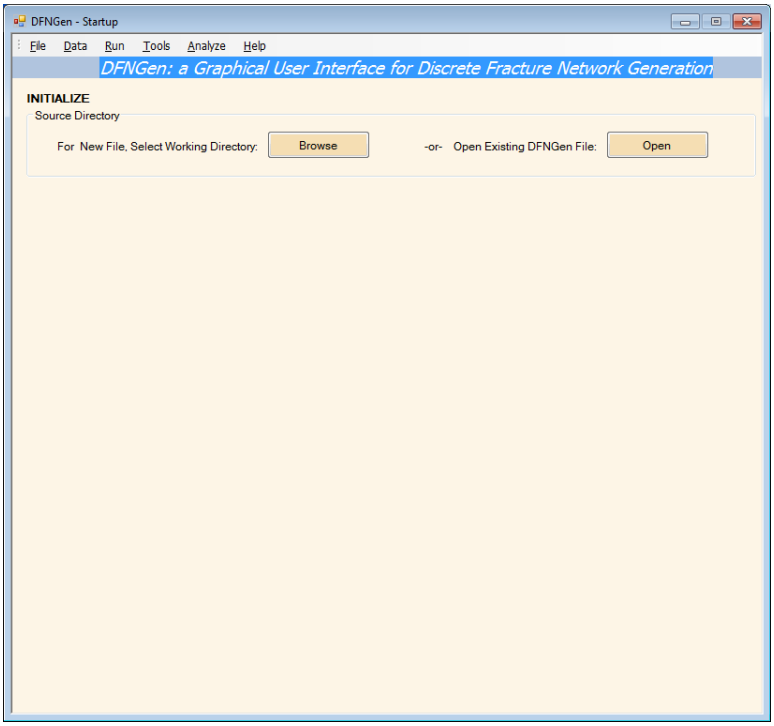

Figure 1: DFNGen Startup form before selecting a working directory.

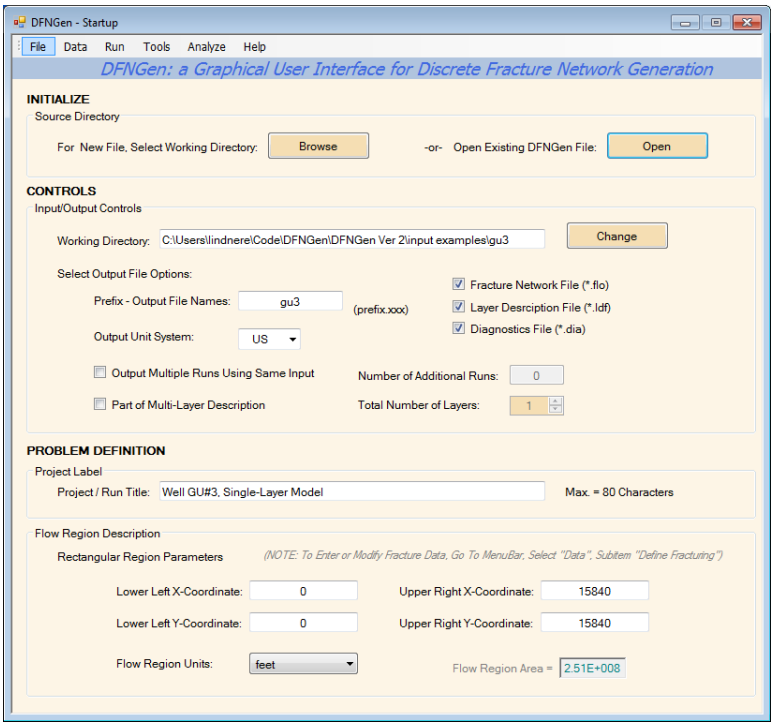

Figure 2: DFNGen Startup form after selecting an existing file.

The Layer window will now appear (Figure 3). This form provides for input of basic parameter values for a layer on the right (i.e., the designated layer number,[8] layer thickness, depth and selected input units). Fracture sets defined for the layer (if any) are shown in the large box at the left of the form using a "TreeView" display in Microsoft Windows Forms. Each layer can incorporate several fracture "sets" to define the fracture network across the layer, which appear as separate nodes on the tree.[9] Each set (node) is based on a single fracture generation option (model0, model1, model2, or model3) and stochastic parameters are entered as required for the specific model.

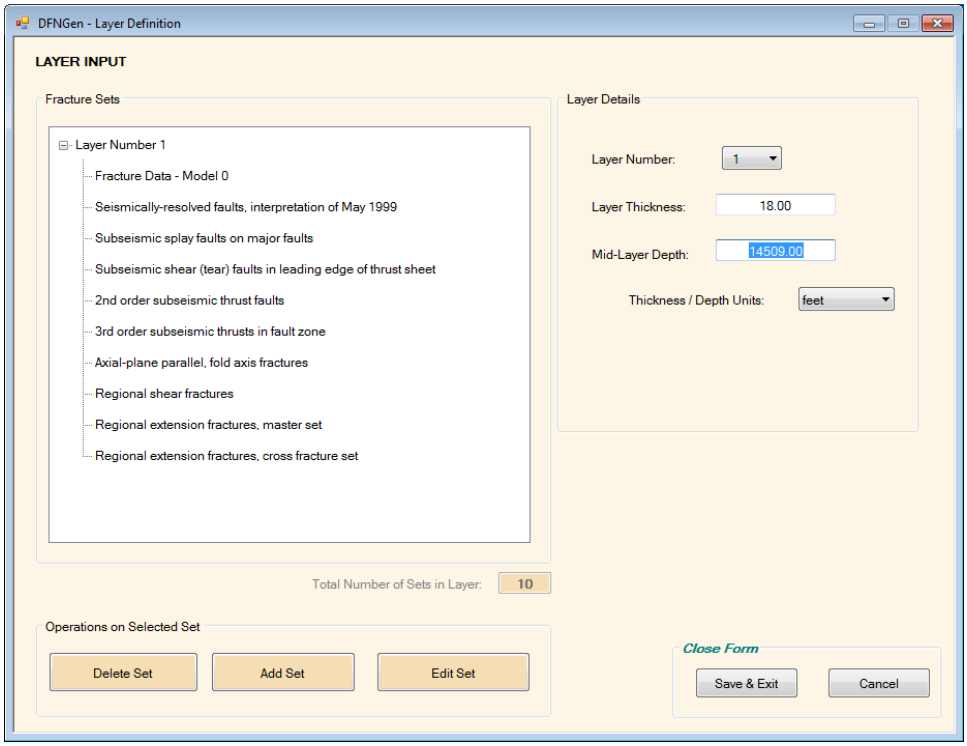

Figure 3: DFNGen Layer input form.

At the bottom-left of the form, below the TreeView, are three buttons. The buttons define options for controlling fracture sets for the layer. The user can add, delete, or edit existing sets using a

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8 Each DFNGen file (or set of input parameters in DFNGen) defines only one layer in the subsurface (i.e., a 2-D horizontal plane which is cross-cut by vertical fracturing). For a single-layer analysis by FracGen, the layer number and the total number of layers should be set to 1. When the option of a multi-layer FracGen analyses is selected, these parameters become important as described in Section 7.2.

9 The current maximum number of sets for a layer is 10.

simple tree structure shown inside the fracture set box. The specific use of these controls is explained in more detail later in Section 6.2.

Assuming that the user has opened a previous *.fgn file[10] with several fracture sets already defined, the user can then select one of the set names listed in the TreeView box and then select the ***Edit Set*** button, and a full fracture form will appear, as shown in Figure 4.

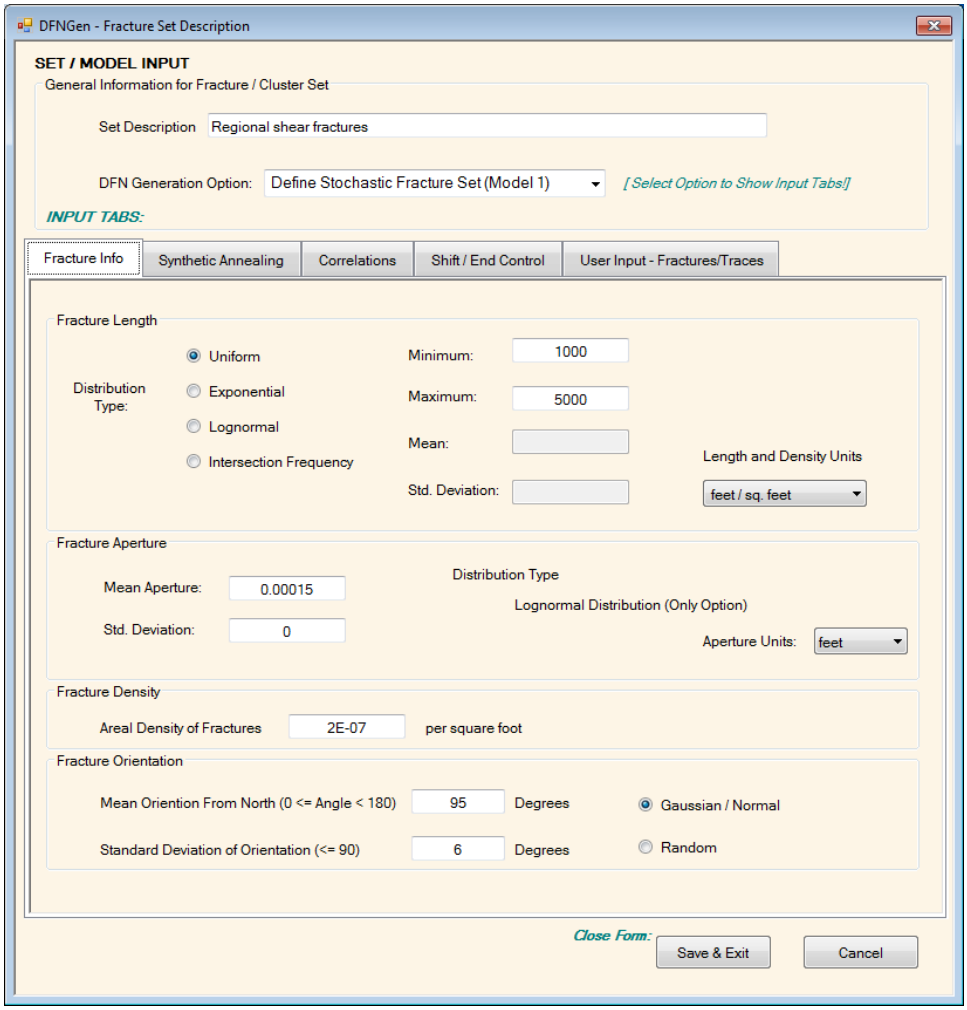

Figure 4: DFNGen Fracture input form after selecting *Edit Set*.

The Fracture form overlies the Startup form and Layer form in the background. At the top of the Fracture form, the user can designate a name for the fracture set. More importantly, on the second line, the generation option is shown.

10 If just starting out, the user can open an example file provided with the code, provided in the *.\input examples* directory.

This selection box allows the user to select one of four options (listed in the drop-down box):

1. User-Defined Traces/Fractures (Model0)
2. Define Stochastic Fracture Sets (Model1)
3. Define Fracture Swarms/Clusters (Model2)
4. Define Fracture Patterns (Model3)

This choice affects what is shown on the remainder of the form – the subform, starting with the line of tabs directly below the second line. The various tabs and model choices are described more in Section 6.3.

After defining the desired parameters, the user can save the changes by selecting the **Save & Exit** button at the bottom right of the form. The input will be saved, the form will close, and the Layer form will now be evident. The user can then exit the Layer form in the same fashion.

If the user does not wish to make a change and discard any changes made on the form, the user can close the form by selecting the **Cancel** button. In this case, if the user has made changes, a message box will appear to confirm the action. If the user still wishes to exit without saving (by selecting the **Yes** option in the message box), the message window and the Fracture form will simply close. If the user has hit the key by accident, selecting the **No** option will return the user to the Fracture form.

3.3 USING OTHER FRACGEN FILES - IMPORT AND EXPORT

DFNGen employs a specific file format for saving layer definitions and running FracGen 14M, with each fracture network file having an extension "*.fgn." This file format differs from (and contains more information than) the input files for other versions of FracGen. For cross compatibility with other FracGen work, DFNGen has the ability to read (import) the input file from other versions of FracGen (i.e., *.dat files), and save the work as a *.fgn file. Conversely, DFNGen also has the ability to produce (export) information to a *.dat file format. These two options can be accessed from the File menu, under the import and export sub-options. Note that in exporting to a *.dat file from DFNGen, some user information is lost. The file format for a *.fgn file and the specific data lost in export are discussed further in Appendix B.

3.4 RUNNING FRACGEN

After defining the fracture sets for a layer, the user can then generate a 2-D discrete fracture network with FracGen, and view the results by selecting the appropriate menu option on the Startup form. The menu selections are briefly described in the next section.

4. DFNGEN MENU DESCRIPTION

Various options in DFNGen can be accessed from the menu strip at the top of DFNGen Startup form (the first window provided to the user). All top menu items can be selected using the mouse or by using a keyboard shortcut (i.e., the **Alt** key together with the first letter of the menu item name; e.g., **Alt-F** for File operations).

The top menu allows the user to:

- Open and close files
- Define fracture network input and wells
- Run FracGen and FracOut computer codes
- Implement ancillary codes to FracGen
- Analyze the output from FracGen using standard approaches
- Obtain more information about the Ancillary Tools or contacting the developers

In selecting a menu item, italics and the greater than (or angle bracket) symbol is used in this manual to indicate the menu selection process. For example, *File>New,* indicates selecting the "*New*" option under the "*File*" tab from the menu bar. The set of menu options is described in more detail in the following sections.

4.1 FILE

Selecting the "File" from the top menu provides access to seven file operations, which are subdivided into five groups by horizontal lines (Figure 5). These options can be selected using a mouse click or by using the control key (**Ctrl**) and a letter designation; in most cases, the designated letter is the first letter of the action (as in **Ctrl-O** for open) except for "Save-As" option, which is implemented with **Ctrl-A**.

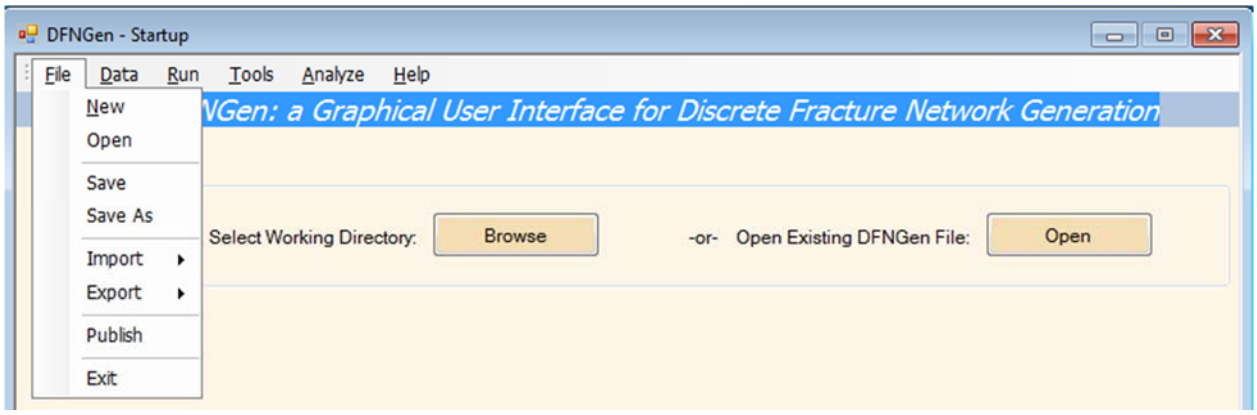

Figure 5: File menu from DFNGen startup form.

The first File group is for producing a FracGen input file. Selecting the *File>New* option will clear all DFNGen forms, thereby starting a new analysis, and is also typically used to restart the DFNGen entry process. The *File>Open* option will open an existing *.fgn file for the user, using a standard Windows file selection process window. Upon choosing a file, all prior input is cleared and the new input shown on the DFNGen forms is from the selected file.

The second group of options involves saving DFNGen files.[11] The *File>Save* command will save the current data set using the current file name and directory path. (If a file name has not yet been defined, the user will be prompted to define a file name.) Once a file name and path are defined, this option does not allow the user to choose a new file name or alter the path. However, the user can create a new file name and new file path under the second option, "Save As." By clicking on *File>Save As*, the user will be prompted to save the file with a new file name with an extension of "fgn".

The third group of operations Import and Export (*File>Import>*.DAT File* and *File>Export>*.DAT File*) provides the import or export of the alternative FracGen files with the "dat" extension. The *.dat files were developed for use with other, earlier versions of FracGen, and the import/export options in DFNGen allow for compatibility. However, the *.fgn file format contains more information (see Appendix B), so exporting a file from DFNGen to the *.dat format loses some information and importing the file will leave several fields blank in DFNGen, especially on the startup form. No information on fracture definitions will be lost as both formats contain the same information in this regard.

The command in the fourth group, *File>Publish*, creates a text file which documents the current data set using a more user-friendly format and which explains the input values in more detail. The command in the fifth and final option, *File>Exit*, terminates the DFNGen session and does <u>not</u> save the current data set. If a "Save" command has not been selected during the DFNGen session, selecting the Exit command will first prompt the user to save the file prior to closing.

4.2 DATA

Selecting "Data" on the main menu provides the user with two options to define input for FracGen analyses (Figure 6). The first option is the "Define Fracturing" option. After selecting this item (*Data>Define Fracturing*), the user is presented with a form to define layer input for FracGen.

As a side note, the data in a single DFNGen file represents the input for one layer or horizon in the subsurface. The layer form permits the user to define up to 10 fracture sets for this layer. This form is described in more detail in Section 6.

The second option under the Data menu (i.e., *Data>Wells*) defines the well characteristics for NFflow analyses, which appears at the bottom of the *.fgn file, if defined. Note that well input is solely intended for use with NFflow and has no effect on fracture network generation with FracGen.

[11] The current version of DFNGen does not automatically save input or create backup files. If the DFNGen program closes without saving, the current input on the forms in DFNGen are lost. The user is encouraged to backup entry work frequently to prevent loss in the event of a power interruption.

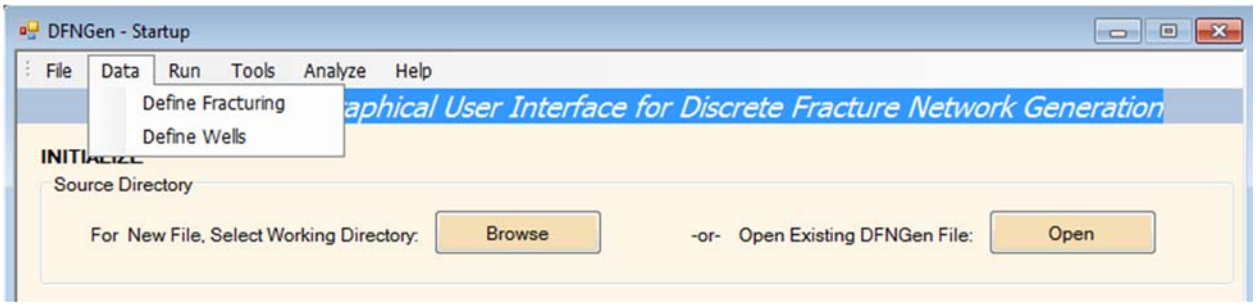

Figure 6: Data menu from DFNGen startup form.

4.3 RUN

As shown in Figure 7, the "Run" menu provides the user three choices: 1) running FracGen in a single layer mode, 2) running FracGen in a multi-layer mode, and 3) running FracOut. Selecting the first choice (*Run>FracGen - Single*) will use the existing values shown in DFNGen forms as input and execute the FracGen code to produce a fracture network for a single layer. The selection will also create the FracGen output files designated on the Startup form in DFNGen. Running a FracGen analysis is discussed further in Section 7.1.

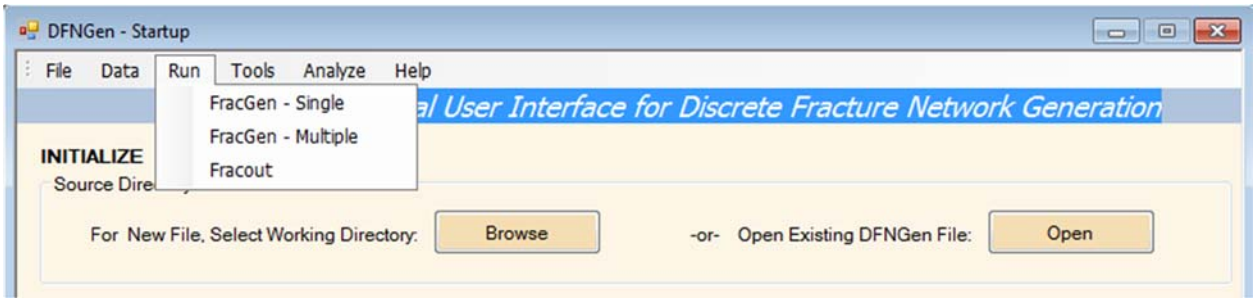

Figure 7: Run menu from DFNGen startup form.

To model fracture systems in layered rock, FracGen incorporates the option to generate fracture systems in several strata (layers) while accounting for fractures crossing from a layer into adjacent strata.[12] The second menu option (*Run>FracGen - Multiple*) implements this operation. To generate a multi-layer network, the user is first required to develop individual fracture network definitions for all layers (i.e., develop a *.fgn files for each layer) prior to selecting the option. If the user wishes to use the current fracture network definition, the user must first save the input to a *.fgn file. Then, the user can select the DFNGen option to perform a multi-layer analysis and will be prompted for the file name of each of the individual layers, starting from the bottom up (i.e., the deepest layer is defined first).

The last option, (*Run>FracOut*) will start the FracOut code's user input form. FracOut creates graphical displays for both FracGen and NFflow fracture networks. The FracOut form will

[12] In FracGen, fractures created in one layer can penetrate (extend) upward to one or more the adjacent layers.

initially display in the mode to produce a 2-D discrete fracture network from a FracGen fracture network file (i.e. from a *.flo file). Hence, to use FracOut, a fracture network file from a FracGen analysis must be available for use. FracOut also requires the associated layer definition file (*.ldf file) created for the same network.

4.4 TOOLS

The "Tools" menu accesses several computer programs that assist in the use or analysis of field data as part of developing input for FracGen and NFflow (NETL, 2014). These programs were written in Fortran and are implemented by DFNGen as independent executable code, which, when selected in DFNGen, run in a separate window and require console input for defining input. If the operation of an ancillary code fails, control reverts to DFNGen, without impact to DFNGen operations.

The following ancillary codes are available under *Tools* menu (shown in Figure 8):

1. FARM
2. BHP
3. Kappa
4. logSTAT
5. spa_L
6. ClusDen
7. EXPmean

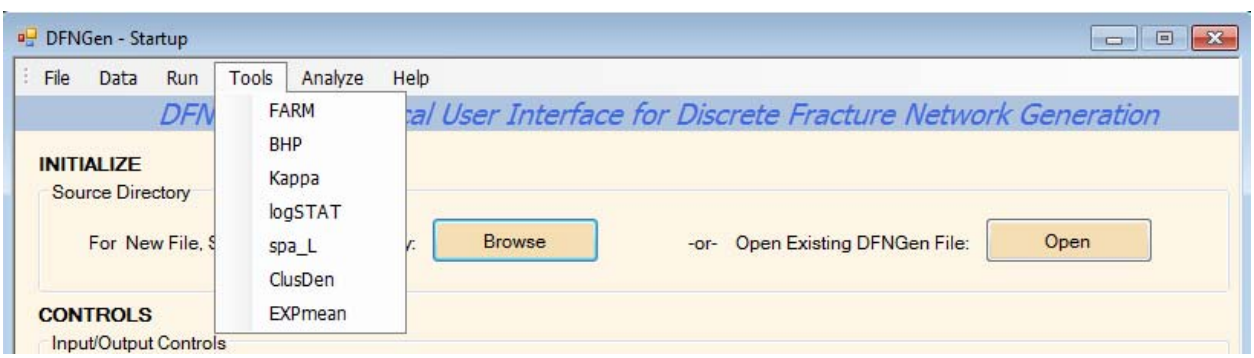

Figure 8: Tools menu from DFNGen startup form.

Clicking on one of these code options from the Tools menu will start the selected code. These codes are described in more detail in the *FracGen & NFflow: Naturally-Fractured Natural Gas Reservoir Simulator, User's Guide* (NETL, 2014). A summary statement on each code can be found under the "Help" menu option in DFNGen.

4.5 ANALYZE

The DFNGen "Analyze" menu (Figure 9) provides the user with options to evaluate and view the fracture network characteristics using standard statistical charts or figures. In addition to providing an image on the console, these forms can provide a bitmap image of the chart or figure, and a listing of the selected data in a text file.

Figure 9: Analyze menu from DFNGen startup form.

The Analyze options include:

1. Display the fractures in the flow region (*Analyze>Display Network*)
2. Evaluate the distribution of fracture lengths (*Analyze>Analyze Distributions>Length*)
3. Evaluate the fracture orientation distribution using a rose diagram (*Analyze>Analyze Distributions>Orientation*)
4. Count the number of intersections (*Analyze>Count Intersections*)
5. Compute fracture spacing distances along a user-defined scan line (*Analyze>Compute Scan Lines*)
6. Display and evaluate the density of fracture centers within the flow region (*Analyze>Determine Areal Density*)

4.6 HELP

The "Help" menu option (Figure 10) provides the user with options to better understand the DFNGen ancillary codes implemented by DFNGen and report concerns on DFNGen operations. The first option (*Help>Help Topics*) will provide the user with a short summary of each of the ancillary codes in DFNGen, based on the descriptions in NETL (2014). The second option (*Help>About*) provides a window describing the code version and date, together with a scroll box, which contains a brief summary of DFNGen and the contact address to suggest changes and report errors. (To see all the text, the user must scroll down using the slider control at the right.)

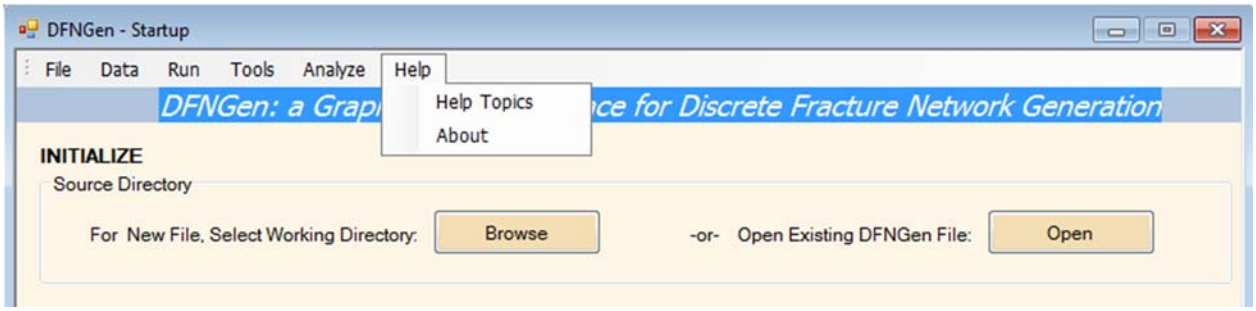

Figure 10: Help menu from DFNGen startup form.

5. DEFINING CONTROL INFORMATION

5.1 RUN CONTROL AND PROBLEM PROPERTIES

The initial DFNGen Startup form provides for three categories of input, which apply to the entire fracture generation definition. The sections as titled are: (1) Initialize; (2) Controls and (3) Problem Definition. The categories appear in bold font on the form (Figure 11).[13]

The first, "Initialize," category provides for the selection of the working directory and or an existing *.fgn file as a starting point in problem definition. The working directory is the file location where all FracGen external output files are created. By selection of the appropriate button (either Browse or Open) the user is presented a standard Microsoft Windows dialog for directory or file selection. Upon selection of a working directory, the result is shown below in the text box in the next category area. Upon selection of a previously defined file, all information in the file will be moved into the DFNGen form and appear in the appropriate boxes.

The second category of input ("Controls") directs the output of the FracGen code when executed. The topmost control in this group displays the current working directory, which can be changed manually by the user. DFNGen allows the user to change the working directory and adjust a prior selection at any point during the process of defining the input prior to running FracGen. The easiest way to change the working directory is to select the "change" button to the right of the directory name. Clicking this button allows the user to select a file name using the typical Window's dialog and save time and errors caused by manual input of a path name.

Directly below this control is a space for input of a short name, termed "Prefix - Output File Names". This string of characters determines the base name used for all output from FracGen, with a different file extension for each file type. For example, if the user inputs a prefix, "gu3", the flow file generated by FracGen will be stored in the working directory with the filename "gu3.flo." and a layer file with the name "gu3.ldf." To the right of the prefix input box are check boxes, which will determine the files output by FracGen; a check indicates that the user desires the related file output.[14]

Below the prefix definition, the user can select the units for use in the input file generated by DFNGen (i.e., *.fgn file). As the NFflow code assumes U.S. (English) units, the user is encouraged to output the files with this selection. Note that DFNGen allows for different units for different parameters on the various input forms described later; all these values however will be converted to the designated output system units when the *.fgn file is generated.

The two remaining check boxes in this area control special operations of FracGen. The first check box indicates the desire to generate a number of different output files with FracGen using the same input definition. The number of files sets is identified in the input box to the right.

---

[13] A list of all parameters used in FracGen is included in Appendix C.

[14] See Appendix B for a brief description of file types output by FracGen.

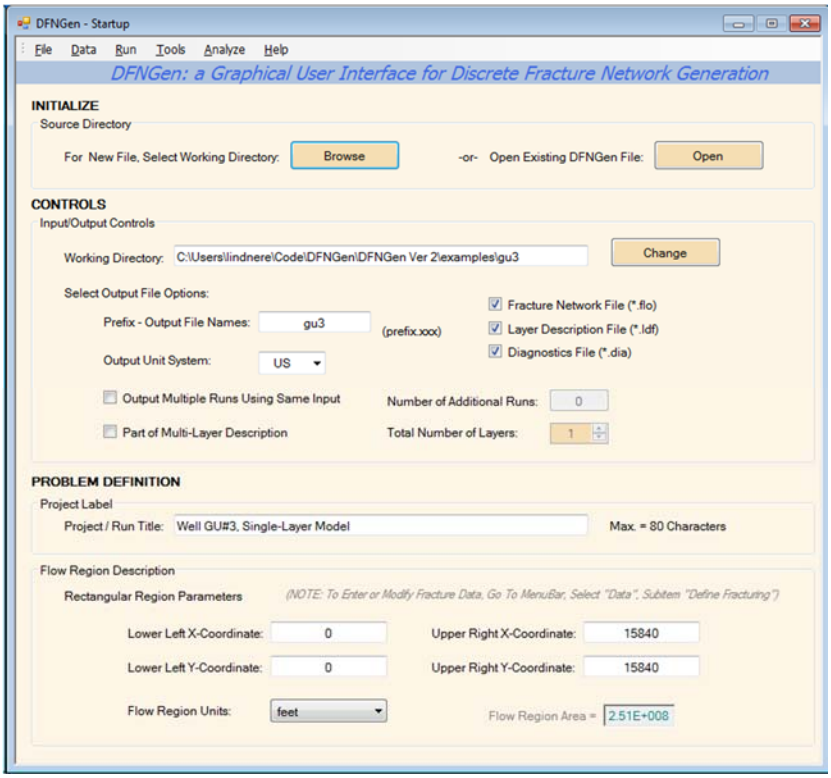

Figure 11: Control and region input.

The second checkbox indicates the current definition is one of several "layers" with the total number of layers specified by the user to the right.[15]

The third category of input ("Problem Definition") provides for general input for a FracGen analyses, including a problem title and the coordinates of the overall flow region to be modeled. The title is entered from the keyboard and can be any set of characters designated by the user up to a length of 80 characters.

The coordinates of the flow region assume a rectangular area or plane, using a Cartesian coordinate system with x and y axes, with the x-axis as the base or horizontal axis. The region is fully defined by input of the lower left x and y coordinates and the upper right x and y coordinates. A consistent set of units is assumed, increasing from left to right in the boxes, so that a positive area is computed. As an error check, the resulting area is computed by DFNGen and shown in the lower right corner of the form shown in a read-only box. If the resulting area is positive, the area value is displayed in green. If the coordinates result in a negative area, the area value will be shown in a red together with an error message.[16]

---

15 FracGen allows the creation of several "layers" to represent adjacent strata. A maximum of 5 layers is permitted with the current FracGen version.

16 FracGen performs the same check internally and will stop operation for a negative area value.

The boxes for all numeric values in DFNGen incorporate various checks on the characters input by the user. For example, on this form, DFNGen allows the input of negative coordinate values. As coordinate values can be large, the boxes will also allow input of an exponential number (using an exponential in the form of "E+xx"). However, use of extremely large values (in excess of +/- 99,999) or the use of any letters will cause an error message to the user, and the current textbox will be cleared.

At the bottom left of the form is a control to select the units for the input values. The units of the coordinate values can be elected as either feet, miles, meters or kilometers.

6. DEFINING FRACTURING AND WELLS

6.1 DEFINING LAYER PROPERTIES ON THE LAYER FORM

To add or edit layer and set properties, the user selects the *Data>Define Fracturing* at the top of the Startup form to display the layer form. As mentioned, this form (shown in Figure 12) provides for input basic parameter values for the layer on the right of the form: 1) the layer number, 2) layer thickness, 3) depth, and 4) units used. The layer number is to designate the current layer position from the bottom of a sequence of layers for multi-layer FracGen analyses. For single-layer FracGen analyses, the layer number is set to 1.

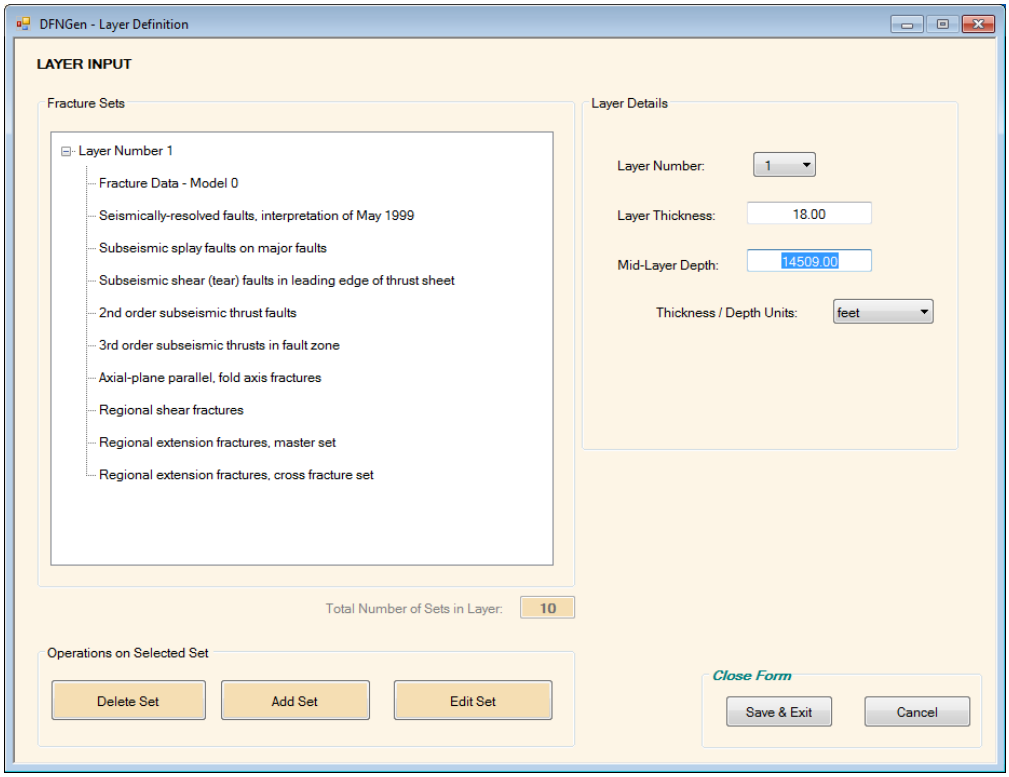

Figure 12: Layer information input.

The layer thickness and depth (of the layer center) are input by the user from the keyboard; the text boxes on the form will prevent negative numbers or the use (in general) of non-numeric characters except a period. However, the textbox has been structured to allow the use of plus and negative signs together with the letter "E" for exponential notation (i.e., in the form xE+xx, where x is a number).

For multi-layer analyses, the user is cautioned to check that the thickness and depth values for each layer so they do not indicate an overlap between adjacent layers, as this will cause a FracGen error.

At the lower right of the Layer form (e.g., Figure 12), the user is presented with two control buttons: 1) **Save & Exit**; and 2) **Cancel**. Hitting the **Save & Exit** button, the changes made on the particular form will be added to the current data base; selecting **Cancel** button will close the form without saving. The user can also exit the form without saving by clicking on the small box

at the top-right of the form with the "X" symbol. Note that exiting the Layer form without saving will lose all work on the associated fracture sets as well.

6.2 DEFINING FRACTURE-SETS ON THE LAYER FORM

On the left side of the Layer form are a fracture set box and a line of buttons, which control the definition of fracture sets for the layer. Each layer can use several fracture "sets" to define the fracture network across the layer. Each defined fracture set is named and listed in the fracture set box. Each fracture set is based on a single fracture generation option (described in the next section) and stochastic parameters are entered as required for the specific model.

When the form is initiated, previously defined fracture sets for the layer (if any) are shown in the fracture set box. Control of the fracture sets is performed by selecting an action button at the base of the fracture set box. Three options are available: 1) delete a fracture set; 2) add a fracture set; and 3) edit a fracture set. To edit or delete a fracture set, the user must first select (highlight) the set name shown in the box, and then select the action.

To delete any fracture set shown for a specific layer, the user selects the set name (i.e., by clicking with the mouse directly on the set name), and then selecting the **Delete Set** button. In response, the user is presented with a message window, asking the user to confirm the delete action. Selecting the **Yes** button in the message box will confirm the action; the message box will close and the name will be deleted from the fracture set box. Selecting the **No** button will close the message box without any further action.

To add a set, the user selects the **Add Set** button. If the user tries to add more than the maximum limit of sets, a message box will appear, requiring the user to respond before proceeding. After selecting the button, the Fracture form will open

Similar to deleting, to edit a specific fracture set, the user must first select the fracture set name from the list, and then select the **Edit Set** button. If the user does not first select a set, a message box will appear, indicating the error. As with adding a set, after selecting a set and hitting **Edit Set** button, the Fracture form will open.

Depending on the option selected, the Fracture form will open in one of two modes. If the user has selected to add a new set, the Fracture form will hide most controls until the key parameter, the "DFNGen Generation Option," is selected on the second line on the form (see Figure 13). Upon defining a set name at the top of form and selecting a generation option (directly below), the full form (with the remainder of the controls on the form) will appear.

If the user has already defined a fracture set, the entire Fracture form will immediately be visible, and the information entered and saved in prior sessions will be visible in the appropriate text boxes (Figure 14). The full form reveals a subform with a line of tabs just below the top two entry lines. Selecting a specific tab will change the subform directly below the tab line. This subform, the tabs, and the model generation options are discussed in the next section.

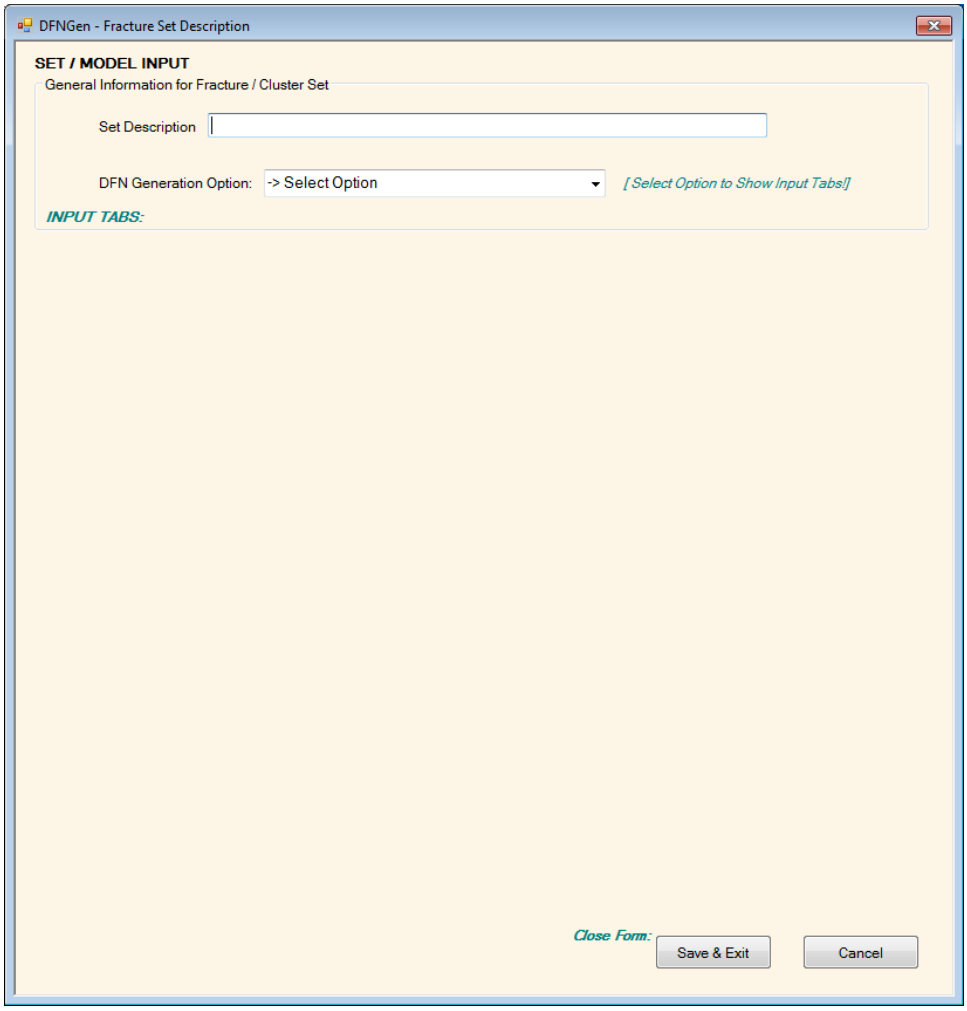

Figure 13: DFNGen Fracture input form before selecting a generation option.

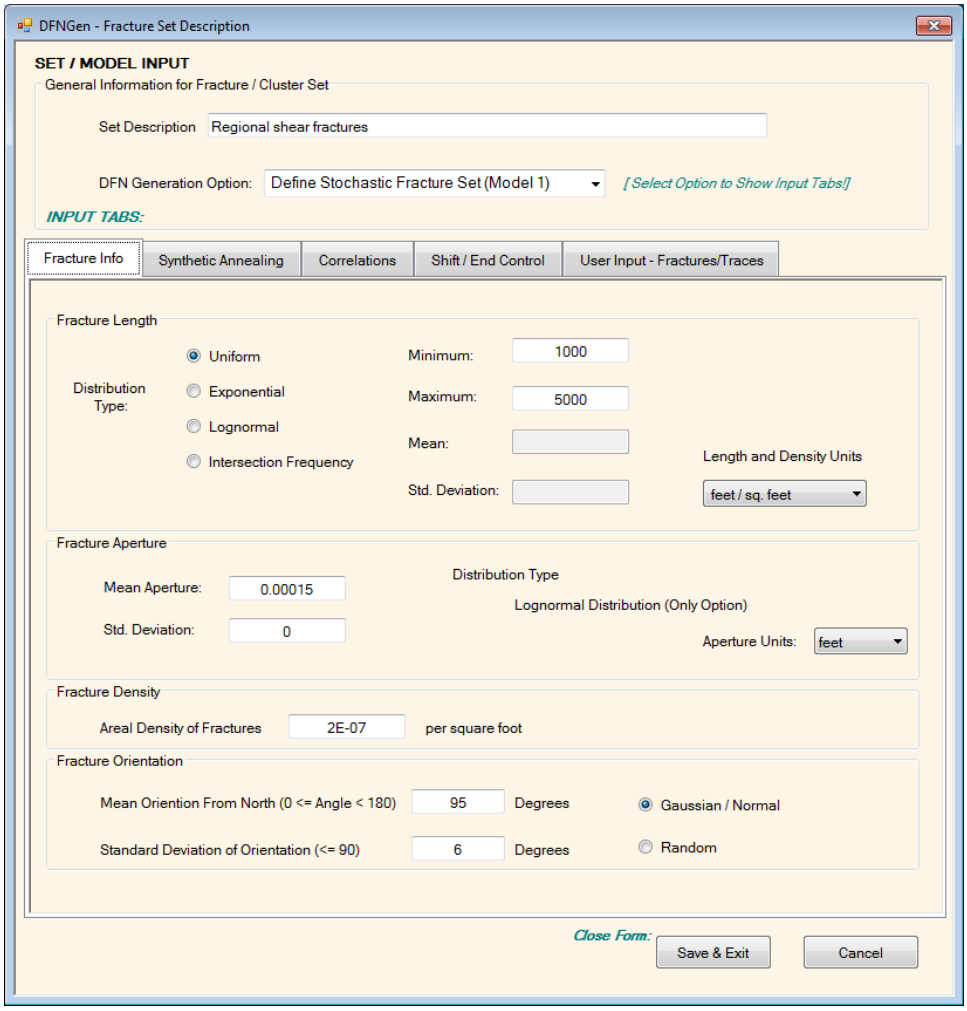

Figure 14: DFNGen Fracture input form after selecting generation option Model 1.

6.3 DEFINING FRACTURE MODEL PARAMETERS ON THE FRACTURE FORM

The fracture generation selection box allows the user to select one of four options to generate fractures[17]:

1. User-Defined Traces/Fractures (Model0)[18]
2. Define Stochastic Fracture Sets (Model1)
3. Define Fracture Swarms/Clusters (Model2)
4. Define Fracture Patterns (Model3)

Upon selecting a specific generation model at the top of Fracture form, a specific set of tabs is presented to the user, just below the generation selection box as part of a subform. These set of tabs differs with the model selected, as the tabs are tailored to the selected generation option. Several tabs are used for all fracture models (i.e., for options Model1, Model2 and Model3), including fracture info, synthetic annealing, correlations, and shift/end control, but specific parameters on each of these subforms can vary as required by the model.

For the first generation option, Model0, only two tabs are shown (see Figure 15)[19]. The options allow for user input of defined fractures either from a separate file or from the keyboard. Selecting the "File Data" tab, presents a subform with a text box for entry of the name of the file which contains additional user-defined fractures, and a browse button to find the file using a Windows query. Selecting the second tab, "User Input – Fractures/Traces" presents a gridded entry form for the input of the parameters for each fracture (shown in Figure 15)[20]. In this case, the user selects the **Add Line** button and enters the available data on the new line on the form. The user can move through the form using the arrow keys and a line can be removed by selecting the line and selecting the **Delete Line** button.

The second option, Model1, provides the user with a set of tabs as shown in Figure 16 (the "Fracture Info" tab is selected in the figure). The user can move from subform to subform by selecting the desired tab.

---

[17] The parameters for each model are described in details NETL (2014); a list of the parameters for these models in FracGen 14M is presented in Appendix C.

[18] The option "Model0" provides for the input of fractures from a separate file or from keyboard input. It is not a model per se and does not generate a set of stochastic fractures.

[19] As required by FracGen, the Model0 option (if desired) must be the selected for the first set defined for a layer and can only be used once. This option, however, is not required to be used, if not needed.

[20] An alternating color scheme for the line input is adopted on the subform. The yellow indicates where the next data entry will be displayed.

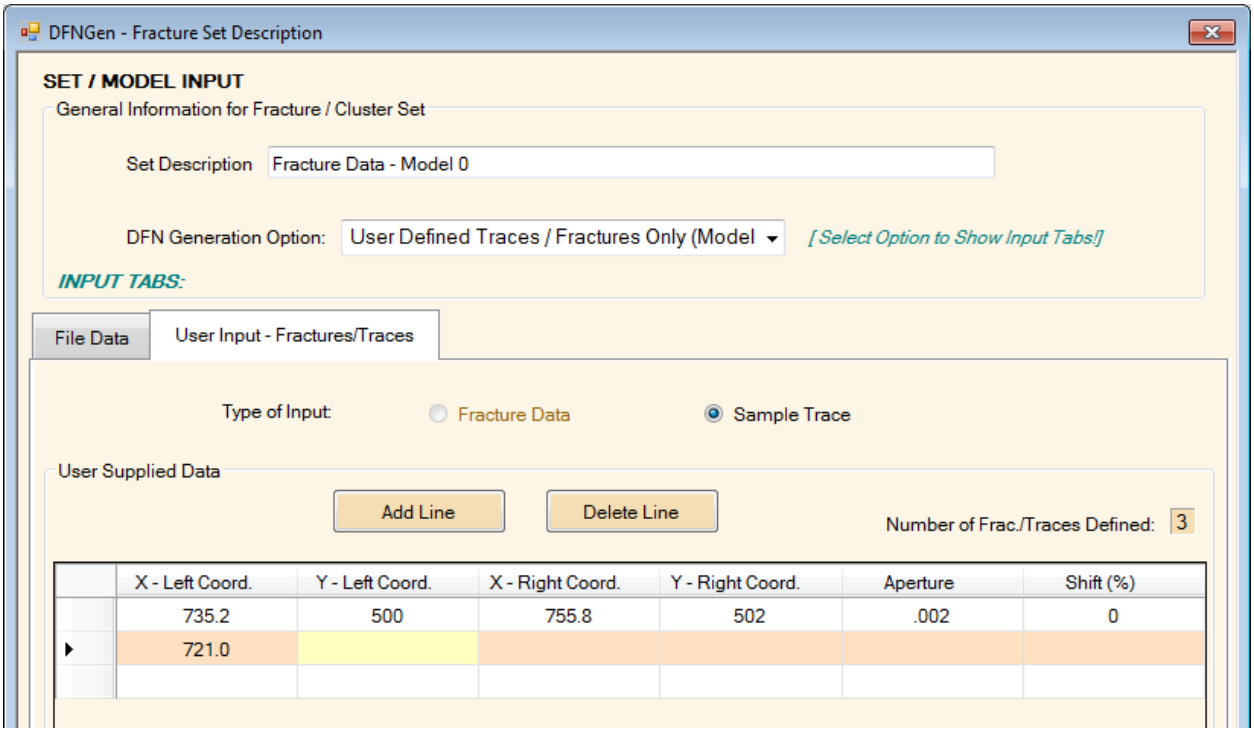

Figure 15: Fracture Model0 tabs ("User Input – Fractures/Traces" tab selected).

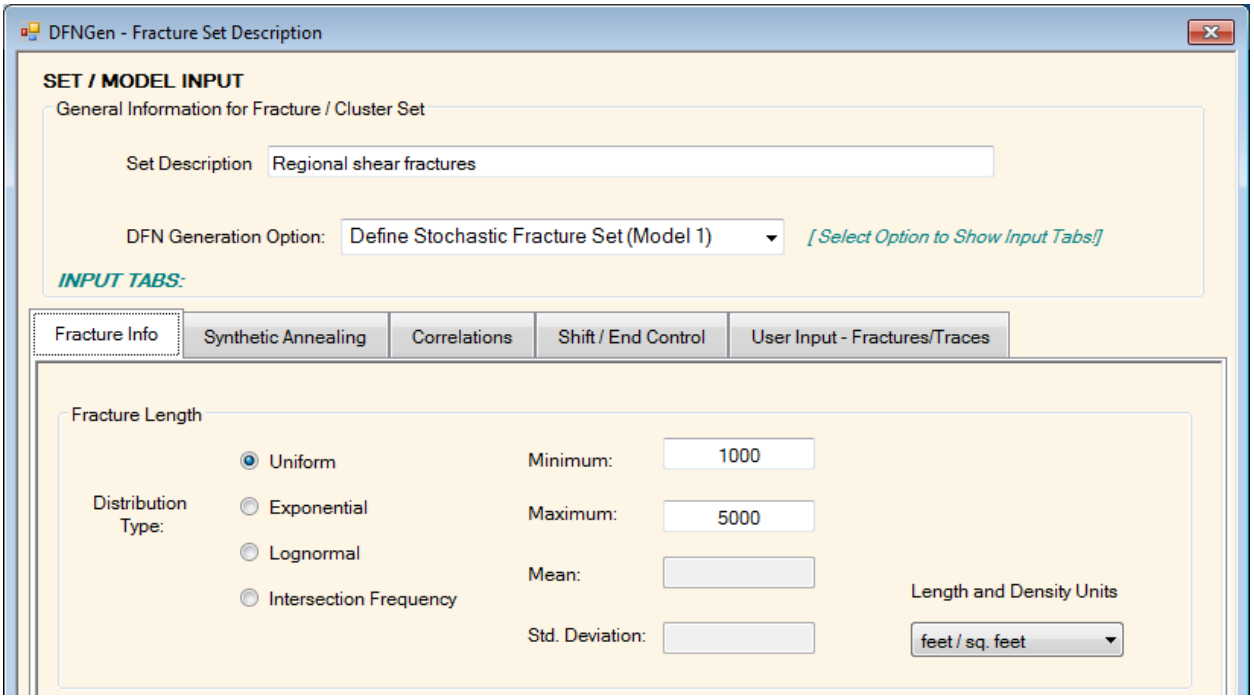

Figure 16: Fracture Model1 tabs ("Fracture Info" tab selected).

Parameter entry (text) boxes on a subform will also vary with the model selected and only the parameters relevant to the selected model are enabled; simply, input for one model option can differ from another on a subform with the same tab name. Further, entry boxes may be enabled (unlocked) or disabled (locked) based on the user selections during the entry process.

In more detail, Model1 provides a set of tabs to define all parameters for this model: a) "Fracture Info" for fracture set characteristics; b) "Synthetic Annealing" for controls on fracture generation and positioning; c) "Correlations" for the parameters defining user-selected correlations; d) "Shift/End Control" for fracture intersections/terminations; and e) "User Input – Fractures/Traces" for keyboard entry of fracture data.[21]

As mentioned, input on all subforms is conditioned to restrict input only into appropriate boxes based on selected input options. All other boxes are disabled on the form, depending on input options. For example, as shown in Figure 16, selecting a "Uniform" distribution type for fracture length (on the "Fracture Info" tab), will disable the "Mean" and "Std (Standard) Deviation" input boxes and allow input only into the "Minimum" and "Maximum" boxes immediately to the right of the selection.

In this regard, it is recommended that the user proceed from top to bottom for entry in a subform and proceed from left to right along the tab line in selecting tabs for additional input during the input process. However, the subforms will allow the user to input data for a specific model in any order desired. The user can also change the generation option selected for the entire fracture set, which will change the tab set.[22]

The set of tabs for Model2 are shown in Figure 17. Two new tabs are introduced ("Cluster Info" and "User Input – Clusters") and one tab is deleted ("User Input – Fractures/Traces"). The method of user input for clusters with this model is the same for the fracture input on Model1, but the input parameters have changed. Some of the parameters have also changed.

[21] Manual entry of fracture data is similar to the manual data entry for Model0 described earlier.

[22] In this case, data entries in many cases (but not all) will be deleted, and it is recommended that the user re-examine all entries after changing the generation option, if data have been defined previously for the fracture set.

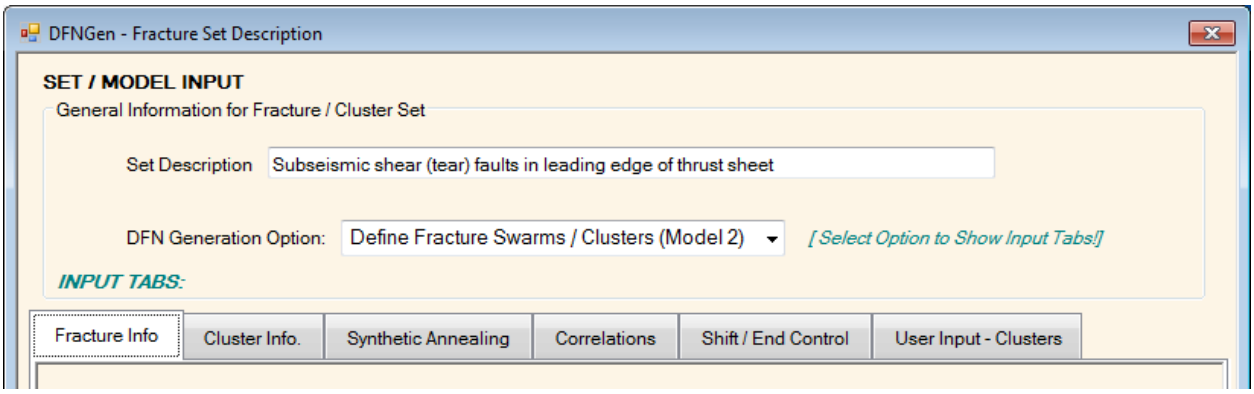

Figure 17: Fracture Model2 tabs ("Fracture Info" tab selected).

The set of tabs for Model3 are shown in Figure 18. The "Cluster Info" for Model2 is replaced with the tab, "Cluster Zones" and the "User Input – Clusters" is replaced with "User Input – Fractures/Traces". Again, some of the parameters have changed on the associated subforms for the model type.

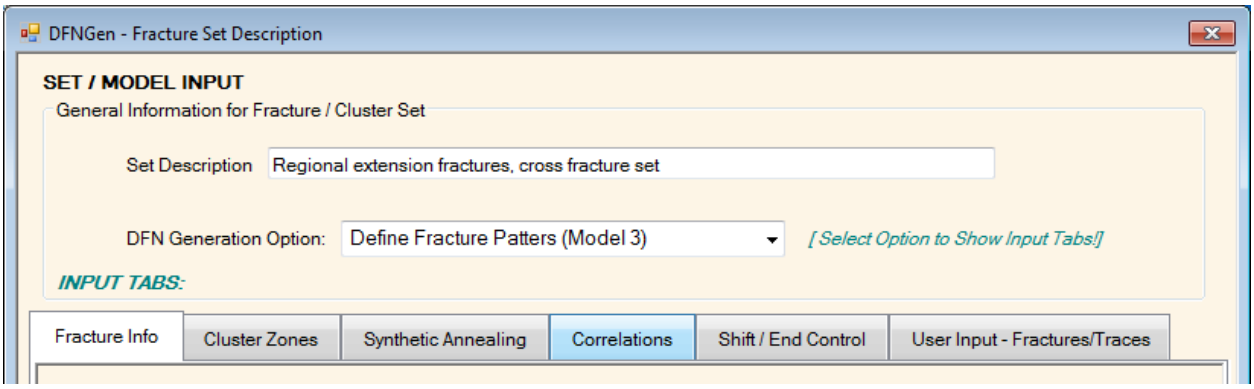

Figure 18: Fracture Model3 tabs ("Fracture Info" tab selected).

After data entry is completed for a selected generation option, the user selects one of the two control buttons on the lower right of the form: 1) Save & Exit; and 2) Cancel (e.g., see Figure 14). Hitting the **Save & Exit** button, the changes made on the particular form will be added to the current data base; selecting the **Cancel** button will close the form without saving.

6.4 ADDING WELLS

The aspect of defining wells in the FracGen record is in support of NFflow computations and will not influence fracture network generation by FracGen. This form is included for completeness in defining a FracGen input file. The Well form is shown in Figure 19.

The setup of Well form input is straightforward, requiring the definition of the total number of wells prior to allowing input of other variables of the well, and definition of the total number of laterals for a specific well before allowing the input of information for each lateral.

At first, a Well form without input (Figure 19) is locked except for the input box for the total number of wells and the units box (both at the top of the form). As a first step, the user should specify the units for the data fields using the units box. Then the user can start the input process. Input of the total number of wells to be input with this form enables (unlocks) the top half of the form on well information. This permits the user to define the basic information for well: the location (X-coordinate and Y-Coordinate), radius, depth, and relative depth.

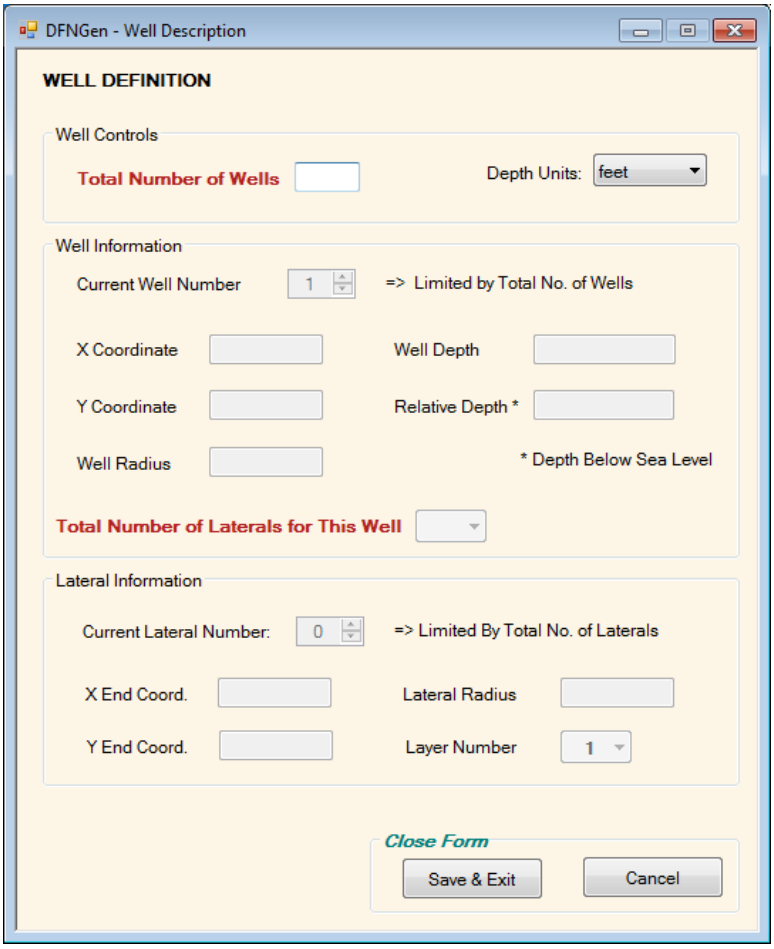

Figure 19: Well input form.

At this point, the user can enter the basic information boxes for Well #1, and then proceed with defining the same information for the remaining wells.[23] Increasing the count (scroll) box under "Current Well Number" provides a new set of text boxes for input; decreasing the count will show the prior input. It is recommended that the user first define the well information (i.e., the 5

[23] A maximum of 50 additional wells is allowed by the current version of FracGen; See Appendix D for array limits.

input boxes in the middle of the form, but not the total number of laterals for the well) for all wells, prior to defining the lateral information.

After specifying the basic information of each well, the user can proceed to defining the laterals for each well. At this point, the lower half of the form on laterals is locked. Before entering any data on the lower half of the form, the user must first specify the total number of laterals for the specific well.[24] This will unlock the lateral input boxes, and the user can enter the information for each lateral (X-coordinate and Y-Coordinate, radius, depth, and the layer number in which the lateral is located). Again, it is recommended that the information for each lateral is defined before moving on to the next well. However, the user can later revisit a well or lateral to specify missing data or correct an entry.

As with other forms, the user can close the form and save the new entries or changes by selecting the **Save & Exit** button, or close the form and discard any changes made on this form by selecting the **Cancel** button.

[24] A maximum of 10 laterals per well is allowed by the current version of FracGen; See Appendix D for array limits.

7. RUNNING FRACGEN

7.1 SINGLE-LAYER FRACGEN COMPUTATIONS

After defining the fracture network parameters for a layer, a FracGen analysis can be performed by the user using FracGen 14M. (Details on how this code was modified from version 6 of FracGen are provided in Appendix D.)

The basic operations associated with a FracGen computation are illustrated in Figure 20. Upon selecting the *Run>FracGen - Single* option, the parameters in current DFNGen forms are used to construct a single-layer input file, named "input1.txt" in the *.\programs* directory, and then the FracGen code is launched. FracGen will use this file for input. The input1.txt file has the same format as a *.fgn file.

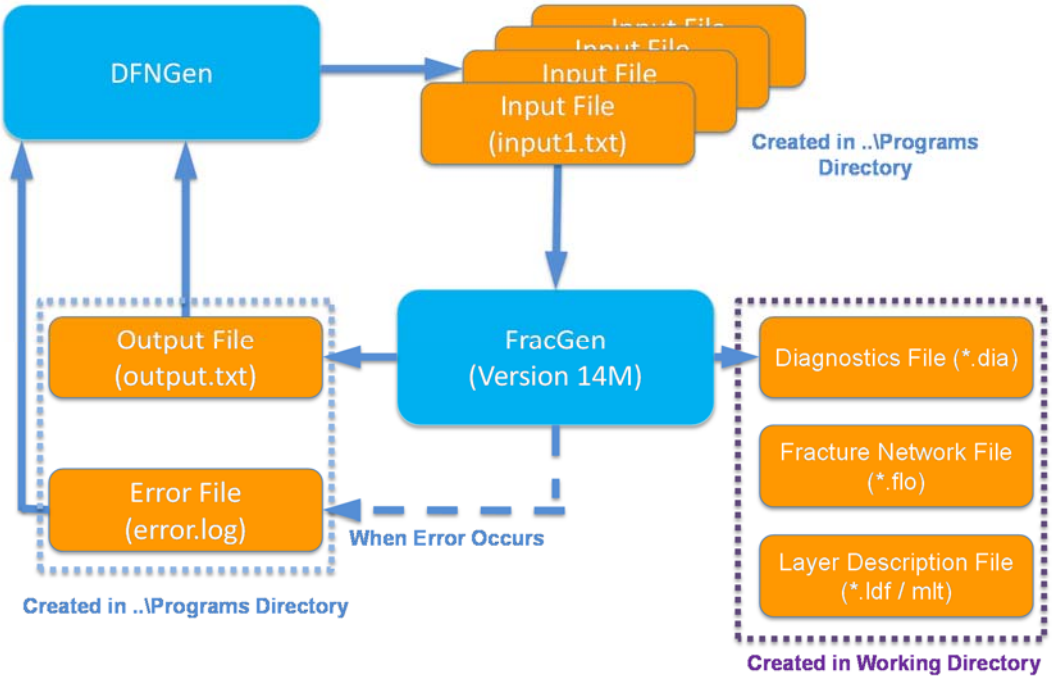

Figure 20: FracGen operations logic.

When FracGen starts its analysis, a small child window appears, indicating that FracGen has started (e.g., Figure 21). However, in many cases, especially for single-layer analyses, FracGen will conduct the analyses so rapidly that the user may not see it (or if the window is seen, the user may be unable to read the text). FracGen then performs a network analysis, and provides an output file for use by DFNGen. If an input or run error occurs during the run, FracGen will also produce an error log file. For a successful run, FracGen will create the selected external files in the user-defined working directory.

After the completion of the FracGen run, and when DFNGen has resumed control, another child window will appear informing the user of completion (Figure 22). After clicking on the OK button, the user can then employ the "Analyze" menu options in DFNGen to examine the results in the output.txt file, use the reporting files with FracOut, or employ the files with other computer codes such as NFflow.

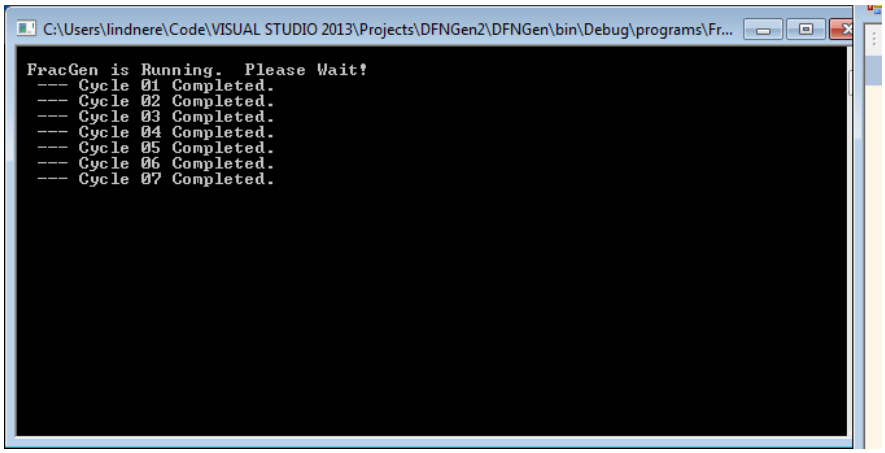

Figure 21: FracGen operations window.

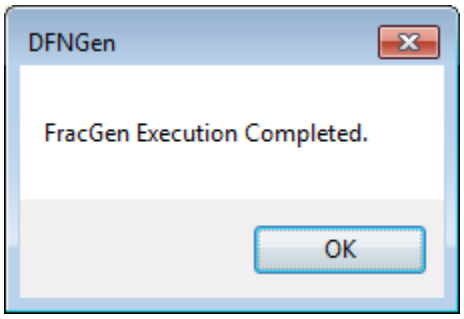

Figure 22: FracGen successful completion window.

7.2 MULTI-LAYER FRACGEN COMPUTATIONS

FracGen provides the option to model the fracture network for several adjacent geologic units with each unit described by a single layer file. Fractures in one layer can extend (or penetrate) from one layer to an adjacent layer. This is described in more detail in NETL (2014).

To conduct this multi-layer analysis using DFNGen, the user must first define all the layer files for the entire analysis and save each single-layer file as an *.fgn file. The user must indicate on each form that a multi-layer analysis is desired by checking (clicking on) the box to the left of the text, "Part of a Multi-Layer Description" on the Startup form.[25] The user must also indicate the total number of layers in the text box to the left of the label, "Number of Layers" on the Startup form. Of importance, only when the number of total layers is greater than one (1) on the Startup form, will the option boxes related to define fractures penetrating adjacent layers be

[25] See Figure 2.

visible on the Layer and Fracture form.[26]

After all the layer files are defined[27], the user can then select *Run>FracGen – Multiple* option from the Startup form menu. This will cause a new form to appear, the Multi-Layer form, as shown in Figure 23.

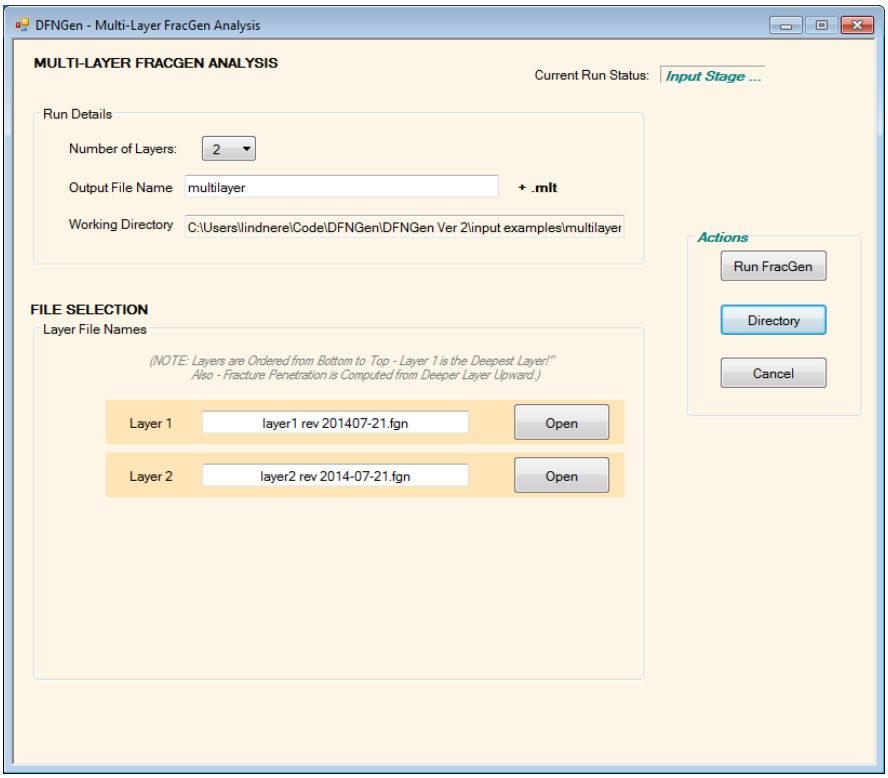

Figure 23: Multi-Layer form.

At the top right of the form is a status display box (to the right of the "Current Run Status" label), which displays the current status of the multi-layer analysis. This box will echo the status of the analysis process and indicate when a successful FracGen has been performed.

For the input stage, the first task is to designate the total number of layers[28] to be included in the analysis in the box near the top of the form. Selecting the desired number of layers will create the appropriate number of text boxes at the base of form for file name input. The user then should designate the prefix for output files (to the right of the "Output File Name" text). A default name

[26] The percent penetration is defined under the "Correlations" tab on the Fracture form.

[27] The user can select this option immediately after selecting a working file at the start of a DFNGen session, if all the layer files have been previously defined.

[28] A maximum of 5 layers is permitted by the current version of FracGen.

"multilayer" is supplied by DFNGen. The fracture network file will have a ".mlt" extension instead of ".flo" when generated, to indicate that the file contains more than one layer.

The next line on the form indicates the current working directory where input files are located and where output file will be created. The user can change the working directory by selecting the **Directory** button under the "Actions" heading on the right. The user can exit this form by selecting the **Cancel** button in this same location.

As the last input step, the user must indicate the layer files to be used in the multi-layer analysis. Using the text boxes at the bottom of the form, the user defines the layer files in the order from the bottom up, so that the deepest layer is defined first (line 1). The second deepest layer is defined as layer 2, etc.

To assist in defining a file name, selecting the **Open** button to right of a file name box will open a standard Windows file query form, allowing the user to select a file in the working directory. After the query window closes, the selected file name will be displayed in the box. Alternatively, the user can manually enter the file name and extension in the text box (assuming the working directory as the path name).

Upon completing the file name entry for each box, the user can then select the **Run FracGen** button (under the "Actions" heading) on the form to conduct an analysis. DFNGen will then check the file names, check the layer number and total number of layers on each form, and save the file as "inputX.txt," where X indicates the layer number (Figure 20). FracGen will then execute using these files for input.

After the completion of the FracGen run, and when DFNGen has resumed control, another child window will appear informing the user of completion, as for the single-layer analysis as shown in Figure 22 (if unsuccessful, an error message from FracGen will be in the box). Closing the message window, will also close the Multi-Layer form and restore control to the Startup form. After a successful completion, an output file with the combined fracture network definitions for all layers is available for use with the Analyze menu option.

7.3 MULTI-RUN FRACGEN COMPUTATIONS

FracGen can also conduct several sets of analyses using the same input file (a "multi-run" analysis). For each analysis or run with FracGen, a different set of variables is selected stochastically (as defined by the user parameters). The process of defining the input for a multi-run run is generally similar to a single-layer computation. One change in the input process is that the user must select the option for a multi-run analysis on the Startup Form under the "Controls" heading.[29] This is accomplished by checking the box to the left of the text, "Output Multiple Runs Using Same Input." The user must also indicate how many runs to perform in the text box to the left of the label, "Number of Additional Runs."

At this point, the user selects the FracGen single option run (*Run>FracGen – Single*) from the Startup windows menu bar, and the FracGen will conduct the specified number of analyses. As for other FracGen analyses, at completion of a successful run, a child window will inform the

[29] The Controls heading is shown in Figure 2.

user (Figure 22). If the run was unsuccessful, the FracGen error will appear in a similar message box. After selecting **OK**, the box will close and restore the Startup window.

As part of this process, the user should note that each set of output files will be named using the prefix label (see Section 5.1) and the run number. Simply stated, if the user inputs "Rock" as a prefix, the tenth file set will all be named, "Rock10" with the appropriate file extension. Thus, the user is encouraged to use a short prefix label (15 characters or less) for these analyses. In addition, prior to selecting this option, the user should ensure that there is sufficient space on the file system for the number of files to be created.

In displaying the resulting network data, the user will be limited to examining the fracture network from only the last run with the DFNGen analysis options (*Analyze*). To examine the data from other runs, the user will need to employ FracOut (*Run>FracOut*) and examine output files in the working directory where the multi-run output was created.

8. DATA ANALYSIS

8.1 DFNGEN GRAPHICS

DFNGen provides several options to analyze the 2-D stochastic fracture network generated by FracGen. The graphic displays for these options are based on Windows graphics design interface (GDI+) graphics functionality available with Microsoft's Net Framework 4.5. This graphics library was directly incorporated into the C# code generated for DFNGen.

For each display selected by the user, DFNGen draws the results on the console in real time directly for examination by the user. The GDI+ functionality also allows for creating a bitmap (*.bmp file) of the image that can be saved by the user. At the top left of each analysis form in DFNGen is a *Save* option, which when selected, will allow the user to save the image shown on the console. It will also allow the user to save the underlying subset of the network data used in generating the image as a text file.

8.2 ANALYSIS OPTIONS

The "Analyze" options incorporated into DFNGen are:

1. Display the fractures in the flow region
2. Evaluate the distribution of fracture lengths
3. Evaluate the fracture orientation distribution using a rose diagram
4. Count the number of intersections
5. Compute fracture spacing distances along a user-defined scan line
6. Display and evaluate the density of fracture centers within the flow region

With each option, the user can examine single layer and multi-layer analysis results generated by FracGen but the forms can only examine one layer at a time.[30] However, the user can select a specific combination of fracture sets to examine for a selected layer.

DFNGen uses the "output.txt" file generated by FracGen 14M as the data source for all displays for these analyses. This source file is located in the *.\programs* directory of DFNGen, and DFNGen will examine only the current version of this file. If the user has previously conducted a FracGen run, the user can examine this network immediately after starting DFNGen by selecting the Analyze option from the Startup form menu (without selecting a working directory on the Startup form or without having just completed a run with DFNGen) as long as the output.txt file is present. DFNGen, however, deletes the output.txt file at the start of every new FracGen analysis, so only the most recent data from a successful FracGen analysis can be examined. Further, if a FracGen run fails (provides an error message), no output.txt file is generated and the

[30] For multi-run FracGen analyses, only the last, single-layer network generated can be examined.

prior file is no longer available for analysis.[31] Selecting an Analyze option when no output file is present will produce an error message box.

The following sections briefly describe and illustrate each analysis option.

8.3 SELECTING LAYERS AND FRACTURE SETS FOR DISPLAY

In conducting any analysis option with DFNGen, the user must first select the specific layer to display (only one layer is displayed at a time). This choice is provided in the upper left corner of each form, using a drop-down scroll box (e.g. Figure 24). Selecting the box will provide a drop-down list of layers from which to make a choice; the user can select one of the options. The layer choices shown; however, are limited to the number of layers in the output source file.

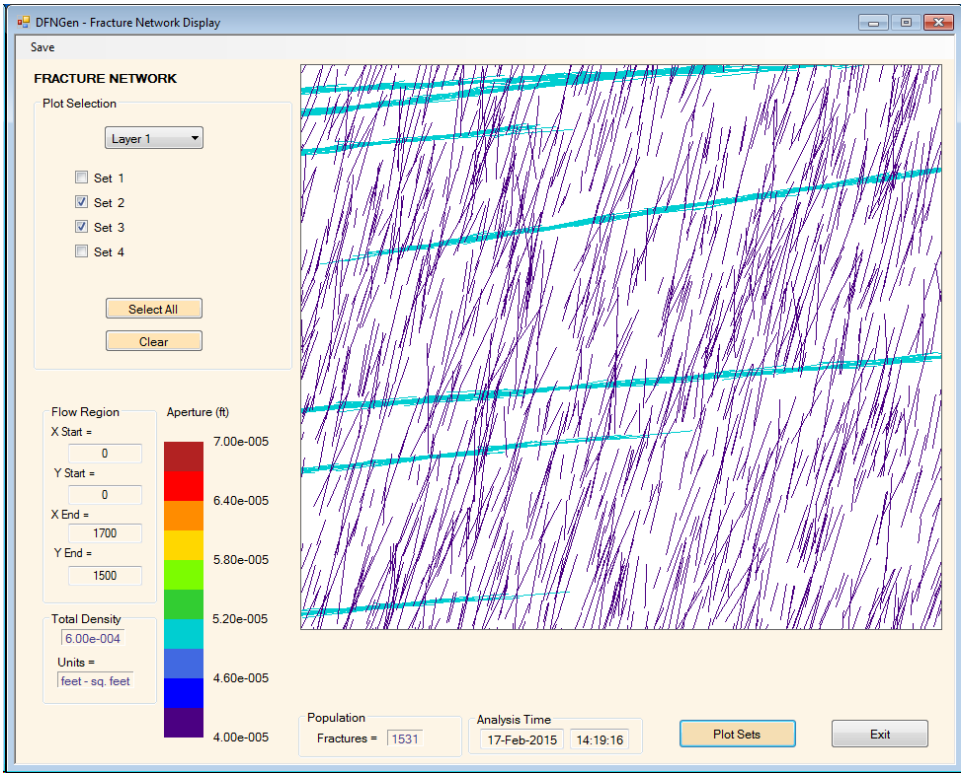

Figure 24: Network display with the Fracture Network form.

Directly below this box is a set of check boxes and two control buttons (at the upper left of the form). The user selects a fracture set for display by checking the check box next to the appropriate set number (the order for display is the same as input for the analysis). If all sets are desired, the user can check all boxes by selecting the **Select All** button. Similarly, the user can clear all check marks on the form by selecting the **Clear** button.

[31] DFNGen does not currently support the ability to save the output file or open a prior output with a different file name.

8.4 FRACTURE NETWORK ANALYSIS

DFNGen provides a graphical display of the 2-D network using the Fracture Network form (as illustrated in Figure 24). The form is displayed by selecting *Analyze>Display Network* from the Startup form menu.

Upon form creation, the plot area (the box at the right side of the form) is blank. The user must first select the specific layer and some or all of the fracture sets (as used to generate the network) of this layer to display. Then the user selects the **Plot Sets** button (at the lower right of the form) to generate an image.

The plot area rectangle in the display is sized based on the region area so the display is to scale. Each fracture is colored based on the fracture aperture value, according to the color scale shown at the lower left of the form. The extent of the flow region is also provided numerically in the display (left of the color scale), together with the overall density of the network and units of fracture length. Also shown along the base of the form, are the number of fractures in the display and the time and date of the FracGen analysis run.

The user can save the results to a graphics format (.bmp file) or to a text file using the *Save* menu option. The user can also select another layer and group of fractures and again select the **Plot Sets** button to realize another result. By selecting the **Exit** button in the lower right, the user closes the form and returns to the Startup form.

8.5 LENGTH DISTRIBUTION

DFNGen provides a bar chart of fracture lengths using the Length form (illustrated in Figure 25). The form is displayed by selecting *Analyze>Analyze Distributions>Length* from the Startup form menu.

As for other display forms, the plot area (the box at the right side of the form) is blank upon form creation. The user must first select the specific layer and some or all of the fracture sets (as used to generate the network) of this layer to display. Then the user selects the **Plot Lengths** button (at the lower right of the form) to generate the chart.

The total number of fractures shown in the chart and units of fracture length are shown in the bottom left corner of the form. In addition, the time and date of the FracGen analysis run are shown in the upper right corner. The user can save the results to a file or to a text file using the *Save* menu option. The user can also select another layer and group of fractures and again select the **Plot Sets** button to realize another result. By selecting the **Exit** button in the lower right, the user closes the form and returns to the Startup form.

8.6 ORIENTATION DISTRIBUTION

DFNGen provides a graphical display of the fracture orientation of the network using a modified rose diagram. The Rose form (illustrated in Figure 26) is initiated by selecting *Analyze>Analyze Distributions>Orientation* from the Startup form menu.

At creation, the form will display a framework for the rose diagram, with North at the top of the form, and 15° grid lines to the east and west for a semicircle (i.e., +/- 90° from North). It may be observed that this grid is atypical from a rose diagram frequently used in geospatial analyses. A rose diagram is typically a circular polar area plot, which displays the orientation of fractures as a circular frequency chart, based on the strike and dip of the fracture.

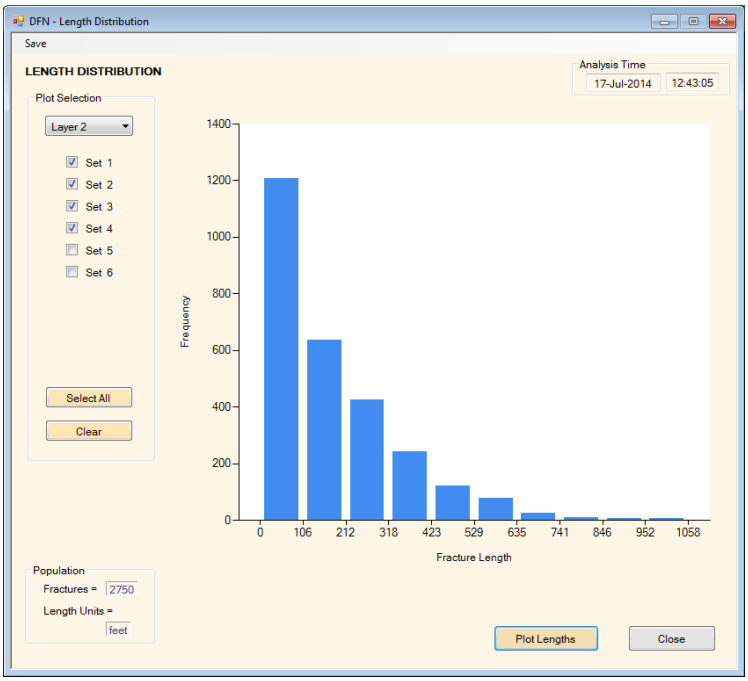

Figure 25: Analyze distribution – fracture lengths with the Length form.

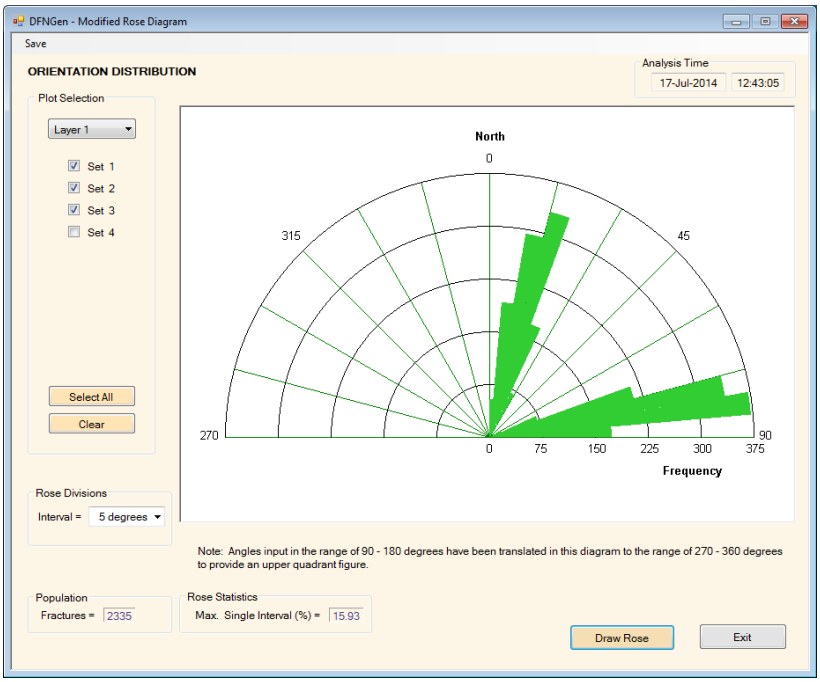

Figure 26: Analyze distribution – fracture orientations with the Rose Diagram form.

However, the fracture network from FracGen is limited to near vertical fractures (i.e., with ~90° dip) and actual strike and dip information is not generated. To display fracture orientation, a

modified projection is employed; for efficiency, this projection limits the display of orientation to the semicircular region of +/- 90° from North. The orientation of a fracture is taken as the shorter (absolute) arc measured from North, with + designated as a positive (clockwise) arc.[32]

To create an orientation chart, the user must first select the specific layer and specific sets to display (as discussed earlier). The user can also modify the range or width of the segments displayed on the form. Using the "Divisions" scroll box at the lower left corner of the display area, the user can define the width of a division on the rose plot by selecting the size of the section in degrees of arc. The user can select 1°, 2°, 5° and 10° of arc for each segment (division in the plot. Selecting the **Draw Rose** button will provide a rose diagram for the parameters chosen.

The rose diagram form will also display the total number of fractures in the distribution and the maximum number of fractures in a division (in percent) along the base of the form. The time and date of the FracGen analysis run are shown along the top right of the form.

Again, the user can save the results to a graphics file or to a text file using the *Save* menu option, specify another set of parameters and re-plot the diagram using the **Draw Rose** or select the **Exit** button to close the form and return to the Startup form.

8.7 INTERSECTION DISTRIBUTION

DFNGen provides a frequency chart of the number of fracture intersections along a fracture line for all selected fractures, using the Intersection form (illustrated in Figure 27). The form is displayed by selecting *Analyze>Count Intersections* from the Startup form menu.

As for other display forms, the plot area (the box at the right side of the form) is blank upon form creation. The user must first select the specific layer and some or all of the fracture sets to display. Then the user selects the **Plot Data** button (at the lower right of the form) to generate the chart.

A frequency chart is then created, dividing intersection frequency into ten groups, with the first nine groups incrementally ranging from 1 to 9, and with the last group of 10 or more (10+) intersections. Additional statistics for the chart are shown numerically directly below the plot area: total number of fractures and the total number of intersections. In addition, the time and date of the FracGen analysis run are shown in the upper right corner.

As with other forms, the user can save the results to a graphics file or to a text file using the *Save* menu option, specify another set of parameters and replot the diagram using the **Plot Data** or select the **Exit** button to close the form and returns to the Startup form.

---

[32] For example, a generally east-west trending fracture (line) can have an arc of 100° measured clockwise from North; it will also make an 80° arc measured counterclockwise. The shorter arc is measured in a negative (counterclockwise) direction, and therefore, the fracture is plotted at -80° (80° to the left or west of North).

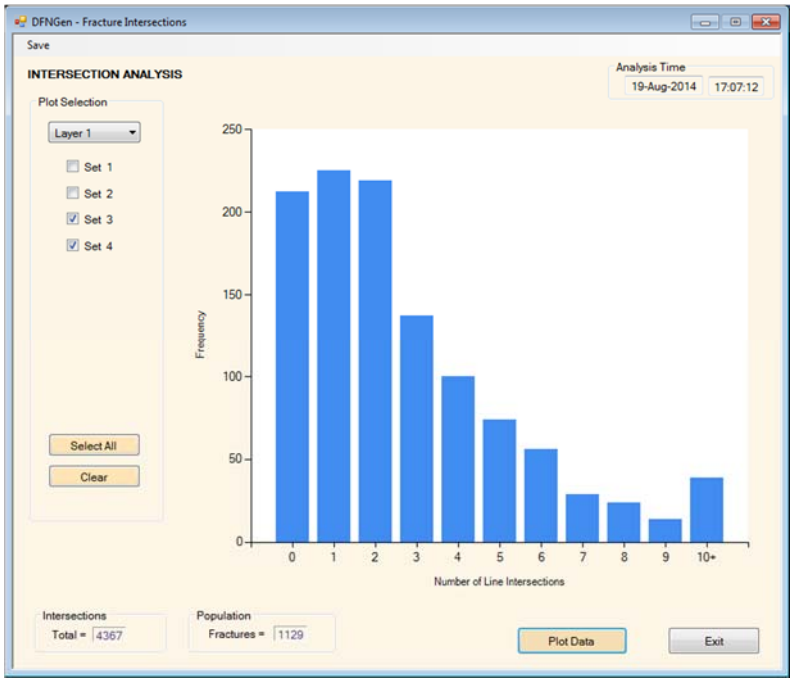

Figure 27: Number of intersections distribution with the Intersection form.

8.8 SCAN-LINE DISTRIBUTION

DFNGen provides a fracture-spacing frequency chart along a user defined (scan) line across the fracture region using the Scan form (illustrated in Figure 28). The form is displayed by selecting *Analyze>Compute Scan Lines* from the Startup form menu.

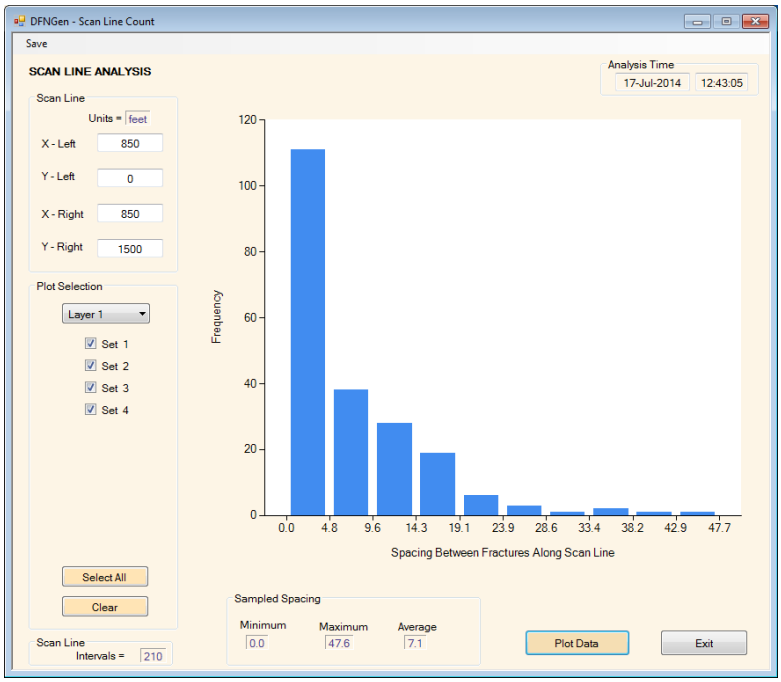

Figure 28: Scan line fracture spacing frequencies with the Scan form.

For this plot, the user first must select the reference or scan line along which the intersections and the spacing's will be computed. The X and Y coordinates of the two points defining the scan line are input using the text boxes at the left of the plot area. The user must also select the specific layer and some or all of the fracture sets (as used to generate the network) for the analysis. Then the user selects the **Plot Data** button (at the lower right of the form) to generate the chart.

A frequency chart is then created, dividing the spacing-frequency into ten groups or ranges based on the maximum spacing between fractures along the scan line. The spacing statistics for the chart are shown numerically directly below the plot area: minimum, maximum, and average spacing between fracture intersections along the reference line. In addition, the total number of intersections is shown in the lower left corner, and the time and date of the FracGen analysis run are shown in the upper right corner.

As with other forms, the user can save the results to a graphics file or to a text file using the *Save* menu option, specify another set of parameters and replot the diagram using the **Plot Data** or select the **Exit** button to close the form and returns to the Startup form.

8.9 FRACTURE CENTER DISPLAY

This option provides for a graphical display of the fracture centers of fractures of the network. The Center form (illustrated in Figure 29) is initiated by selecting *Analyze> Determine Areal Density* from the Startup form menu. The operation and controls used with this form are similar to the fracture network form (Network form) described in Section 8.3.

Upon form creation, the plot area (the box at the right side of the form) is blank. The user must first select the specific layer and some or all of the fracture sets (as used to generate the network) of this layer to display. Then, the user selects the **Plot Centers** button (at the lower right of the form) to generate an image.

The center point for each fracture in the selected network is shown with a 10 x 10 grid overlay with red lines in the plot area box. The average density of the centers on a per grid block basis is provided, together with maximum and minimum density values, the area of each grid block and the units used. In this display, the overall plot area rectangle is sized based on the region area, so the display is to scale. The number of fractures in the display and the time and date of the FracGen analysis run are also shown along the base of the form.

The user can save the results to a file or to a text file using the *Save* menu option. The user can also select another layer and group of fractures and again select the **Plot Centers** button to realize another result. By selecting the **Exit** button in the lower right, the user closes the form and returns to the Startup form.

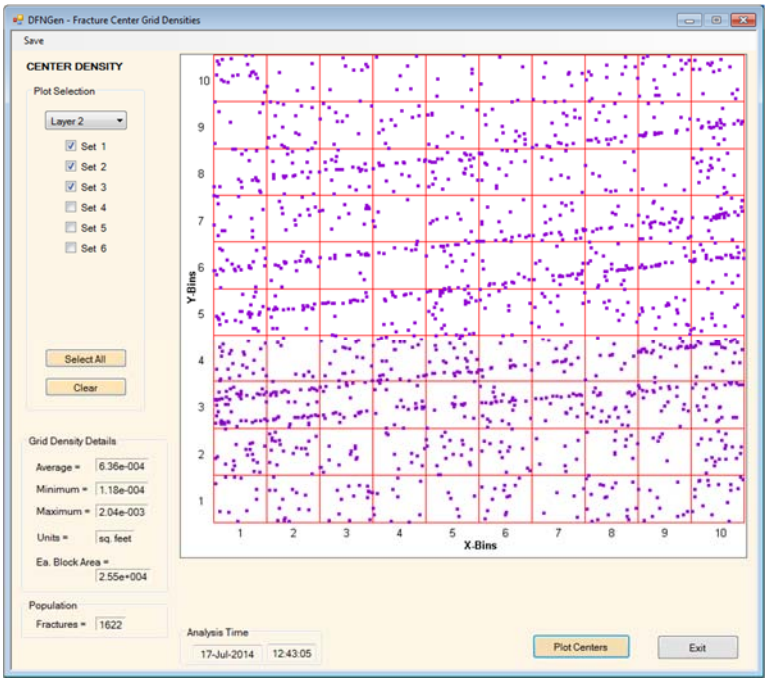

Figure 29: Areal density of fracture center points with the Center form.

9. ADDITIONAL TOOLS - ANCILLARY CODES

A set of ancillary codes included with DFNGen can be accessed from the Tools menu on the Startup form (*Tools*). As noted Section 4.4, only six of the ancillary codes described in NETL (2014) are implemented. All these codes are written in Fortran and compiled separately.

Upon selecting a menu item, the code will run in a separate window as an independent console application (e.g., Figure 30) and will respond only to keyboard input. The user can exit this window by clicking on the exit button on the top right of the form (red box with the "X" label), or entering control-C from the keyboard.

The ancillary codes and their implementation are not described in this manual, and the reader is referred to NETL (2014) for further details. However, a short description of each of the ancillary codes is provided in Appendix E and is available from the Help menu of DFNGen (*Help>Help Topics*).

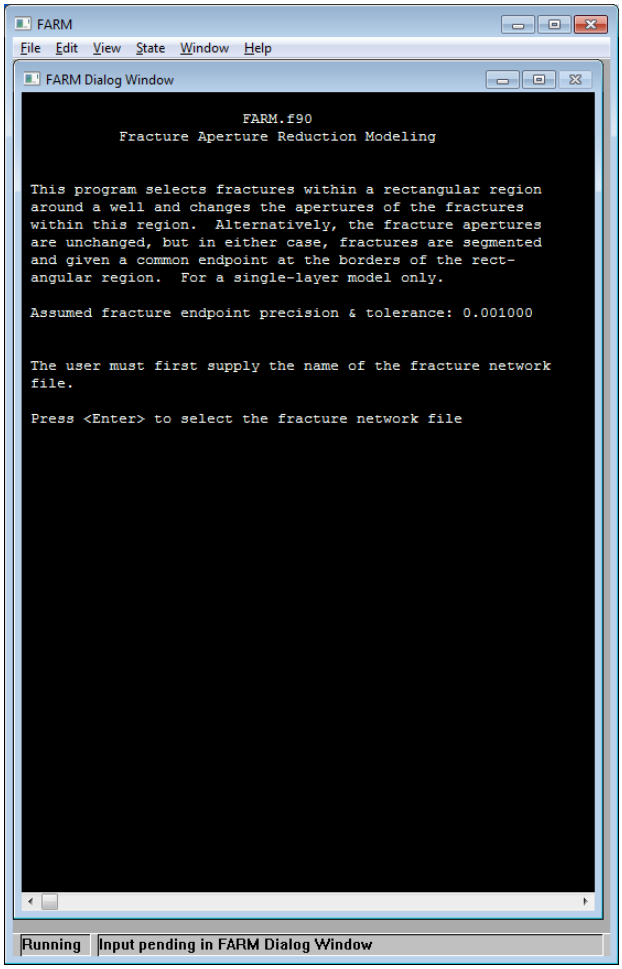

Figure 30: FARM code analysis window.

10. RUNNING FRACOUT

10.1 GENERAL

As described in NETL (2014), FracOut is a stand-alone graphics display program originally developed by James H. Dean, and modified by Phillip Nicoletti and Seth King. The main body of the program was written in Fortran and uses OpenGL, a multi-platform application programming interface for rendering 2-D and three-dimensional (3-D) vector graphics. A Windows form interface was developed to select the files for plotting and provides controls for changing the display output. For the current application, the Windows interface has been modified slightly to mate with DFNGen.

The FracOut program was developed to visually examine the output files from both the FracGen and NFflow computer codes. In this regard, the FracOut sub-form has two different modes, which change the controls shown on the form:

1. Aperture plot, which is utilized for, output files from FracGen output files
2. Pressure plot mode is used to examine NFflow output files

10.2 IMPLEMENTING FRACOUT

As employed in DFNGen, FracOut is used to display a fracture network from FracGen using a higher resolution graphics package, which allows rotation, and other display options not included in the DFNGen analysis options. The user can implement the FracOut code from the DFNGen Startup window menu (*Run>FracOut*). After selecting this menu option, the FracOut form appears (Figure 31). The aperture mode of FracOut is shown by default for use with FracGen files (as indicated by the radio button at the top of the form), together with the working directory path from DFNGen in the "working directory" text box.

The user first selects the layer description file (*.ldf file) file path to be used for plotting. As with other file input, the user can employ a standard Windows query to locate the file by selecting the **Select File** button or input the file name manually from the keyboard (including the entire file path to the file). Then, the user must identify the working directory path in a similar fashion by selecting the **Select Folder** button or again from the keyboard. The entire path name is required in this case as well.

Upon selecting the working directory, all available fracture network files (*.flo or *.mlt files) in the working directory will appear in the file operation box in the lower half of the FracOut form. At this point, the user highlights a file name in this box to plot and selects the **Plot** button at the base of the FracOut form, and three FracOut windows will appear.

The three FracOut windows shown are: 1) the code operations (Command) window; 2) the Plot window; and 3) the Plot Menu. These windows are shown in Figure 32 and 33. The Command (console window) displays the operations for FracOut and is not directly manipulated by the user to produce/change the graphic plot; it will be displayed in the background. The Plot window displays the fracture network in color in the center of the window. The Plot Menu window provides a list of keyboard commands that the can used, and the user can close this window at any point (the key codes and mouse commands in this window are also shown in Tables 1 and 2).

The user can then change the image in the plot window using the keyboard commands shown in the plot menu. For example, the user can use the ***I*** and ***O*** keys to zoom into or out of the plot area. Hitting the **Home** key will restore the plot to the original view. Right clicking on the mouse when over the plot window will echo the coordinates of the mouse cross in the Command window. Hitting a number key (*1* to *5*) will hide or show the fracture data for the respective layer number. In addition, a bitmap image of the plot file can also be produced by hitting the *B* key.[33]

After completing an examination of a selected network, the user can exit this display stage by closing either the Command window or the Plot window, which is performed by clicking on the X on the top right corner of either window. The user can also exit the display stage by selecting the Command window, and then hitting *control-C*. In either case, the Command and Plot windows will close and the Plot Menu window will remain open and the FracOut form is on top again. The user can then select another file to plot, or change the input to plot another set of files in the FracOut form.

At completion of using FracOut, the user selects the **Exit** button at the base of the FracOut form. This action will close both the FracOut form and Plot Menu form (if visible), and return control to the Startup form.

[33] FracOut does not echo the completion of this file operation. The resulting *.bmp file is created in the working directory, and the path name is indicated (in whole or part) in the code operations window.

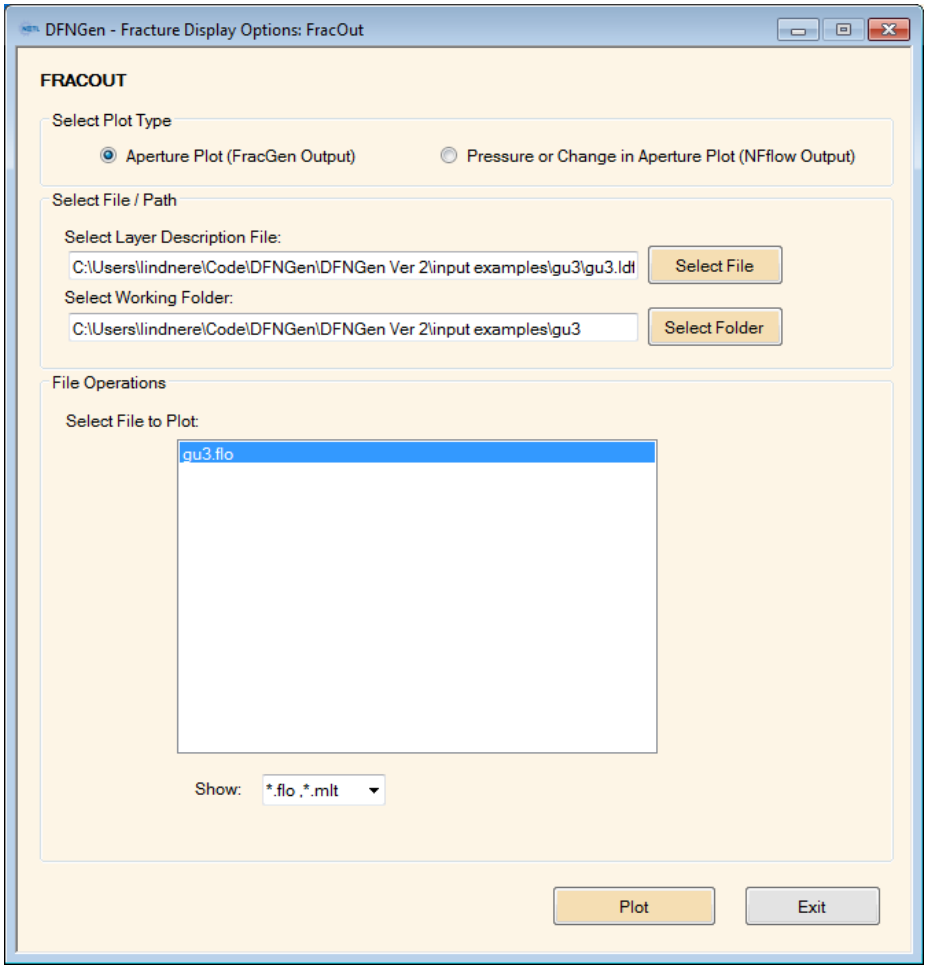

Figure 31: FracOut input window.

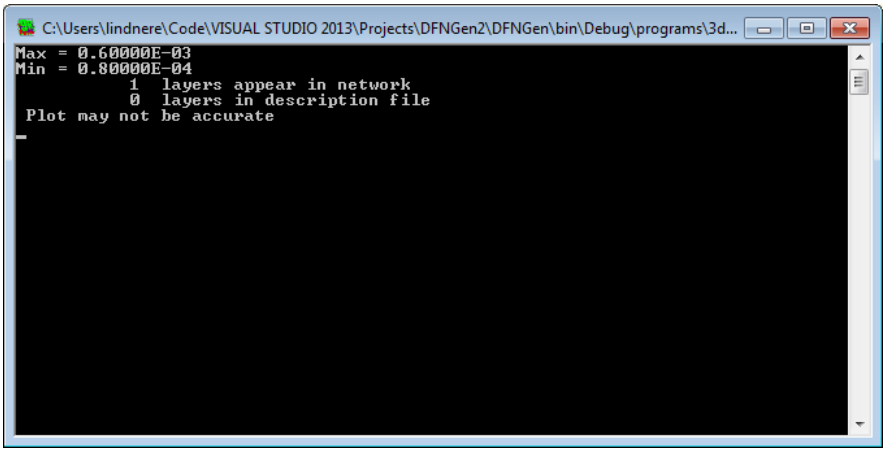

Figure 32: FracOut operations (Command) window.

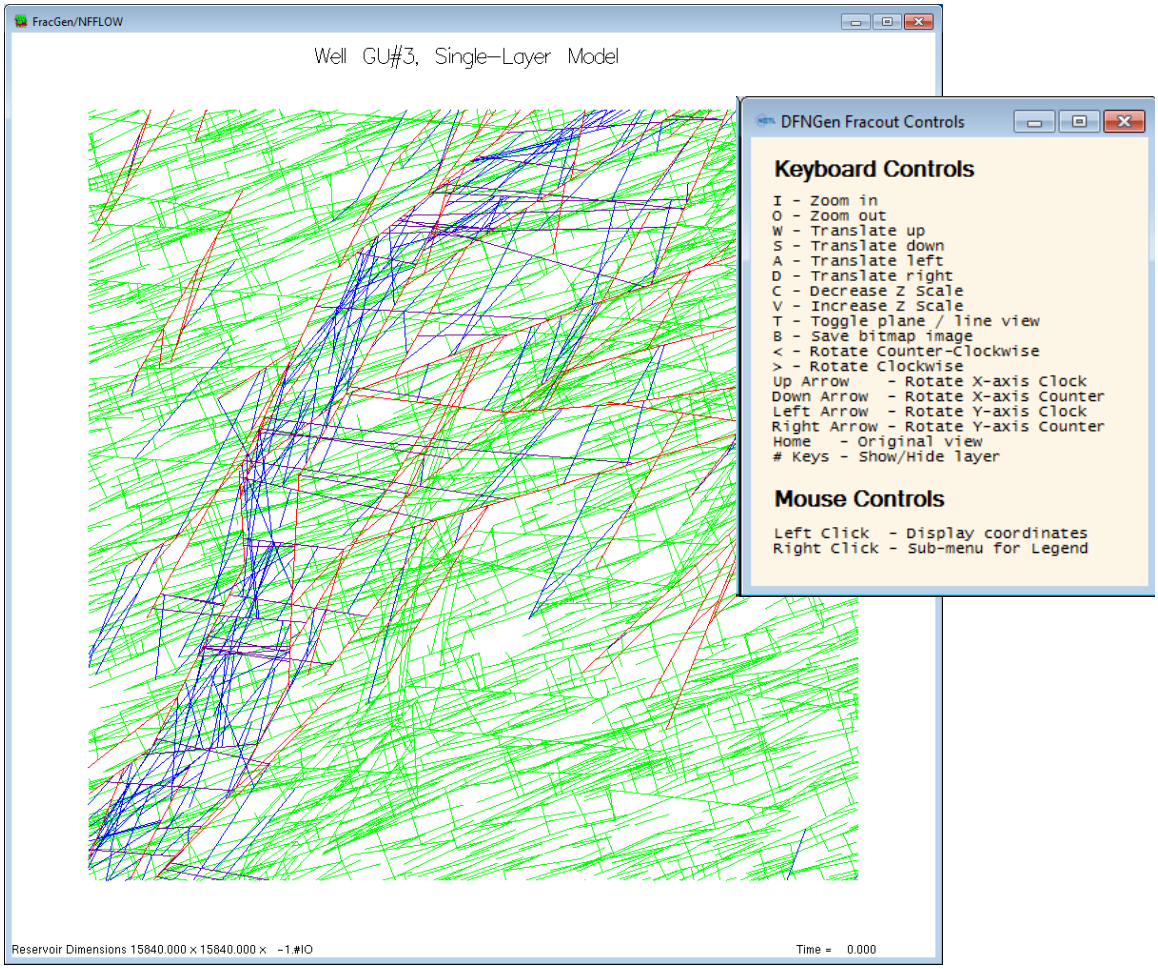

Figure 33: FracOut Plot and Plot Menu windows.

Table 1: Applicable FracOut control commands using keyboard

Key	Action/Function
I	Zoom in (+)
O	Zoom out (-)
W	Translate Up
S	Translate Down
A	Translate Left
D	Translate Right
C	Decrease Z-exaggeration/Scale
V	Increase Z-exaggeration/Scale
T	Toggle Line/Plane View
B	Save Bitmap Image
<	Rotate Counter-Clockwise
>	Rotate Clockwise
Up Arrow	Rotate on X-axis Clockwise
Down Arrow	Rotate on X-axis Counter-Clockwise
Left Arrow	Rotate on Y-axis Clockwise
Right Arrow	Rotate on Y-axis Counter-Clockwise
Home	Restore Original Plan View
Number Keys (1 to 5)	Show or Hide Layer (Number)

Table 2: FracOut mouse commands

Mouse Control	Action/Function
Left-Click	Display Coordinates
Right-Click	Submenu for Legend

11. CONCLUSIONS

The DFNGen code provides for a Windows-based interface to several computer codes related to the discrete fracture network computer program FracGen. As described, DFNGen provides for error checking and implements simple controls to develop the input file for FracGen 14M and provides analysis tools to examine the resulting fracture network to assist in user understanding. It also implements several ancillary codes for related network computations to develop needed data or modify the resulting network. Overall, it is concluded that DFNGen can broadly assist the novice user with the use of FracGen and support further research of stochastically-generated fracture networks in general.

In the future, it is anticipated that FracGen and DFNGen will be expanded to allow for additional fracture generation models (e.g., to simulate semi-parallel joint systems and more complex fracture swarms), include non-planar layer geometry, incorporate more high resolution graphics capabilities, and perhaps, be expanded to 3-D modeling.

This document provides only an abbreviated summary of the underlying models in FracGen, and the reader is encouraged to become familiar with the *FracGen & NFflow: Naturally-Fractured Natural Gas Reservoir Simulator, User's Guide* (NETL, 2014) prior to generating any fracture system for analysis purposes. The user should also manually inspect the *.fgn files generated by DFNGen for any potential errors to provide a second check before relying on FracGen results.

Please note that DFNGen code and this documentation are provided "As is" without warranty of any kind, express or implied, including but not limited to the warranties of merchantability, fitness for a particular purpose and non-infringement. In no event shall the authors or copyright holders be liable for any claim, damages or other liability, whether in an action of contract, tort or otherwise, arising from, out of or in connection with the software or the use or other dealings in the software.

This is the initial issue of the user's guide for DFNGen. It is expected that this guide and the associated software will be modified to further enhance usability, address comments, and to correct errors or omissions. Therefore, this guide should be considered a "living document" that may evolve over time to reflect the changing circumstances. Comments or suggestions on the code or documentation should be provided to c/o Predictive Geosciences Division at NETL. Contingent on available resources and budget, as the document and software are refined, its interactive role on the NETL website will be used to maintain a living document with routine and continual improvement. Hard copy versions of the guide will not be routinely maintained.

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APPENDIX A: WINDOW FORMS IN DFNGEN

A.1. General

DFNGen employs a number of Microsoft forms specially created for input and control. The main forms in DFNGen are:

1. About form: describes the background information for the code
2. Center form: provides for the display of the centers of generated fractures
3. FracOut form[34]: controls the selection of files for running the 3d3.exe code
4. FracOut control (Command) form[34]: provides a menu of the control keys for the graphic display by 3d3.exe
5. Fracture form: provides for input of fracture set data for each of the fracture model options in FracGen
6. Help form: provides a short description of the ancillary codes under the Tools menu option
7. Intersection form: provides for the computation of fracture intersections, and bar-chart display of results
8. Layer form: provides for the entry of layer information; it also opens the Fracture form for the entry of fracture set data
9. Length form: for the display of the centers
10. Multi-layer form: provides for the entry of the layer forms to be used in multi-layer FracGen analyses and associated information
11. Network form: for the display of the network fractures
12. Rose diagram form: for the display of the fracture orientation (a modified rose diagram)
13. Scan form: provides for the computation of distances between fracture along a line, and a bar-chart display of results
14. Splash form: provides the user with the version number and copyright
15. Startup form: main form, which provides for entry of controls flags and the coordinates of the flow region, and opens the Layer form and Well form
16. Well form: provides for the entry of data on wells

[34] Text and formats on the form were modified from original version.

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APPENDIX B: DFNGEN FILES

B.1. General

The files needed for DFNGen operation are briefly described in this section. Files formats used for a specific file type defined in *FracGen & NFflow: Naturally-Fractured Natural Gas Reservoir Simulator, User's Guide* (NETL, 2014) (e.g., with the extension ".flo") are unchanged in use with DFNGen.

B.2. Input and Output Files Used by DFNGen

A series of files are related to conducting analyses with DFNGen, FracGen and NFflow. A list of the most common files is described in Table B-1. The input file with the extension ".fgn" was specially constructed for use with DFNGen, and supersedes the prior FracGen input file with a ".dat" extension described in NETL (2014). In addition, the version of FracGen (14M) developed for use with DFNGen no longer uses several files as shown in the listing.

There are also several files created by DFNGen and used by FracGen 14M, which are introduced to enable FracGen to operate as a stand-alone executable code in the background. These files (see Table B-2) are termed "reserved" as they are created and deleted by DFNGen without direct input from the user. The files are located in the *.\programs* directory in a text format and can be viewed using a standard editor. In the event of a computer interruption or crash, the user is advised to delete the files before starting new analyses.

B.3. Application Files Used by DFNGen

DFNGen implements a number of stand-alone computer codes developed by others (NETL, 2014). A list of these programs is shown on Table B-3 and are available under DFNGen menu options *Run* or *Tools*.

B.4. *.fgn File Format

The file format for a *.fgn file (the input file for FracGen 14M) is shown in Figure B-1. The FILE format is a free format (column location is not specified) with spaces as delimiters between entries. For the most part, the data is structured with a pair of two lines for each input set, with a descriptor line followed by an associated data line. For example, in Figure B-1, the first line, starting with "FILE IDENTIFICATION: (<= 80 CHARACTERS)" is a descriptor, followed by the second line, a data string, "Well GU#3, Single-Layer Model..." On reading this file, the FracGen code discards the descriptor line and only retains the pertinent variables on the data line.

When there are several entries for a single variable set, the format becomes a header line, followed by the array of data, with a single set on each line. For example, near the bottom of Figure B-1, the line, " X-LEFT Y-LEFT X-RIGHT Y-RIGHT WIDTH SHIFT(%) PERCENT" is the descriptor, followed by a several data lines, as for example, " -2864.1 -1285.9 -1402.8 730.6 0.000600 0.0 0.0", with one line of data for a single fracture.

The general format of the *.fgn file remains constant for each application, with only the data lines changing (a "template" type of approach). While this format lends itself to editing an input

file with a text editor for another analysis, it can be somewhat confusing for the inexperienced user unfamiliar with the parameters. For the user who prefers a more in-depth view, the DFNGen code is provided with a series of example problems in the *.fgn format, which have been modified from NETL (2014). These can be used as template files for the user with a text editor.

The *.fgn file format was modified from the *.dat file described in NETL (2014) for the use with DFNGen and the modified FracGen 14M. While the data entry lines for model descriptions remain the same in both file formats, the initial lines of *.fgn file differ from the *.dat format, as highlighted in Figure B-1.

In more detail, the changes are:

- At the start of a *.fgn file (after the first two lines for the project title), the *.fgn file provides for the input of a reduced set of control flags (previously incorporated in FracGen into as a separate file, fracgen.flg)
- After the control flag input, a pair of lines is included in the *.fgn file to describe the prefix variable used to name output files and a pair of lines for input of a default input directory
- The *.fgn format also requires input of a separate flag variable for multiple runs and the number of multiple runs desired[35]
- The *.fgn file also requires the default units for the FracGen run. As NFflow currently assumes U.S. standard (English) units, it is suggested that the user employ these units in performing FracGen computations
- Rather than providing the dimensions of the flow region, the *.fgn format requires the user to input the bottom left x-y coordinates and the upper right coordinates of the flow area, assuming a rectangular region
- Finally for multi-layer analyses, the *.fgn format requires the total number of layers in the analysis and the current layer number[36]

B.5. output.txt File Format

The file format for the output from FracGen 14M (output.txt) is shown in Figure B-2. It is similar to the *.flo file described in NETL (2014) with the exception of the second line which contains differing data (highlighted in Figure B-2).

[35] The output files created for multiple runs will use the prefix designation and append the run number to the name. For example, the 10th simulation with the prefix "GUA", the flow file output is "GUA10.flo."

[36] In conducting multi-layer analyses with DFNGen, these lines will be altered in accordance with the input form in creating the inputX.txt files used by FracGen to eliminate any numbering errors (where X = 1.n files).

The second data line is defined as follows, with the variable type in square brackets:

1. Lower left x coordinate of the flow region [double]
2. Lower left y coordinate of the flow region [double]
3. Upper right x coordinate of the flow region [double]
4. Upper right y coordinate of the flow region [double]
5. Control flag indicating variable units (0 = us) [integer]
6. Number of layers [integer]
7. Run time [string]
8. Run date [string]

This file is used by DFNGen for data analysis options, but it was not intended for use outside the *.\programs* directory, and is overwritten with every analysis. If the user wishes to save this file format for a specific analysis, the file must be saved in another directory or with a different file name in the *.\programs* directory before starting another FracGen analysis with DFNGen.

Table B-1: Files Related to FracGen and DFNGen Codes

File Name / *.Extension	Description / Purpose
*.fgn file	FracGen input file: a formatted text file created and used by DFNGen to perform FracGen analyses. File format can be saved and opened by DFNGen. The file format is shown in Figure B-1.
*.flo file	Flow network data file created by FracGen, which contains fracture data for a single-layer fracture network.[37] File is created in the working directory defined by user.
*.ldf file	NFflow layer description file created by FracGen to describe the upper and lower boundaries of each layer and properties.[37] File is created in the working directory defined by user.
*.mlt file	Flow network data file created by FracGen, which contains fracture data for a multi-layer fracture network.[37] File is created in the working directory defined by user. Format is similar to *.flo file.
*.dia file	FracGen diagnostics file created by FracGen to provide a list of network and run diagnostics for the FracGen computation.
*.dat files	External text file, employed by prior versions of FracGen for input.[37] Format of this file is similar to a *.fgn file but differs in several important aspects.
fracgen.fi	File used by prior version of FracGen to define arrays and variables as an include file.[37] Not used by FracGen 14M.
fracgen.flg	File used by prior version of FracGen to define various control options.[37] Not used by FracGen 14M.
fracgen.inp	File used by prior version of FracGen to define last directory used by code.[37] Not used by FracGen 14M.

.

[37] The file and file format for this file are discussed in FracGen/NFflow User's Manual (NETL, 2014).

Table B-2: DFNGen Reserved and Temporary Files[38]

File Name / *.Extension	Description / Purpose
help.rtf	Reserved formatted text file, which contains the descriptions of the Ancillary computer programs implemented by DFNGen under the Menu *Tools* option. Text is from NETL (2014). File is included in DFNGen help form when running.
Input1.txt	Reserved file created by DFNGen for input to FracGen 14M for single layer analysis. Format is identical to *.fgn files. File is deleted by DFNGen prior to the start of each analysis run by FracGen.
Input2.txt, input3.txt, input4.txt, input5.txt	Reserved files created by DFNGen for input to FracGen 14M for multiple-layer analysis. Format is identical to *.fgn files. Files are deleted and replaced by DFNGen prior to the start of each analysis run by FracGen.
output.txt	Reserved file, created by FracGen 14M, which contains a list of all fractures from computation. File is used by analysis options in DFNGen under the Menu *Analyze* option. The file is located in .*programs* subdirectory, and is deleted by DFNGen prior to the start of each analysis run by FracGen. The file format is shown in Figure B-2.
error.log	Reserved file, created by FracGen 14M if an error occurs. It is a text file with two strings, which explain the error encountered. File is read and then deleted by DFNGen at the completion of a FracGen analysis, if present. Error messages are discussed in NETL (2014).
prior_directory.txt	Reserved file created by DFNGen for tracking to define last working directory used by code.
scratchC.dat	Temporary scratch file generated by FracGen.
scratchF.dat	Temporary scratch file generated by FracGen.
Fracout.inp	Reserved file created by FracOut and contains the file path for the *.flo and *ldf files used in the prior analysis.
flowfile.inp	Reserved file created by FracOut and contains the file path for the *.flo file used in the prior analysis.
resolut.inp	Reserved file created by FracOut and contain screen resolution control parameters.

[38] All reserved files are created and located in the .*programs* directory.

Table B-3: Executable Files Used by DFNGen[39]

File Name / *.Extension	Description / Purpose
FracGen-14M.exe	Modified version of the FracGen code; the original code is described by NETL (2014). The code generates a network of discrete fractures in 2-D, to represent a horizontal plane through a series of vertical fractures.
3d3.exe	Part of the FracOut sequence of codes, the code draws the fracture network and allows for manipulation of the image. It is also used for depicting NFflow analyses.
BHP.exe	Ancillary code. Calculates bottom-hole static or flowing fluid pressures for gas wells from surface static or flowing fluid pressures, respectively, using the method of Cullender and Smith (1956).
ClusDen.exe	Ancillary code. Calculates various cluster parameters including the expected intra-cluster fracture density (at specified locations along the left end of a cluster), correction factors and the intra-cluster fracture center-point density.
EXPmean.exe	Ancillary code. Calculates the geometric mean and shape factor for a special truncated exponential distribution given the mean and either the minimum or maximum value of the distribution.
FARM.exe	Ancillary code. Selects fractures within a region around a well and changes the apertures of the fractures within this region.
Kappa.exe	Ancillary code. Calculates the fraction (or weight) that upon multiplication with the intra-cluster fracture center-point density in lognormal fracture length distribution provides the weighted average center-point density in the regions of reduced density at each end of a cluster. This parameter is the "κ" term in equations 16 and 17 of McKoy and Sams (1997).
logSTAT.exe	Ancillary code. Calculates data statistics including the lognormal mean and a lognormal standard.
spa_L.exe	Ancillary code. Calculates the frequency of spacing falling within defined class intervals and the cumulative percent frequency distribution based on the locations of fractures as encountered along a one-dimensional (1-D) sample line or bore hole.

[39] All these codes are located in the .*programs* subdirectory, and are written and compiled in the Fortran computer language. They are discussed in FracGen/NFflow User's Manual (NETL, 2014).

```
FILE IDENTIFICATION: (<= 80 CHARACTERS)                                    FRACGEN 14th EDITION
  Well GU#3, Single-Layer Model
 COMPUTATION FLAGS - FLAG1 FLAG2 FLAG3 FLAG4
     1    1    1    0
 PREFIX NAME FOR OUTPUT OPTIONS
  gu3
 WORKING DIRECTORY FOR RUN
  C:\Users\lindnere\Code\DFNGen\DFNGen Ver 2\input examples\gu3
 OPTION TO PRODUCE MULTIPLE RUNS WITH SAME INPUT
     0    0
 UNIT SYSTEM FOR OUTPUT  0 = US UNITS; 1 = METRIC UNITS
     0
 X & Y COORDINATES OF FLOW REGION - LOWER LEFT CORNER
        0.000        0.000
 X & Y COORDINATES OF FLOW REGION - UPPER RIGHT CORNER
    15840.000    15840.000
 NUMBER OF LAYERS FOR ENTIRE COMPUTATION
     1
 LAYER NUMBER
     1
 EFFECTIVE DEPTH OF MID-LAYER; EFFECTIVE THICKNESS OF FRACTURED LAYER
    14509.000      18.000
 NUMBER OF SETS IN LAYER
    10
  MODEL TYPE------------------------------------------------------------ SET 1
     0
  SET IDENTIFICATION (< 80 CHARACTERS)>)
   Fracture Data - Model 0
  NUMBER OF SAMPLE TRACES (OR BOREHOLES)
      0
     X-LEFT    Y-LEFT   X-RIGHT   Y-RIGHT     WIDTH  SHIFT(%)

  NAME OF DATA FILE FOR INTERSECTED FRACTURES

  MODEL TYPE------------------------------------------------------------ SET 2
     1
  SET IDENTIFICATION (< 80 CHARACTERS)>)
   Seismically-resolved faults, interpretation of May 1999
  FRACTURE ORIENTATION DISTRIBUTION, MEAN AND SDEV (0 = UNI)
      0      0.00      0.00
  FRACTURE LENGTH DIST. (0=UNI,1=EXP,2=LOG,3=INT), MIN/MEAN AND MAX/DEV
      0         0.000         0.000
  FRACTURE APERTURE DISTRIBUTION, MEAN AND STD DEVIATION
      0    0.00000000    0.00000000
  DENSITY OF FRACTURE CENTER POINTS
    0.0000000000
  CORRELATIONS (len=F(order), ori=F(len), wid=F(len))
       0.00      0.00      0.00
  MAXIMUM PERCENT FRACTURE SHIFT: MODE I, II, III
       0.00      0.00      0.00
  SYNTHETIC ANNEALING CONTROLS (pstart,nswaps,swapl,ifreq)
     100.00      0     0     0
  RELATIVE FREQUENCIES OF T-TERMINATIONS (T2,T1)
       0.00      0.00
  FRACTURE INTERSECTION FREQUENCIES (%): ZERO TO 10+ INTERSECTIONS
     0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
  PERCENT FRACS PENETRATING OVERLYING LAYER; CORRELATION TO FRAC LENGTH
       0.00     0.00
  NUMBER OF USER-SUPPLIED FRACTURES
     31
     X-LEFT    Y-LEFT   X-RIGHT   Y-RIGHT     WIDTH  SHIFT(%)  PERCENT
    -2864.1   -1285.9   -1402.8     730.6  0.000600      0.0       0.0
    -1402.8     730.6    1285.9    2717.9  0.000600      0.0       0.0
     1285.9    2717.9    3214.8    6487.9  0.000600      0.0       0.0
```

Note:

[a] Lines in red are not included in the *.dat file input.

Figure B-1: Example of *.fgn File Format.

```
Well GU#3, Single-Layer Model
      0.00       0.00   15840.00   15840.00        0       1    10:49:50    22-Jul-2014
    X-left    Y-left   X-right   Y-right Aperture  Layer    Set  Number
     0.000  1767.452  1340.348  2758.144 .600E-03      1      1       1
  1307.241  2759.610  3204.403  6467.578 .600E-03      1      1       2
  3097.800  8416.801  3215.965  6468.689 .600E-03      1      1       3
  3100.496  8422.566  4997.500 12479.101 .600E-03      1      1       4
  5068.912 12536.079  7744.600 14671.000 .600E-03      1      1       5
  7756.220 14680.418  9186.902 15840.000 .600E-03      1      1       6
  1332.492     0.000  2937.945  1786.691 .600E-03      1      1       7
  3040.154  1901.107  4107.568  4036.034 .600E-03      1      1       8
  4119.869  4039.884  4179.200  5640.400 .600E-03      1      1       9
  4179.200  5640.400  4327.925  8349.541 .600E-03      1      1      10
  4356.201  8354.211  5289.700  9994.900 .600E-03      1      1      11
  5289.700  9994.900  6517.201 12216.101 .600E-03      1      1      12
  6517.200 12216.101  7774.080 14729.963 .600E-03      1      1      13
  6500.651 12205.509 12179.657 15840.000 .600E-03      1      1      14
  5186.636  9957.584 10374.938 11836.113 .600E-03      1      1      15
 10283.158 11804.731 14922.634 13391.098 .600E-03      1      1      16
  5205.018 10004.556  8621.400  9615.000 .600E-03      1      1      17
  8621.400  9615.000 10930.202  9790.400 .600E-03      1      1      18
 10933.157  9790.825 15840.000 10494.394 .600E-03      1      1      19
 11150.030  9758.384 13758.855  9378.426 .600E-03      1      1      20
  5318.901  6867.901 13900.796  9340.617 .600E-03      1      1      21
 13893.175  9336.942 15840.000  9959.015 .600E-03      1      1      22
  4178.163  5639.283  5318.902  6867.902 .600E-03      1      1      23
  5321.520  6870.080  8621.412  9615.009 .600E-03      1      1      24
  8706.629  9683.188  9644.201 10433.301 .600E-03      1      1      25
  9635.477 10431.044 15840.000 12036.089 .600E-03      1      1      26
 10850.069   610.316 13449.519  4967.868 .550E-03      1      2      27
 14817.960 10347.848 15840.000 12506.714 .550E-03      1      2      28
 15188.416 10400.966 15840.000 11269.807 .550E-03      1      2      29
  9595.660  5333.177 12690.847 10042.852 .550E-03      1      2      30
  1622.077 11572.345  3496.103 15840.000 .550E-03      1      2      31
   165.292  7595.937  4984.140 12450.530 .550E-03      1      2      32
   118.753  1855.226  2459.114  5010.926 .550E-03      1      2      33
  2466.160  8522.545  4086.849 10531.773 .550E-03      1      2      34
```

Note:

[a] Line in red is different in the *.flo file format.

Figure B-2: Example of output.txt File Format.

APPENDIX C: FRACGEN VARIABLES

C.1. General

Table C-1 provides a list of parameters used in FracGen Version 14M to provide operational controls, describe the flow region and define the fracture layer. Table C-2 provides a listing of the parameters used in the various fracture models, with a filled box indicating which parameter is used in the specific model. Note that "Model0" is not a fracture model per se, but rather provides for the input of fractures from separate files.

Table C-1: FracGen Version 14M - General Parameters

Parameter Description	FracGen Variable
General	
Analysis Title/Descriptor	IDheader
Control Settings: Produce Fracture Network File Produce Diagnostics File Produce layer Description File Conduct Multi-Layer Analyses	 Iflag1 Iflag2 Iflag3 Iflag4
Prefix Text Used in Creating Files	prefix
Working Directory	WorkingPath
Control Flag for Multiple Runs	Iflag_multiple
Number of multiple Runs to Be Performed	Number_runs
Flow Region	
Bottom Left Corner X Coordinate	xleft
Bottom Left Corner Y Coordinate	yleft
Upper Right Corner X Coordinate	xright
Upper Right Corner Y Coordinate	yright
Layer Data	
Total Number of Layers in Analysis	numlayers
Specific Layer Number for Current FracGen Run	layer
Layer Depth for Current Layer	depth
Layer Height for Current Layer	height
Number of Fracture Sets in Current Layer	nsets

Table C-2: FracGen 14M - Model Parameters for Each Generation Option

No.	Parameter Description	FracGen Variable	Model0	Model1	Model2	Model3
1	*Sample Traces/Boreholes*					
	Number of User-Defined Traces	ntraces				
	Intersected Fractures File Path (Separate Text File)	Fracfile				
	Intersected Fractures File - Data	Ut(j), Uxy(j), ori, Uw(j), Ul(j), nstat(j) Uo(j)				
	User-Defined Traces (6 variables)	Txl(j), Tyl(j), Txr(j), Tyr(j), Tw(j), shift(j)				
2	*Title*					
	Set Identification	heading				
3	*Set Orientation*					
	Fracture Orientation - Mean	formean				
	Fracture Orientation - Standard Deviation	sdevfo				
4	*Cluster Orientation*					
	Cluster Orientation - Mean	cormean				
	Cluster Orientation - Standard Deviation	sdevco				
5	*Fracture Length*					
	Fracture Length - Distribution Type	lendist				
	Fracture Length Distribution - Minimum/Mean Length (Parameter #1)	paramL1				
	Fracture Length Distribution - Maximum/Std. Dev. (Parameter #2)	paramL2				

Table C-2: FracGen 14M - Model Parameters for Each Generation Option (continued)

No.	Parameter Description	FracGen Variable	Model0	Model1	Model2	Model3
6	*Cluster Length*					
	Cluster Length - Distribution Type	lendistC				
	Cluster Length Distribution - Minimum/Mean Length (Parameter #1)	paramL3				
	Cluster Length Distribution - Maximum/Std. Dev. (Parameter #2)	paramL4				
7	*Aperture*					
	Facture Aperture - Mean (Parameter #1)	fwidem				
	Facture Aperture - Standard Deviation (Parameter #2)	sdevw				
8	*Intra-Cluster Cluster Spacing*					
	Mean Intra-Cluster Cluster Spacing	spacing				
9	*Location/Density*					
	Density of Fracture Center Points	density				
10	*Intra-Crustal Fracture Density*					
	Intra-Crustal Fracture Density - Mean	fracdenm				
	Intra-Crustal Fracture Density - Standard Deviation	sdevfd				
11	*Cluster Density*					
	Density of Cluster Center Points	clusdens				

Table C-2: FracGen 14M - Model Parameters for Each Generation Option (continued)

No.	Parameter Description	FracGen Variable	Model0	Model1	Model2	Model3
12	*Clustering Parameters*					
	Subzone Partition Control	degX				
	Longitudinal Position Control – Parameter 1	degY				
	Longitudinal Position Control – Parameter 2	typeY				
13	*Cluster Zone Dimensions*					
	Cluster Zone Width	Wz				
	Cluster Zone Length	Lz				
14	*Correlations*					
	Length as a Function Order of Generation	rcoefL				
	Orientation as a Function of Length	rcoefO				
	Aperture as a Function of Length	rcoefW				
	Spacing as a Function of Length	rcoefP				
	En-Echelon Step	latstep				
15	*Fracture Shift Modes*					
	Mode I - Maximum Percent Fracture Shift	shf(iset,1)				
	Mode II - Maximum Percent Fracture Shift	shf(iset,2)				
	Mode III - Maximum Percent Fracture Shift	shf(iset,3)				
16	*Cluster Shift Modes*					
	Mode I - Maximum Percent Cluster Shift	shf(iset,4)				

Table C-2: FracGen 14M - Model Parameters for Each Generation Option (continued)

No.	Parameter Description	FracGen Variable	Model0	Model1	Model2	Model3
17	*Synthetic Annealing Controls*					
	Percentage of Fractures Generated Before Synthetic Annealing Process Begins	pstart				
	Target Number of Swaps for Each Fracture in Synthetic Annealing	nswaps				
	Maximum Number of Swaps for Each Fracture in Synthetic Annealing	nswapl				
	Number of Orientation Changes Before Translating the Fracture Center Point	ifreq				
18	*Relative Frequencies of T-Terminations*					
	T1 Type	T1				
	T2 Type	T2				
19	*Stipulated Fracture Intersection Frequency*					
	0 Intersection	Ei(iset,1)				
	1 Intersection	Ei(iset,2)				
	2 Intersections	Ei(iset,3)				
	3 Intersections	Ei(iset,4)				
	4 Intersections	Ei(iset,5)				
	5 Intersections	Ei(iset,6)				
	6 Intersections	Ei(iset,7)				
	7 Intersections	Ei(iset,8)				
	8 Intersections	Ei(iset,9)				
	9 Intersections	Ei(iset,10)				
	10 or More Intersections	Ei(iset,11)				

Table C-2: FracGen 14M - Model Parameters for Each Generation Option (continued)

No.	Parameter Description	FracGen Variable	Model0	Model1	Model2	Model3
20	*Layer Penetration*					
	Penetration of Overlying Layers (%)	perct				
	Correlation of Penetration to Fracture Length (%)	coefL				
21	*User-Supplied Fractures*					
	Number of User-Supplied Fractures	numfracs				
	User-Supplied Fracture Data (7+C3 variables)	Vxl(j), Vyl(j), Vxr(j), Vyr(j), Vw(j), Vs(j), Vp(j)				
22	*User-Supplied Clusters*					
	Number of User-Supplied Clusters	numclust				
	User-Supplied Cluster Data (7 variables)	Vxl(k), Vyl(k), Vxr(k), Vyr(k), Vw(k), Vs(k), Vp(k)				
	User-Supplied Cluster Zone Data (6 variables)	Wxl(k), Wyl(k), Wxr(k), Wyr(k), Wd(k), Ww(k)				

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APPENDIX D: DEVELOPMENT NOTES

D.1 FRACGEN MODIFICATIONS

DFNGen implements a modified version of FracGen to conduct analyses. The version used by DFNGen (termed, FracGen Version 14M) was modified in 2014 from FracGen Version 6 dated April 14, 2004. Note that tracking of computer program version numbers has recently changed from sequential numbering to a year-based version numbering; hence the current version is designated as 14M.

The modifications to the FracGen code in version 14M did not impact the computational aspects of the code but rather altered only the input and run options of the code. This is to permit DFNGen to run the code in a background mode without direct interaction between the two codes.

Specifically, these changes include:

- Modification of the input format to read the *.fgn file format rather than the *.dat file format
- Deletion of all console-echo write statements and QuickWin controls
- Re-direction of all error messages to a new error file
- Modification of input controls (flags) to reflect external DFNGen control flags
- Elimination of the separate control file (i.e., fracgen.flg), which defines operational control, flags (parameters: iflagA, iflagB, iflagC, iflagD, iflagE, iflagF, iflagG, iflagH and iflagQ)
- Elimination of the separate FracGen include file (i.e., fracgen.fi), which contains the dimension of arrays for fracture attributes
- Change of the file name of the file containing the prior directory from "fracgen.inp" to "prior_directory.txt"
- Addition of subroutines for reading input and producing output, and addition of a subroutine to construct time and date strings
- Addition of variable declarations in most subroutines (and use of the IMPLICIT NONE command) to eliminate implicit variable definitions
- Addition of several comment statements to clarify specific points in code operation

All changes were written in free format and the resulting code compiled with a Fortran 2003 complier.

D.2 FRACGEN LIMITS

The limits in arrays and input strings in the current version of FracGen are shown in Table D-1.

D.3 DEVELOPMENT ENVIRONMENT

This version of DFNGen was developed on a desktop personal computer running Microsoft© Windows 7, Service Pack 3 with an Intel® Xeon® CPU E5-2670, running at 2.6 gigahertz and with 16.0 gigabytes of random access memory. Screen resolution is 1920 x 1080.

The DFNGen code was written in Visual C# as a Windows Form application under NetFramework 4, using the Microsoft© Visual Studio Professional 2013 environment, Version 12.0.21005.1 Release. The Fortran codes used by DFNGen are written in Fortran using Intel® Visual Fortran Composer XE 2013 for Windows OS.

D.4 RUN NOTES

In performing a new analysis with DFNGen, please note the following:

- For each new analysis run, the prior output and error files are deleted by the code in the directory *.\programs*
- Upon starting a new FracGen analysis, the prior input file(s) are overwritten and any prior input is lost
- The output file (output.txt in the *.\programs* directory) from a prior analysis can be accessed by analysis tools before the user starts another FracGen analysis. Therefore, the user can start DFNGen and examine prior results without performing a FracGen run. A message (warning) box will appear informing the user of this fact.

Table D-1: Limiting values in FracGen Ver. 14M

Parameter Description	Limit
Maximum Number of Fractures	60,000
Maximum Number of Layers	5
Maximum Number of Sets per Layer	10
Maximum Number of Laterals per Well	10
Maximum Number of Wells	50
Maximum Number of User-Input Fractures per Set	500
Maximum Number of User-Input Clusters per Set	500
Maximum Number of User-Input Fracture Traces per Set	500
Maximum Number of Clusters	1,000
Maximum Number of Fractures in a Cluster	3,000
Maximum Number of Fracture Intersections Data (in File)	5,000
Maximum X or Y Coordinate	+99,999.0
Minimum X or Y Coordinate	-99,999.0
Maximum Number of Characters in Project Title	82
Maximum Number of Characters in Working Path Directory Name	80
Maximum Number of Characters in Prefix for Output Files	20
Maximum Number of Characters in Path File Name for Output Files[40]	105

[40] Note that the file path name (string) limit is the sum of (a) the maximum directory length, (b) the maximum prefix length and (c) five additional characters: four for the file extension (e.g., ".ldf") and one for the directory character (\).

Table D-2: Limiting values in DFNGen[41]

Parameter Description	Limit
Target Number of Swaps for Each Fracture in Synthetic Annealing	200
Maximum Number of Swaps for Each Fracture in Synthetic Annealing	250
Number of Orientation Changes Before Translating the Fracture Center Point	10

[41] These limits apply in DFNGen in addition to those shown in Table D-1.

APPENDIX E: DESCRIPTION OF ANCILLARY CODES

E.1. General

DFNGen employs a number of smaller supplemental programs (termed "ancillary codes") developed by others at NETL. Descriptions of these codes are (NETL, 2014):

FARM This program selects fractures within a rectangular region around a well and changes the apertures of the fractures within this region. Alternatively, the fracture apertures can remain unchanged (reduction factor = 1.0), but in either case, the fractures that intersect the region's borders are segmented. Each segment is given a common endpoint at the borders of the rectangular region. Fractures intersecting the well can also be added to simulate hydraulic stimulation. The user must first supply the name of the fracture network file. Parameters for aperture changes and fractures can be input in several ways.

BHP This program calculates bottom-hole static or flowing tubing pressures for gas wells from surface static or flowing tubing pressures, respectively, using the method of Cullender and Smith (1956) plus the SAREM subroutine, which calculates the Z-factors.[42] The basic input data plus the flow rate and well head pressure pairs can be listed within an input data file. A template file exists with the input format. For injection wells, the flow rates are negative to indicate flow down the well bore. Data values are space delimited. Alternatively, basic input data can be supplied at prompts. No corrections exist for:

- Slugs of liquids in the tubing
- Nonlinear temperature distributions
- Variations in gas composition
- Condensates
- Changes in tube or casing diameter with distance down the borehole
- Tubing or casing not extending to the pay zone
- Changes in well orientation with down-hole distance

The flow rate is assumed to be based on a standard volume of gas measured at 14.65 psia and 60°F. At the user-prompts, pseudocritical temperature and pressure can be supplied by default (with a null input) using the empirical correlations of Brown et al. (1948). At the user-prompts, the Cullender and Smith Method friction factor "Fr", can be supplied by default (with a null input or with zero) from either the Nikuradse equations or from the Cullender-Smith equation that uses the Moody friction factor. These defaults assume an absolute pipe roughness of 0.0006 inches.

[42] The compressibility factor (Z), is the ratio of the molar volume of a gas to the molar volume of an ideal gas at the same temperature and pressure.

The pipe roughness or friction factor can be found for various pipe and annulus diameters in the SPE Petroleum Engineer's Handbook, Tables 33.10 and 33.11. This program refers to the equations and method as presented in Mian (1992).

Kappa This program calculates the fraction (or weight) that upon multiplication with the intra-cluster fracture center-point density in the kth cluster of Model 2 (lognormal fracture length distribution) gives the weighted average center-point density in the regions of reduced density at each end of a cluster. This fraction or weight is labeled as "κ" (kappa) in equations 16 and 17 of McKoy and Sams (1997), and is presented in its mathematical form in equation 18 of the same report. This program also calculates fracture length at –3.0, +2.0 and +3.0 standard normal deviates, and the program may be used to quickly calculate these values. Kappa applies only to lognormal fracture length distributions.

logSTAT The program calculates a lognormal mean and a lognormal standard deviation plus several other statistics from the data supplied. The user enters the raw data as prompted, along with a "correction factor". The correction factor is any multiplier that the user decides to input. Use 1.0 if no correction is wanted. The data is stored in a file specified by the user. If a data file already exists, the user can input this data file name.

spa_L This program accepts as input the locations of fractures as encountered along a 1-D sample line or borehole and produces as output the frequency of spacing falling within defined class intervals and the cumulative percent frequency distribution. The spacing is adjusted to account for the sample line running at some angle to the mean orientation of the fractures, and the adjusted spacing is normalized to a mean spacing of 10 units per event. The user should input the beginning point and the end point of the survey line where the survey line does not begin and end on fractures. This "wrapping" of the sample line adds another value of spacing to the sample. Where the sample line begins and ends on fractures, "wrapping" should not be used. Where the orientation of the sample line varies relative to the mean orientation of the fracture set, such as where a well bore is curved, correction factors may be specified for each fracture. This program also calculates the t-statistic for a Student's t-Test, which is used to test whether the sampled distribution of fracture locations differs significantly from true random fracture locations. The null hypothesis, Ho, is that the fractures are randomly located. The null hypothesis is rejected in a two-tailed test if the absolute value of the t-statistic (variable: *tSTAT*) is greater than the critical value, variable: *tc*. The critical value is looked up in subroutine *tTABLE*. Following the calculations of the t-Test, the program calculates the degree of clustering in three ways. These are experimental methods of calculating the "degree of clustering". One method comes from the ratio of the sample variance to the maximum possible sample variance (calculated as if all fractures are in one interval). The second method is like the first method except it uses the ratio of the standard deviations. The third method uses two equations, one if the variance is less than the mean (i.e., the sample is more regular than perfectly random), and the other if the variance is greater than the mean. This third method gives a value ranging from -100.0% for regular (or uniform) fracture locations to 0.0% for perfectly random locations to +100.0% for highly clustered locations (all

fractures in one interval). This method cannot reliably discriminate uniform locations from regular locations. The output from this program may be used initially to determine which fracture network model to apply. The output is used directly to estimate two of the clustering parameters for Model 2 clusters.

ClusDen The program calculates the expected intra-cluster fracture density (ft/ft^2) at specified locations along the left end of a cluster having either a uniform, exponential, or a lognormal fracture length distribution. It then calculates correction factors, variables *gamma* and v_I. After this, the program calculates the intra-cluster fracture center-point density either for the mean number of fractures (variable *di*) encountered by an axis-perpendicular sample line (with the standard deviation variable *sdi* = 0.0 in Model 2) or for the number of fractures expected to be encountered by an axis-perpendicular sample line across the kth cluster (variable *sdi* > 0.0 and each cluster must be handled individually). If the lognormal mean number of fractures per cluster encountered by the sample line or bore hole is used, the resulting lognormal mean intra-cluster fracture center point density (variable *Dzi*) value equals the di value that is input to FracGen (and sdi = 0.0 or is estimated). Otherwise, the lognormal mean and standard deviation are calculated from the intra-cluster fracture center-point density of the kth cluster (*Dzik*) values for clusters encountered by the sample line or borehole.

EXPmean This program calculates the geometric mean and shape factor λ (lambda) for a special truncated exponential distribution whenever the user supplies the mean and either the minimum or maximum value of the distribution. The end member value of the distribution not supplied by the user is also calculated.

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NRAP is an initiative within DOE's Office of Fossil Energy and is led by the National Energy Technology Laboratory (NETL). It is a multi-national-lab effort that leverages broad technical capabilities across the DOE complex to develop an integrated science base that can be applied to risk assessment for long-term storage of carbon dioxide (CO_2). NRAP involves five DOE national laboratories: NETL, Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and Pacific Northwest National Laboratory (PNNL).

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