Two-Level Factorial Tutorial (Part 1 – The Basics)

Introduction

This tutorial demonstrates the use of Design-Expert® software for two-level factorial designs. These designs will help you screen many factors to discover the vital few, and perhaps how they interact. If you haven't done the General One-Factor tutorials that precede this (at least The Basics), please do so now because it will be assumed that you already have some familiarity with the software.

The data you will now analyze comes from Douglas Montgomery's textbook, *Design and Analysis of Experiments*, published by John Wiley and Sons, New York. A wafer-board manufacturer must immediately reduce the concentration of formaldehyde used as a processing aid for a filtration operation. Otherwise they will be shut down by regulatory officials. To systematically explore their options, process engineers set up a full-factorial two-level design on the key factors, including concentration at its current level and an acceptably low one.

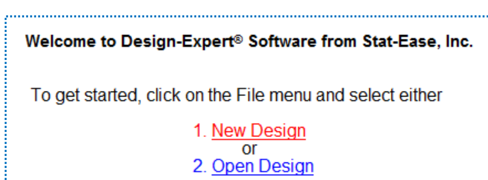
Factor	Units	Low Level (–)	High Level (+)
A. Temperature	deg C	24	35
B. Pressure	Psig	10	15
C. Concentration	Percent	2	4
D. Stir Rate	Rpm	15	30

Factors and levels for full-factorial design example

At each combination of these process settings, the experimenters recorded the filtration rate. The goal is to maximize the filtration rate and also try to find conditions that allow a reduction in the concentration of formaldehyde, Factor C. This case study exercises many of the two-level design features offered by Design-Expert. It should get you well down the road to being a power user. Let's get going!

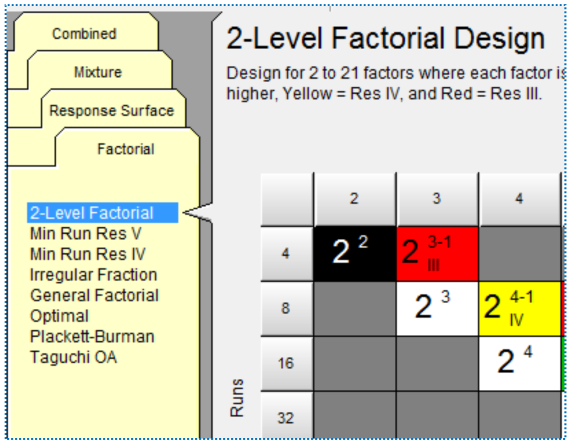
Design the Experiment

Start the program by finding and double-clicking the Design-Expert icon. Click the blank-sheet icon on the left of the toolbar, or select **File, New Design**, or try our new easy-start option by clicking New Design as shown in red below.



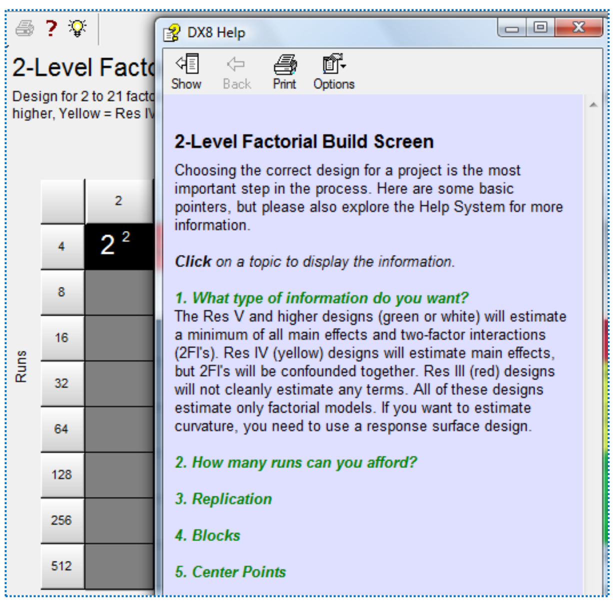
Start-up page – New Design option highlighted in red

You now see four tabs to the left of your screen. Stay with the Factorial choice, which comes up by default. You'll be using the default selection: **2-Level Factorial**.



Two-level factorial design builder

This design builder offers full and fractional two-level factorials for 2 to 21 factors in powers of two (4, 8, 16…) for up to 512 runs. The choices appear in color on your screen. White squares symbolize full factorials requiring 2^k runs for k (the number of factors) from 2 to 9. The other choices are colored like a stoplight: green for go, yellow for proceed with caution, and red for stop, which represent varying degrees of resolution: ≥ V, IV, and III, respectively. For a quick overview of these color codes, press the screen tips button (or select **Tips, Screen Tips**) and click topic 1: "**What type of information do you want?**"



Screen tips for factorial design builder

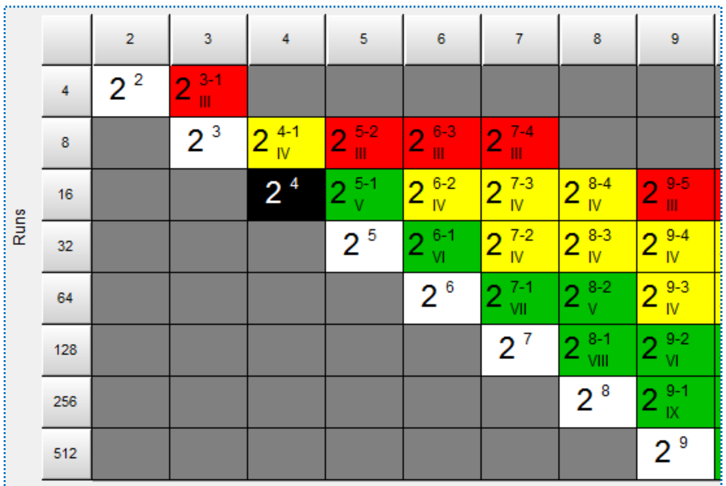
Close the Screen Help by pressing **X** at the upper right of the pop-up window. You now see that the notation shown on the non-white boxes is "2^{k-p}," where p designates the fraction of the design. For example, here's the anatomy of a 2^{5-1} design:

- 5 factors will be tested each at two levels

- A 2^{-1} or one-half (1/2) fraction, with the optimal resolution, will be selected from the original 2^5 (32) combinations, thus this option appears in the 16-run row (one-half of 32).

For complete details on fractional factorials, and the concept of resolution, refer to the Montgomery textbook or see Chapter 5 in *DOE Simplified, 2nd Edition* (Anderson, Whitcomb, Productivity Press, NY, NY, 2007). To gain a working knowledge of two-level designs, attend our Stat-Ease computer-intensive workshop titled Experiment Design Made Easy.

Let's get on with the case at hand – a full-factorial design. Click the white square labeled **2^4** in column 4 (number of factors) in the Runs row labeled 16. It turns black once it is selected, as shown below.

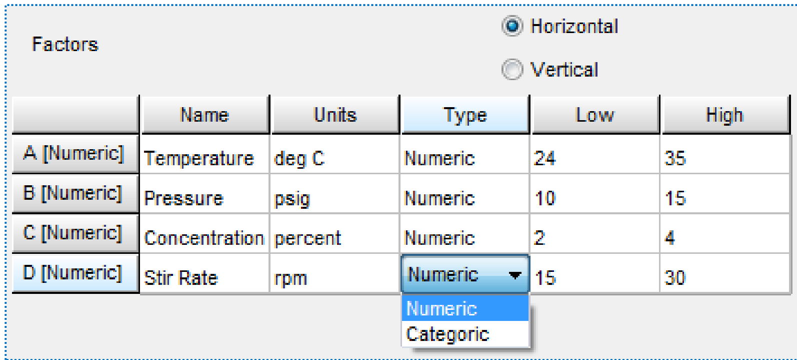


Selecting a full, two-level design on four factors which produces 16 runs

At the bottom of the screen you see options to select the number of replicates of the design, the number of blocks, and the number of center points. Leave them at their defaults.

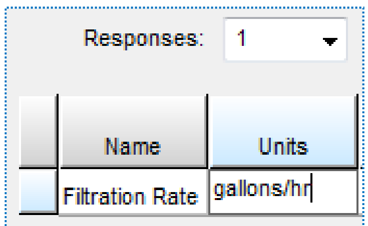
Click the **Continue** button. You are now able to set up your experiment by entering the names, units of measure, and levels for your factors. Use the arrow keys, tab key, or mouse to move from one space to the next. The Tab (or Shift Tab) key moves the cursor forward (or backward) between entry fields.

Factors can be of two distinct types – "Numeric" or "Categoric." Numeric data characterizes a continuous scale such as temperature or pressure. Categoric data, such as catalyst type or automobile model, occurs in distinct levels. Design-Expert permits characters (for example, words like "Low" or "High") for the levels of categorical factors. You change the type of factor by clicking on cells in the Type column and choosing "Categoric" from the drop down list, or by typing "C" (or "N" for numeric). Give this a try – back and forth! Leave the default as "Numeric" for all factors in this case. Then enter for each factor (A, B, C and D) the **Name**, **Units**, **Low** and **High** levels shown on the screen shot below.



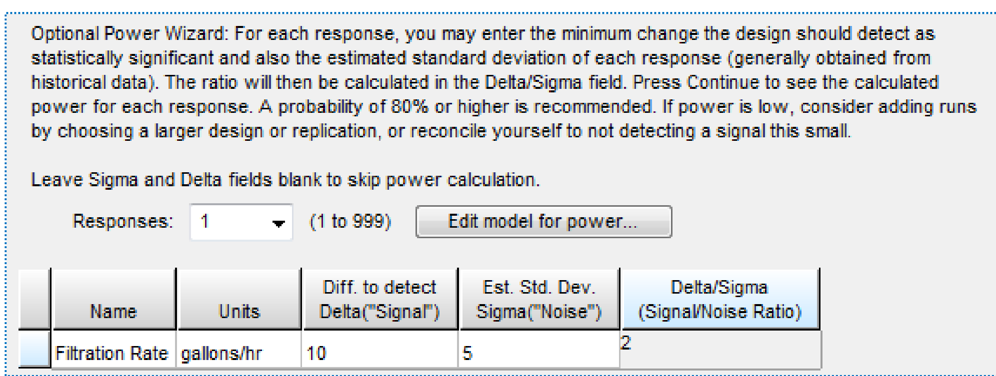
Factors – after entering name, units, and levels (plus a peek at options for "Type")

Now click **Continue** to bring up the Responses dialog box. With the list arrow you can enter up to 999 responses (more than that can be added later if you like). In this case we only need to enter a single response name (Filtration Rate) and units (gallons/hour) as shown below.



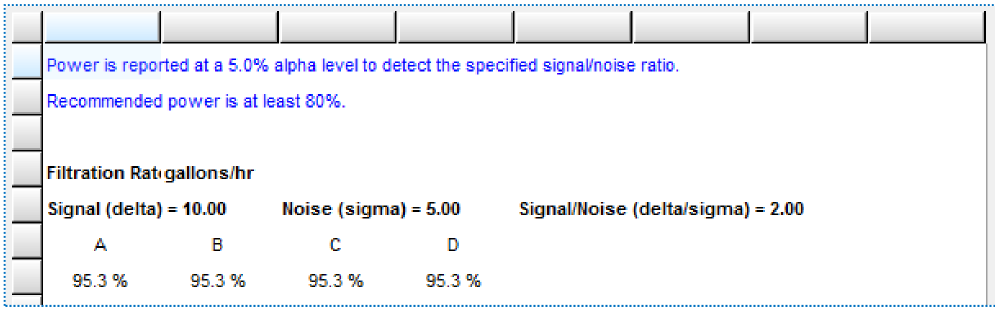
Response values entered

At this stage you can skip the remainder of the fields – used for calculating the power of your design – and continue on. However, it is good to gain an assessment of the power of your planned design of experiment. In this case, manufacturing management does not care if averages differ by less than **10** gallons per hour and engineering records provide the standard deviation of **5**. Enter these values as shown below so Design-Expert can compute a signal to noise ratio of **2**.



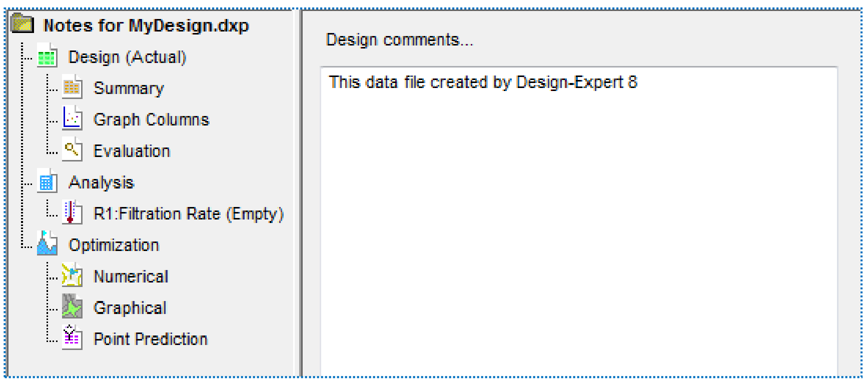
Optional power wizard – necessary inputs entered

Press **Continue** to view the positive outcome – power that exceeds 80 percent probability of seeing the desired difference.



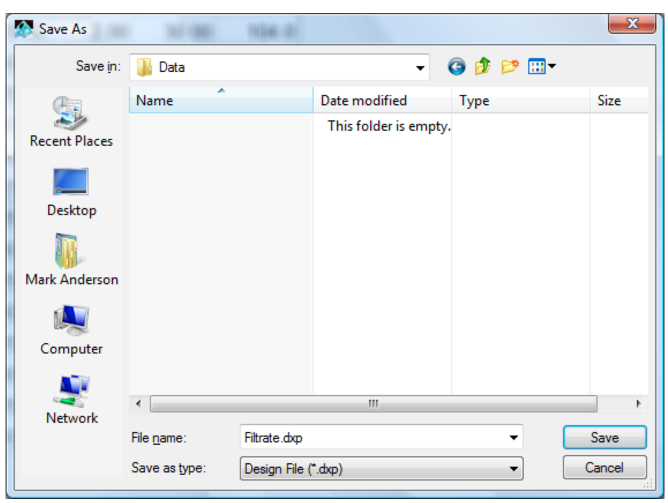
Results of power calculation

Click **Continue** to accept these inputs and generate the design layout window. You've now completed the first phase of DOE – the design. Notice that this is one of three main features offered by Design-Expert software, the others being Analysis and Optimization. You're also provided an area to write notes for yourself and others accessing the designs. Click the **Notes** node to take a look at what's written there by default. Add your own comments if you like.



Notes on data file

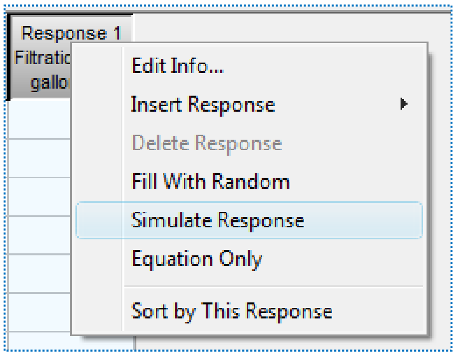
You've put in some work at this point so it is a good time to save it. The quickest way of doing this is to press the standard save icon 🖫. But you can also go to the File menu and select **Save As**. Type in the name of your choice (such as **Factorial.dxp**) for your data file. Then click **Save**.



Saving the design

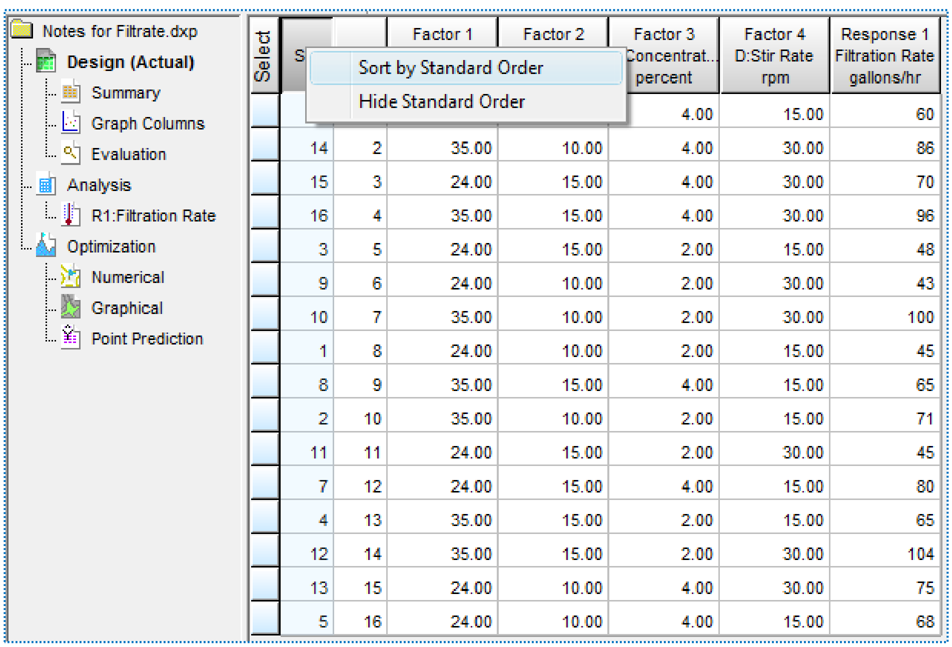
Enter the Response Data

Exit the notes page by clicking the **Design** node. (Notice the node appears as **Design (Actual)** – meaning your factors are displayed in actual levels, as opposed to coded form). At this stage you normally would print the run sheet, perform the experiments, and record the responses. The software automatically lists the runs in randomized order, protecting against any lurking factors such as time, temperature, humidity, or the like. To avoid the tedium of typing numbers, yet preserve a real-life flavor for this exercise, simulate the data by right-clicking the **Response** column header to bring up a new menu. (Notice that one of the options – **Insert Response** – allows you to insert more responses as mentioned earlier.) Select **Simulate Response**.



Simulating the response

You will now see a list of "sim" files. Double-click **Filtrate.sim** (or press Open). The filtration process simulation now generates the response data. Right click the **Std** column header (on the gray square labeled Std) and select **Sort by Standard Order** as shown below. Note that the Column Header for Factor 3 is truncated

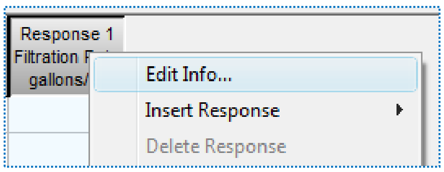


Design layout in standard order – response data entered (via simulation) (ie. Concentrat… percent). To automatically re-size the column, move the cursor to the right border of the column header until it turns into a double-headed arrow (⇔). Double-click and the column will be resized to fit the Column Header.

Your data will now match the tutorial except for a *different random run order*. (When doing your own experiments, always do them in random order. Otherwise, lurking factors that change with time will bias your results.)

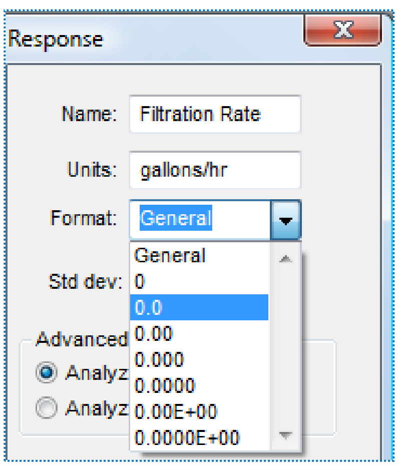
Now that you've got responses recorded, it's another opportune time to save the updated file by clicking the Save icon.

The response data came in under a general format. You will get cleaner outputs if you change this to a fixed format. Place your mouse over the **Response** column heading (top of the response column), right click and select **Edit Info...**.



Selecting Edit Info option

Click the **Format** arrow and choose **0.0** from the drop list. Press **OK**.



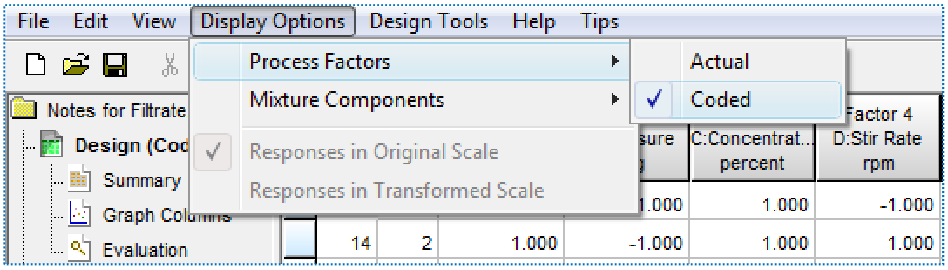
Changing the format

Using the same Edit Info feature, you can also change input factors' format, names, or levels. Try this by right clicking any other column headings. Then continue with this tutorial.

Design-Expert provides two methods of displaying the levels of the factors in a design:

- Actual levels of the factors.
- Coded as -1 for low levels and +1 for high levels.

The default design layout is actual factor levels in run order. To view the design in coded values, click **Display Options** on the menu bar and select **Process Factors - Coded**. Your screen should now look like the one shown below.



Design layout - coded factor levels (your run order may differ)

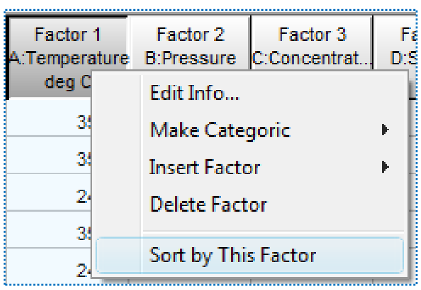
Notice that the Design node now displays "coded" in parentheses – **Design (Coded)**. This can be helpful to see at a glance whether anyone changed any factor levels from their design points.

Now convert the factors back to their original values by clicking on **Display Options** from the menu bar and selecting **Process Factors - Actual**.

Pre-Analysis of Effects via Data Sorts and Simple Scatter Plots

Design-Expert provides various ways for you to get an overall sense of your data before moving on to an in-depth analysis. For example, via the same right-click menu used to Edit Info, you can sort by any column.

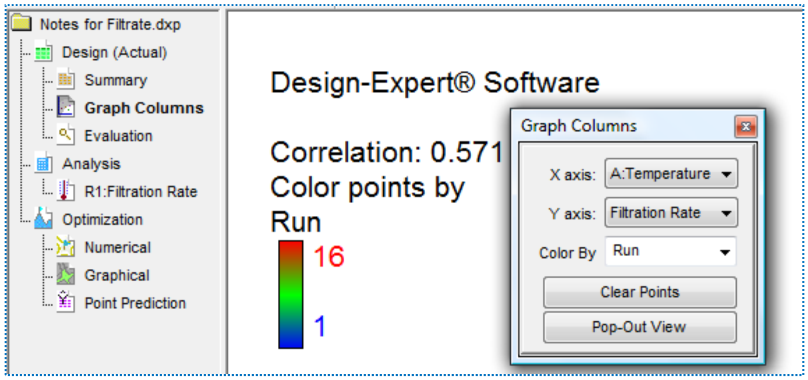
To see this, move your mouse to the top of column **Factor 1** (A: Temperature) and right-click. Then select **Sort by This Factor**.



Sorting the design on a factor

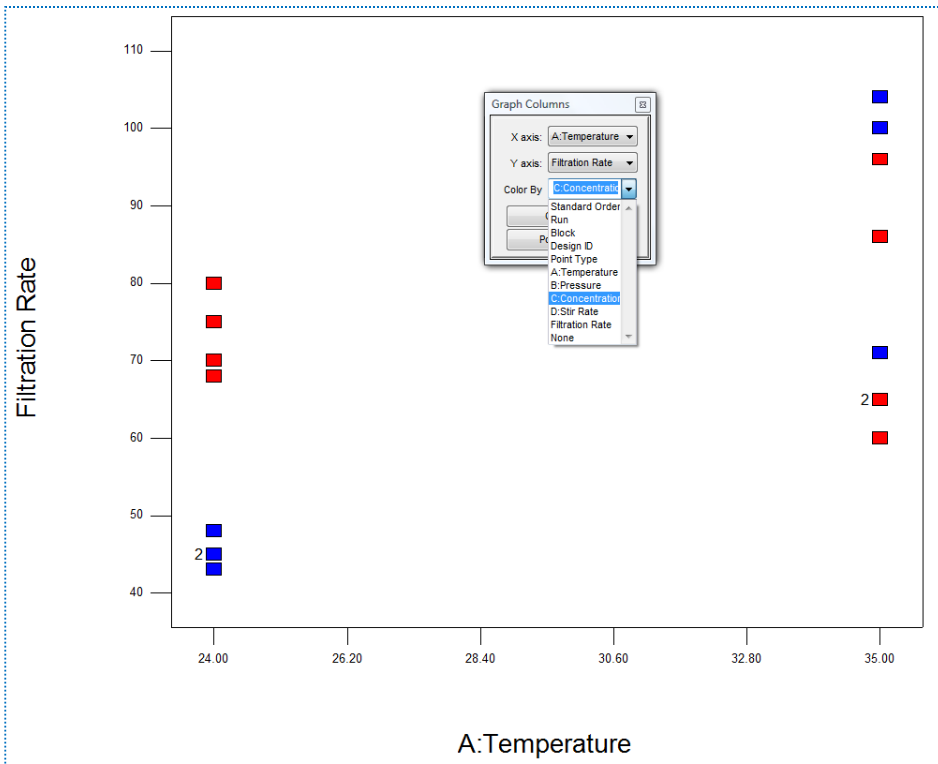
You will now see more clearly the impact of temperature on the response. Better yet, you can make a plot of the response versus factor A by selecting the **Graph Columns** node that branches from the design 'root' at the upper left of your screen. You should now see a scatter plot with factor A:Temperature on the X-axis and the response of Filtration Rate on the Y-axis.

Observe that temperature makes a big impact on the response. Notice the high correlation reported on the legend.



Legend for default graph columns on filtration data

The points are colored by run number. Just for fun, mouse over to the **Graph Columns** floating menu, click the **Color By** drop-down list and select **C:Concentration** as shown below.



Graph columns for temperature versus filtration rate, colored by concentration

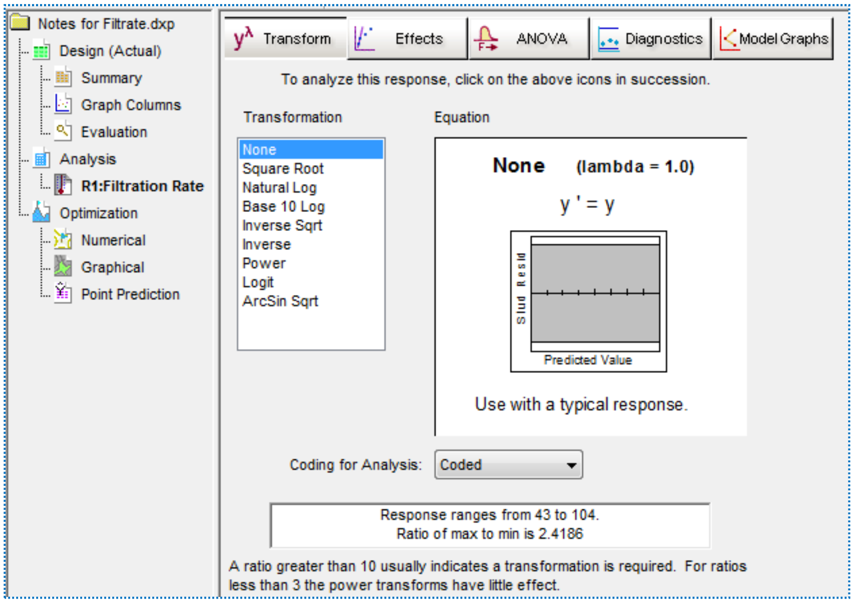
Do you see how two colors stratify at each level of temperature – but oppositely – red at the top for the rates plotted at the left (temperature 24) versus blue coming out higher for filtration rate at the right? Consider what this may indicate about how concentration interacts with temperature to produce an effect on filtration rate. However, let's not get ahead of ourselves – this is only a preliminary to more thorough analyses using much more sophisticated graphical and statistical tools.

You may wonder why the number "2" appears besides a few points on this plot. This notation indicates the presence of multiple points at the same location. Click on one of these points more than once to identify the individual runs. Coming up soon you will use powerful analysis features in Design-Expert software to find out what's really going on in this wafer-board production process.

Analyze the Results

To begin analyzing the design, click the **Filtration Rate** response node on the left side of your screen. This brings up the analytical tool bar across the top of the screen. To do the statistical analysis, simply click the buttons progressively from left to right.

The ***Transform*** button is initially highlighted, as shown below. It displays a list of mathematical functions that you may apply to your response. For details press the Tips button.

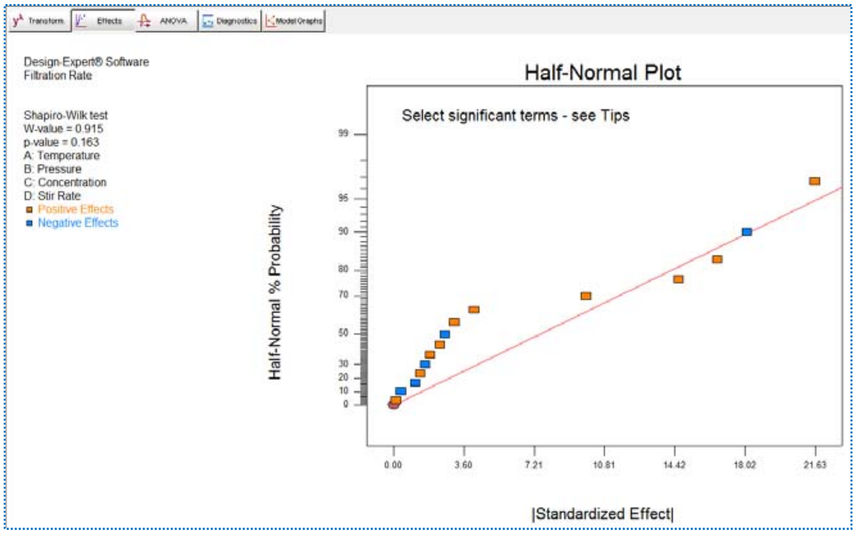


Transformation options

Near the bottom of your ***Transform*** screen, Design-Expert notes that the response range is 2.4-fold ("Ratio of max to min is 2.4186"). This number falls below the ratio of 3 where "...power transforms have little effect." Therefore, you can leave the transformation at its default: **None**.

Choosing Effects to Model

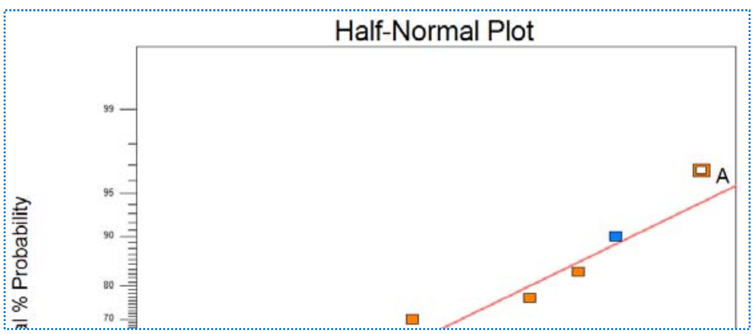
Click the ***Effects*** button. The program displays the absolute value of all effects (plotted as squares) on a half-normal probability plot. (Color-coding provides details whether the effects are positive or negative.)



Half-normal plot of effects – nothing selected

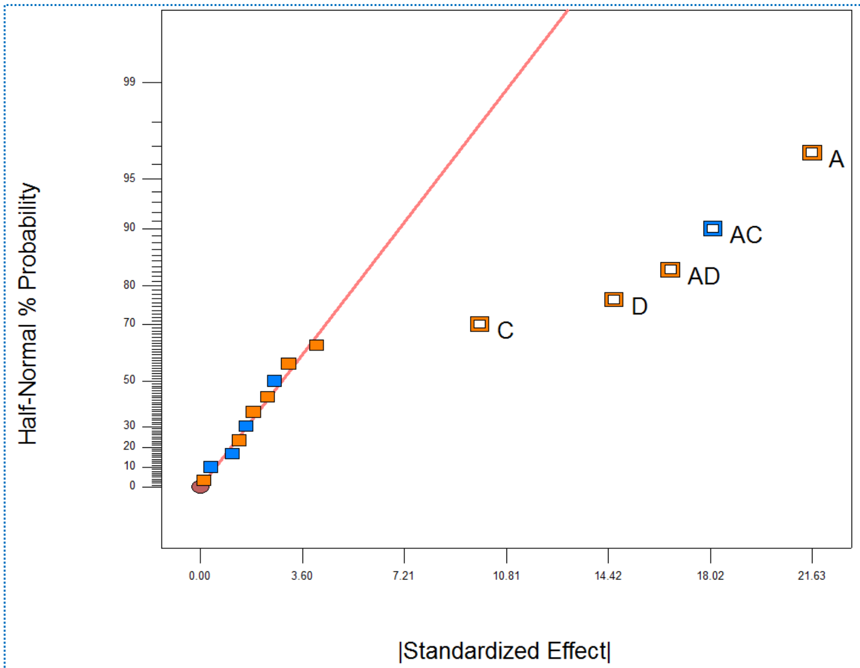
Note the message on your screen: "Select significant terms – see Tips." You must choose which effects to include in the model. If you proceed without doing so at this point, you will get a warning message stating "You have not selected any factors for the model." The program will allow you to proceed, but with only the mean as the model (no effects), or you can opt to be sent back to the ***Effects*** view (a much better choice!).

You can select effects by simply clicking on the square points. Start with the largest effect at the right side of the plot, as shown below.



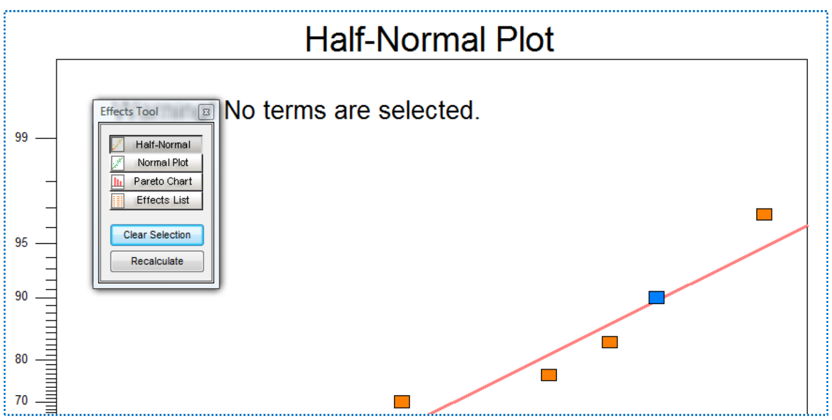
First effect chosen

Keep selecting individual effects from right to left until the line matches up with the majority of the effects near zero. Notice that Design-Expert adjusts the line to exclude chosen effects. At the point where you should stop, this line 'jumps up,' leaving a noticeable gap as shown below. In this case, the gap appears between the main effect of factor C and the near-zero effects that fall on the line.



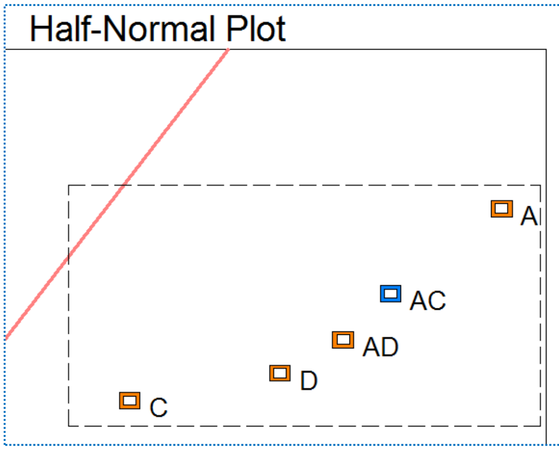
Half-normal probability plot - all big effects selected

Until you get familiar with the half-normal plot, it is best that you continue picking effects one at a time from the largest (right-most) on down. However, after doing this many times, you will get tired of all this mouse-clicking. Instead you may want to start 'roping' the obviously significant effects. To see how this feature works, first go to the floating **Effects Tool** and press **Clear Selection** as shown below.



Clearing the selection of effects

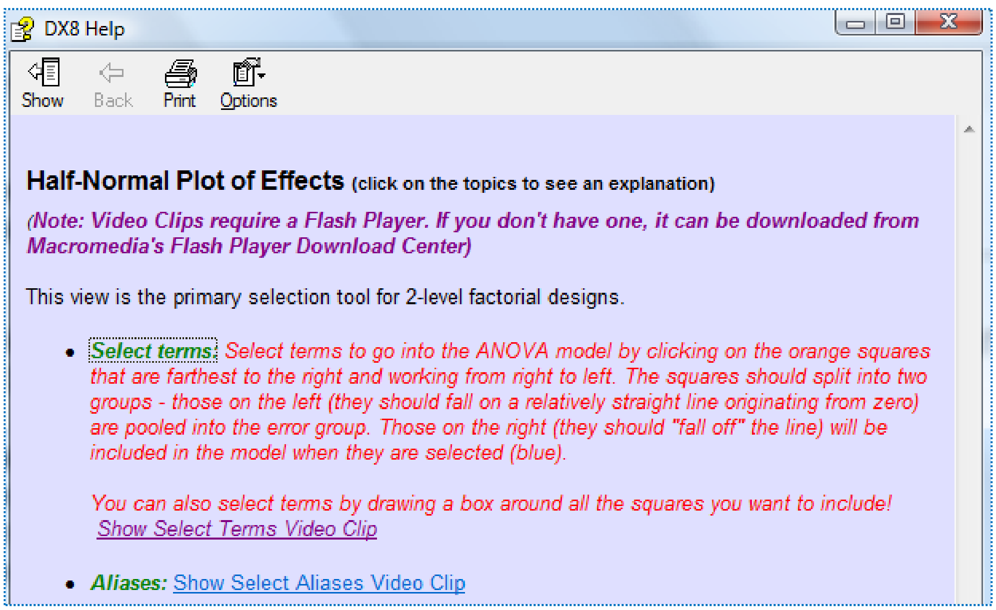
Now, as shown in the screenshot below, do a <u>mouse drag</u> (depress left button and pull down) to form a <u>box around the effects that stand off at the right</u> from the trivial many that are lined up near zero. This is like a cowboy roping stray cows.



Roping the effects

Notice that when you release the mouse button Design-Expert labels the roped effects.

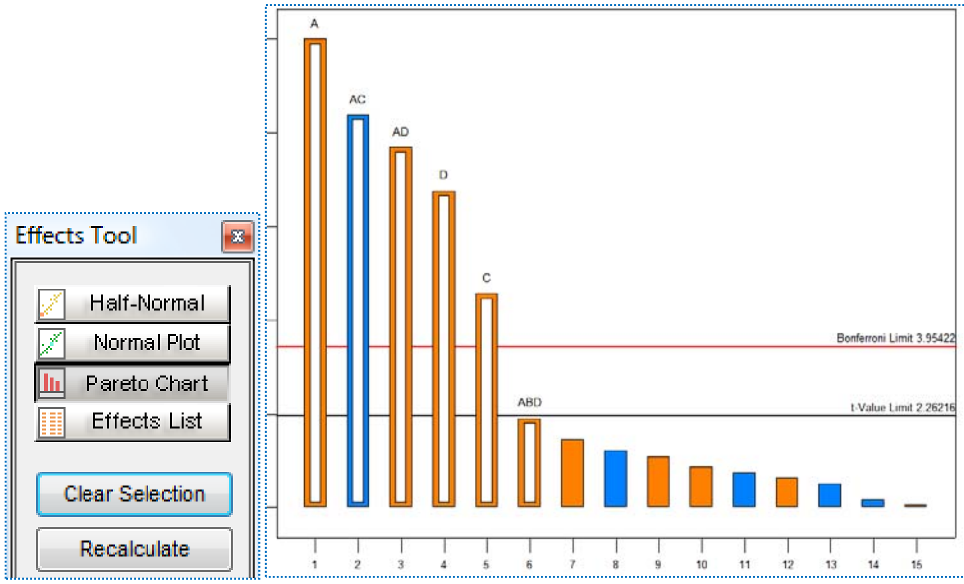
Now is a good time to click the handy screen tips button. Then click the topic ***Select Terms*** for a re-cap of the process for choosing effects just demonstrated in this tutorial.



Screen Tips for half-normal plot of effects

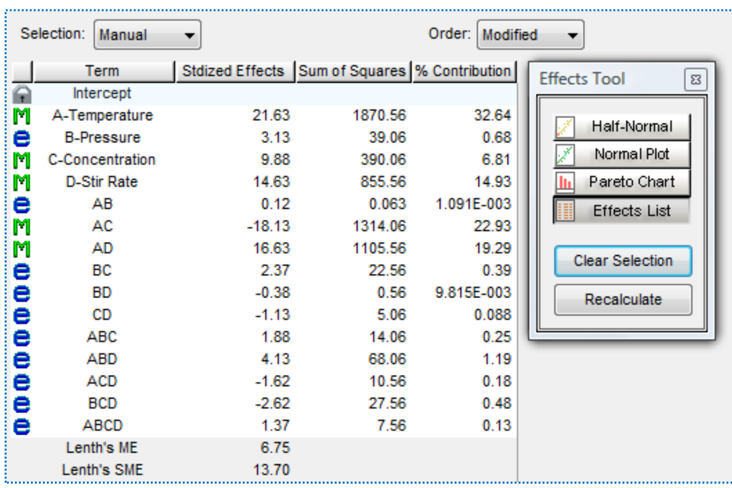
Now try the ***Show Select Terms Video Clip*** for a movie that illustrates how to select effects. After viewing this 'demo' and perhaps checking out other video clips and tips, **X** out of this window.

It may help you visualize the magnitude of the chosen effects by displaying them on an ordered bar chart. Do this via the floating **Effects Tool**, **Pareto Chart**. Notice the vertical axis shows the t-value of the absolute effects. This dimensionless statistic scales the effects in terms of standard deviations. In this case, it makes no difference to the appearance of the chart, but when you encounter botched factor levels, missing data, and the like, the t-value scale provides a more accurate measure of relative effects. Click the next biggest bar and notice it is identified as **ABD** as shown below (lower right).



Pareto chart of effects with ABD picked (a mistake!)

Notice that the **ABD** bar falls below the bottom limit, so click off the **ABD** bar. Now, to see quantitative detail on the chosen model effects and those remaining for estimation of error, on the floating **Effects Tool** click **Effects List**.



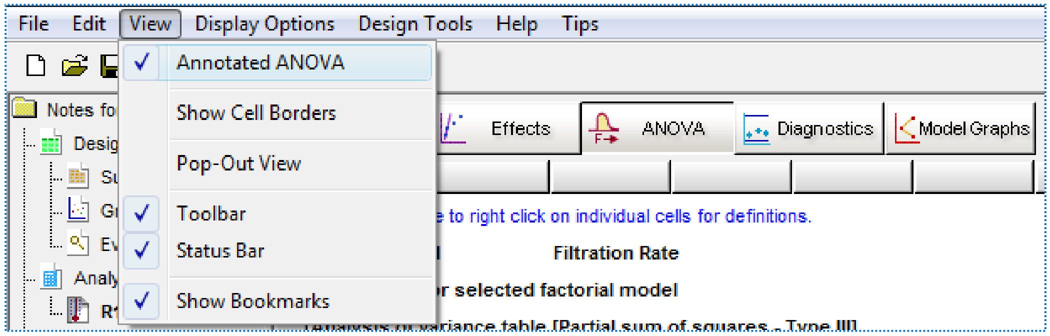
	Term	Stdized Effects	Sum of Squares	% Contribution
	Intercept			
M	A-Temperature	21.63	1870.56	32.64
e	B-Pressure	3.13	39.06	0.68
M	C-Concentration	9.88	390.06	6.81
M	D-Stir Rate	14.63	855.56	14.93
e	AB	0.12	0.063	1.091E-003
M	AC	-18.13	1314.06	22.93
M	AD	16.63	1105.56	19.29
e	BC	2.37	22.56	0.39
e	BD	-0.38	0.56	9.815E-003
e	CD	-1.13	5.06	0.088
e	ABC	1.88	14.06	0.25
e	ABD	4.13	68.06	1.19
e	ACD	-1.62	10.56	0.18
e	BCD	-2.62	27.56	0.48
e	ABCD	1.37	7.56	0.13
	Lenth's ME	6.75		
	Lenth's SME	13.70		

Effects list

If you see an "M" (model designated) for ABD, double-click it back to "e" (error.) For details regarding this screen, investigate Tips. However, it may be best to move on fairly quickly so you can finish this tutorial before being overwhelmed with too much information (TMI). You can always return to screens later (perhaps after a suitable period of rest) and study the details found in Tips and our program Help.

ANOVA and Statistical Analysis

It is now time to look at the statistics in detail with the analysis of variance (ANOVA) table. Click the ***ANOVA*** button to see the selected effects and their coefficients. By default, Design-Expert provides annotations in blue text. This can be toggled off via the View menu. Note that if turned off, it will not tell you if your model is significant.



Annotated View

Check the probability ("p-value") for the Model. By default, Design-Expert considers values of ≤ 0.05 to be significant. Via Edit, Preferences, Math, the significance threshold can be changed to 0.1 or 0.01, depending on how much risk you wish to accept. Also inspect the p-values for the model terms A, C, D, AC, and AD: All pass the 0.05 test with room to spare.

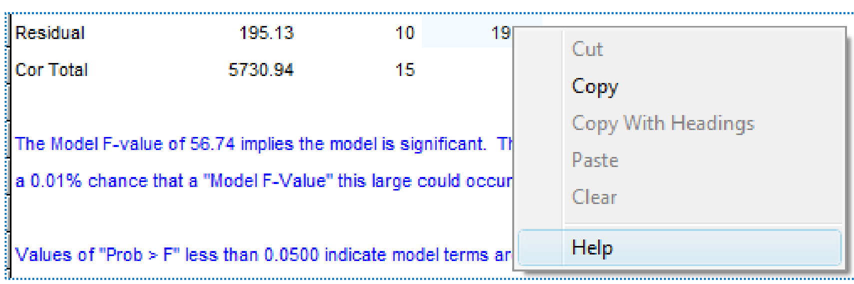
ANOVA for selected factorial model

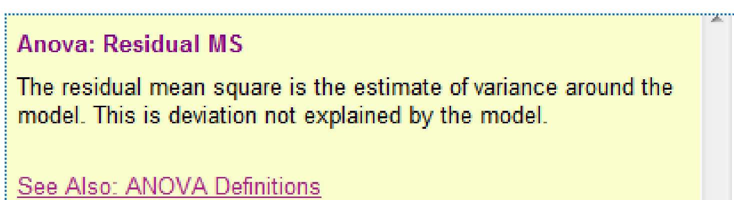
Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	5535.81	5	1107.16	56.74	< 0.0001	significant
A-Temperature	*1870.56*	*1*	*1870.56*	*95.86*	*< 0.0001*	
C-Concentration	*390.06*	*1*	*390.06*	*19.99*	*0.0012*	
D-Stir Rate	*855.56*	*1*	*855.56*	*43.85*	*< 0.0001*	
AC	*1314.06*	*1*	*1314.06*	*67.34*	*< 0.0001*	
AD	*1105.56*	*1*	*1105.56*	*56.66*	*< 0.0001*	

ANOVA report

Pop-up definitions for numbers on the ANOVA table can be obtained by <u>right clicking</u> and choosing **Help**. Try this for the Mean Square Residual statistic, as shown below.

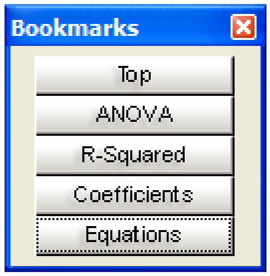




Accessing context-sensitive Help

When you finish with Help, close it by clicking the red **X** in the corner.

Scroll down the ANOVA output for further statistics such as R-squared and the like. Refer to the annotations and also access Help for details. Then continue on for a look at the estimates for the model coefficients and their associated statistics. Lastly, page down to the end of the report and see the predictive equations both in coded and uncoded form. Use the handy floating Bookmarks tool to move around the report.

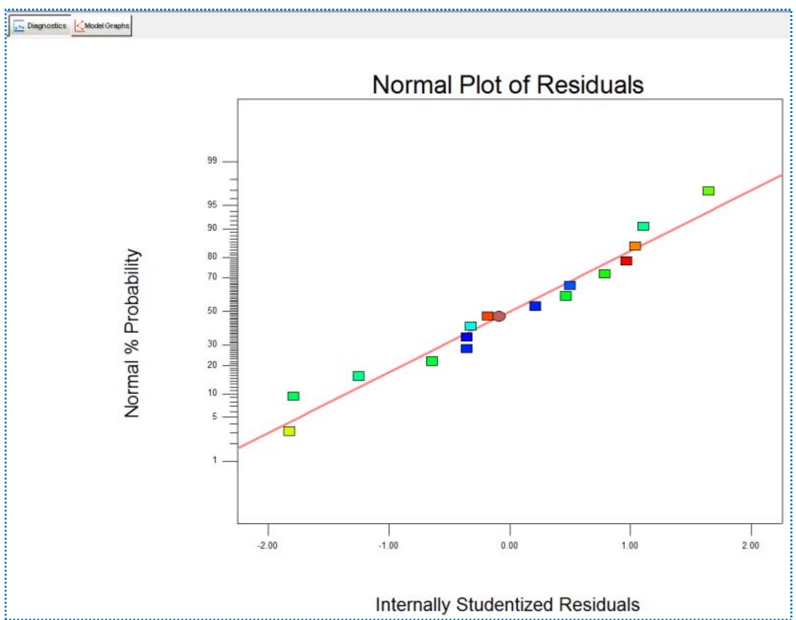


Bookmarks to quickly move to a section in the ANOVA report

Rather than belabor the numbers, let's move on and ultimately let the effect graphs tell the story. However, first we must do some diagnostics to validate the model.

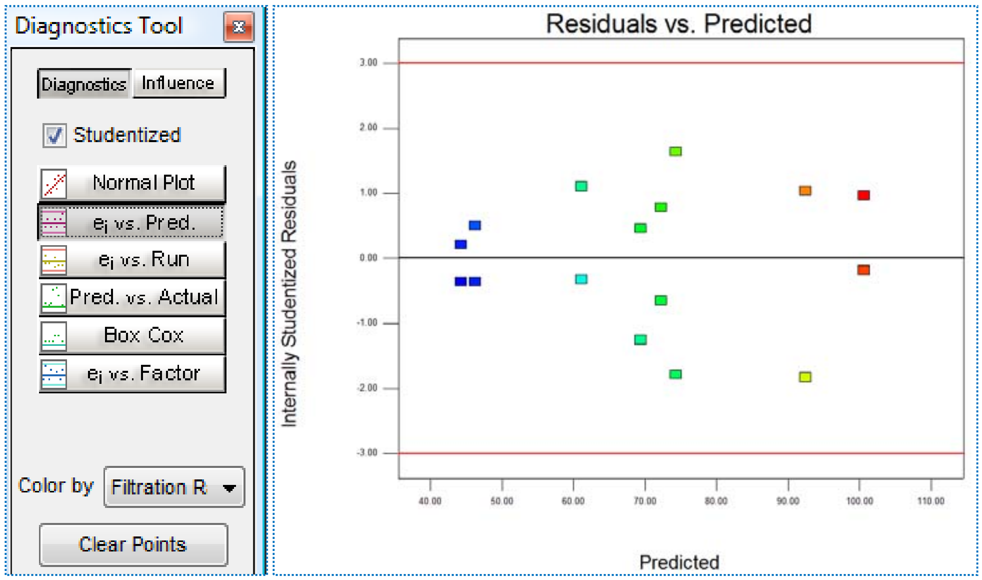
Validate the Model

Click the ***Diagnostics*** button to generate a normal probability plot of the residuals.



Normal plot of residuals

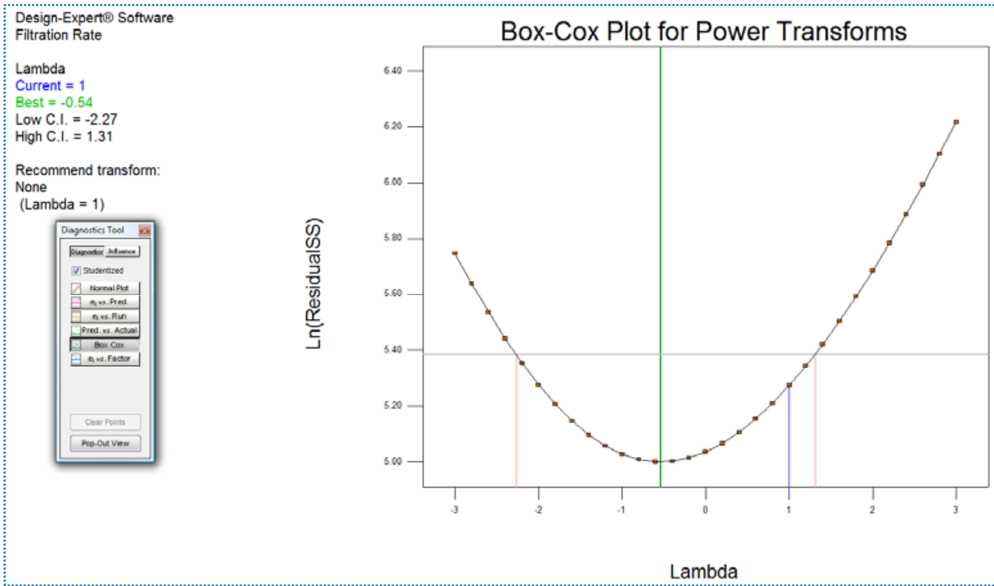
By default, residuals are studentized – essentially a conversion to standard deviation scale. For standard two-level factorial designs like this, plotting the raw residuals (in original units of measure) will be just as effective. On the Diagnostics Tool, check (√) Studentized off and on to satisfy yourself that this is true (the pattern will not change), but we advise that you return to studentized scale in the end, because as a general rule this is the most robust approach for diagnosing residuals. Ideally the normal plot of residuals is a straight line, indicating no abnormalities. (The data doesn't have to match up perfectly with the line. A good rule of thumb is called the "fat pencil" test. If you can put a fat pencil over the line and cover up all the data points, the data is sufficiently normal.) In this case the plot looks OK so move on. From the floating **Diagnostics Tool** select **e_i vs. Pred.** (residuals versus predicted), shown below.



Residuals versus predicted response values

The size of the residual should be independent of its predicted value. In other words, the vertical spread of the studentized residuals should be approximately the same across all levels of the predicted values. In this case the plot looks OK.

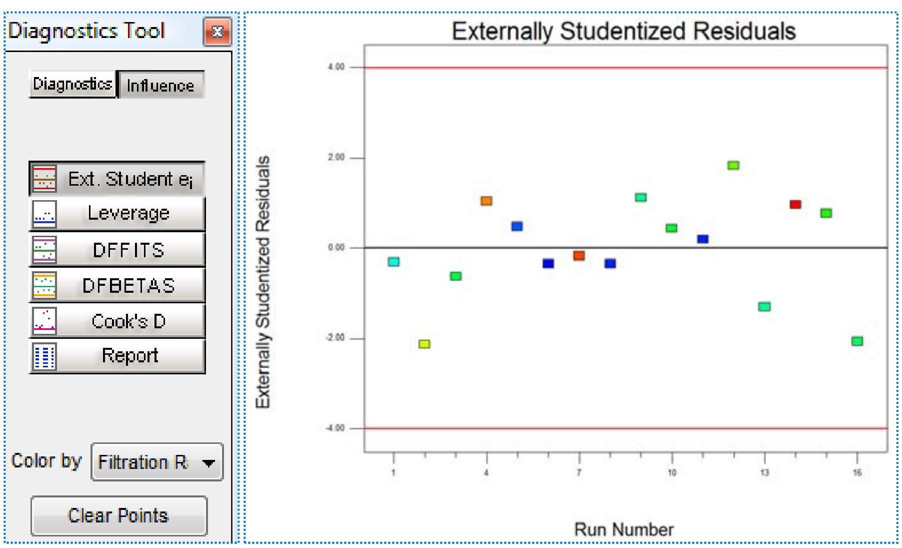
Skip ahead to the **Box Cox** plot. This was developed to calculate the best power law transformation. (Refer to Montgomery's *Design and Analysis of Experiments* textbook for details.) The text on the left side of the screen gives the recommended transformation, in this case "None." That's all you really need to know! However, for those of you who want to delve into the details, note that the Box-Cox screen is color coded to help with interpretation. The blue line shows the current transformation. In this case it points to a value of 1 for "Lambda," which symbolizes the power applied to your response values. A lambda of 1 indicates no transformation. The green line indicates the best lambda value, while the red lines indicate the 95% confidence interval surrounding it. If this 95% confidence interval includes 1, then no transformation is recommended. It boils down to this: If the blue line falls within the red lines, you are in the optimal zone, so no change need be made in your response transformation (in this case – none).



Box Cox plot for power transformations

P.S. The Box Cox plot will not help if the appropriate transformation is either the logit or the arcsine square root transformation. See the program's Help system write-up on "Response Transformations" for further details.

At the top of the **Diagnostics Tool** select **Influence** to see a very useful plot that's technically the externally studentized residuals ("Ext. Student e_i"), but often referred to as "Outlier t" because it shows how many standard deviations (t-values) a given run falls off relative to what one would expect from all the others. This is one of several measures of influence that are referred to as "deletion" diagnostics due to their being calculated externally – that is, without the run in question being included. Thus, if something goes wrong in your experiment and it generates a true outlier for a given run, the discrepant value will be removed before assessing it for influencing the model fit.



Influence plot for detection of outliers <u>*(yours may differ due to random run order)*</u>

Design-Expert provides upper and lower red lines that are similar to 95% confidence control limits on a run chart. In this case none of the points stands out. Because this graph is plotted in randomized run order, the ordering of the points on your screen will be different than shown here. But we're not looking for patterns, just outliers. There's nothing out of the ordinary here – all the points fall well within the red lines set by the software to keep you from tampering with the response data. However, if there were an outlier, you could click on it to get the coordinates displayed to the left of the graph. The program remembers the point. It will remain highlighted on other plots. This is especially helpful in the residual analysis because you can track any suspect point. This feature also works in the interpretation graphs. Give it a try! Click anywhere else on the graph to turn the point off.

Finally, go back to the **Diagnostics Tool** and press **Report**. Here you see the numerical values for diagnostic statistics reported case-by-case in standard order. (In previous versions of Design-Expert this appeared under ANOVA.) Discrepant values will be flagged. In this case nothing is detected as being abnormal.

Response 1 Filtration Rate Transform: None

Diagnostics Case Statistics

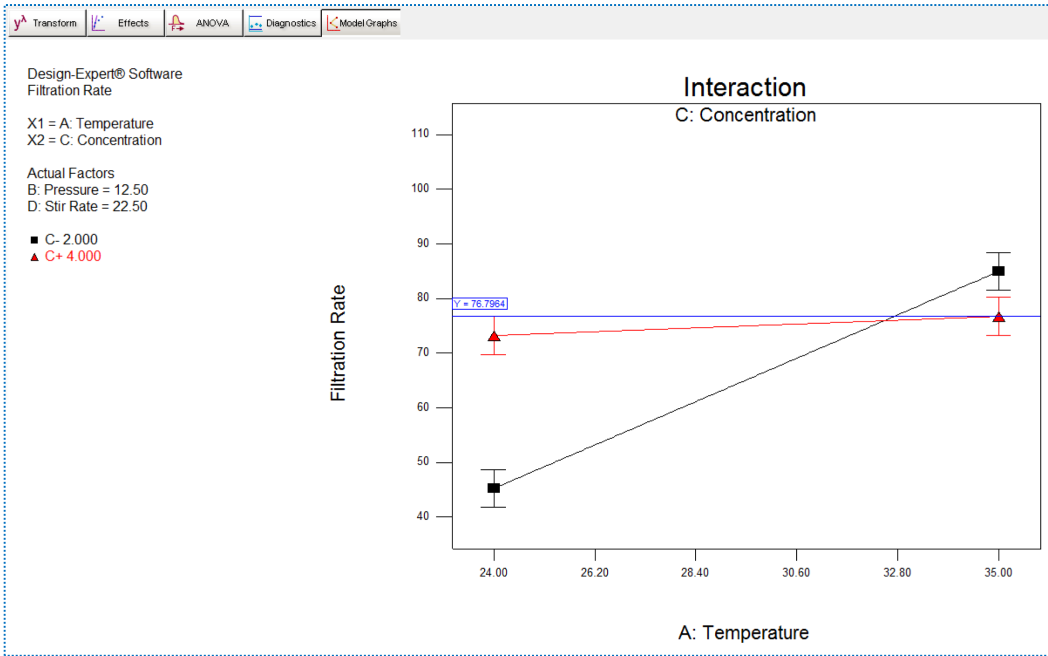
Standard Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residual	Externally Studentized Residual	Influence on Fitted Value DFFITS	Cook's Distance	Run Order
1	45.00	46.25	-1.25	0.375	-0.358	-0.342	-0.265	0.013	8
2	71.00	69.38	1.63	0.375	0.465	0.446	0.346	0.022	10
3	48.00	46.25	1.75	0.375	0.501	0.481	0.373	0.025	5

Diagnostics report (only partially show in this screen shot)

Examine Main Effects and Any Interactions

Assuming that the residual analyses do not reveal any problems (no problems are evident in our example), it's now time to look at the significant factor effects.

On the analytical tool bar at the top of the screen, choose the ***Model Graphs*** button. The AC interaction plot comes up by default. (If your graph displays the x-axis in coded units, return to actual units by choosing **Display Options, Process Factors - Actual**.)



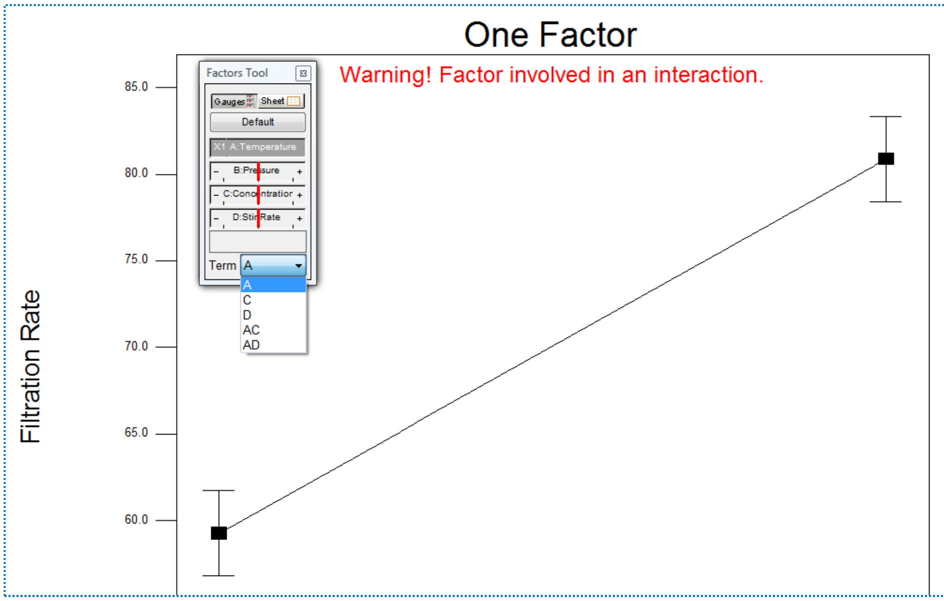
Interaction graph of factors A (temperature) versus C (concentration)

The "I-Beam" symbols on this plot (and other effect plots) depict the 95% least significant difference (LSD) interval for the plotted points. (If the "I-Beam" symbols do not appear, right-click within the graph's boundary, then choose **Graph Preferences**, XY Graphs tab. Under Factorial Graphs, click on Use **LSD Bars**.) To view a numerical value for LSD, click any of the points (squares or triangles representing predicted outcome). Try it!

Those points that have non-overlapping intervals (i.e. the LSD bars don't intersect or overlap from left to right through an imaginary horizontal line) are significantly different. An easy way to check this is to draw a horizontal reference line. Right-click on the graph near the top of the left red LSD bar (C+ at 24 degrees) and choose **Draw Horizontal Reference**. This will put a blue reference line on the graph as shown above. The reference line makes it clear that the left red LSD (C+ at 24 degrees) overlaps with the right red LSD (C+ at 35 degrees), thus there is not a statistically significant difference between those two predictions.

Note also that the spread of the points on the right side of the graph (where Temperature is high) is smaller than the spread between the points at the left side of the graph (where Temperature is low.) In other words, the effect of formaldehyde concentration (C) is less significant at the high level of temperature (A). Therefore, the experimenters can go to high temperature and reduce the concentration of harmful formaldehyde, while maintaining or even increasing filtration rate. This combination is represented by the black square symbol at the upper right of the interaction plot.

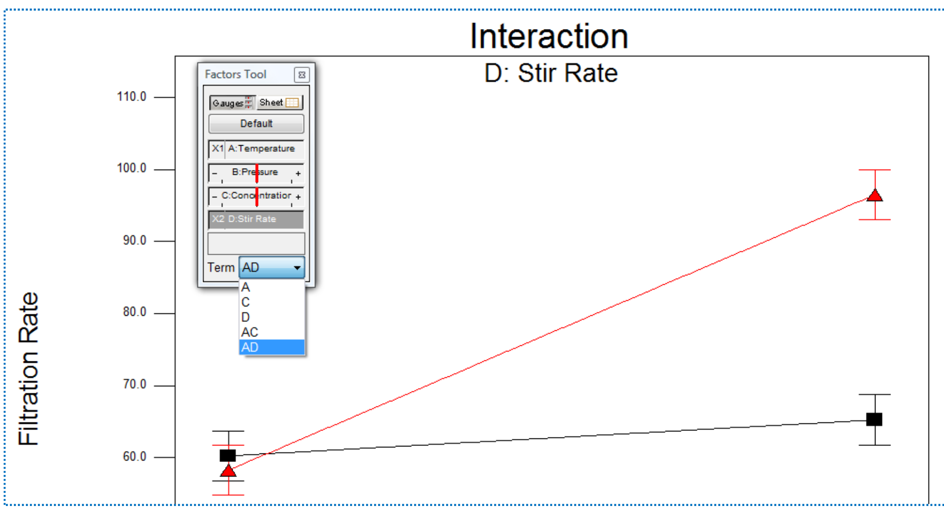
The floating **Factors Tool** palette opens along with the default plot. Move the floating palette as needed by clicking the top blue border and dragging it. This tool controls which factor(s) are plotted on the graph. At the bottom of the Factors Tool is a pull-down list from which you can also select the factors to plot. Only the terms that are in the model are included in this list. Click the **Term** list down-arrow and select **A**.



Changing to the main effect of A (a one-factor plot)

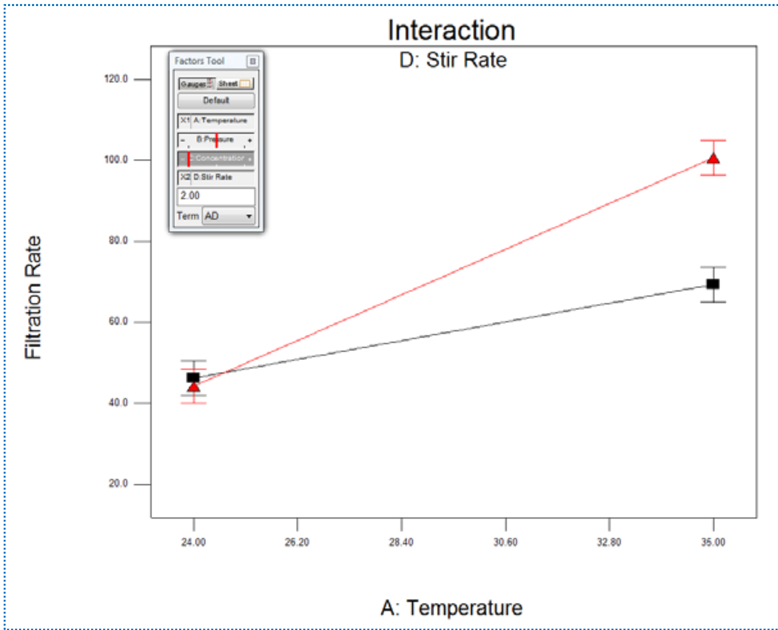
Note the warning at the top of the plot of A (Temperature). It states "Factor involved in an interaction." You should never try to interpret main effects plots of factors involved in interactions because they provide misleading information.

Let's do something more productive at this stage: Go back to the **Factors Tool** and select from the **Term** list the other significant interaction **AD**.



Interaction AD

Notice on the Factors Tool that factors not already assigned to an axis (X1 or X2) display a vertical red slider bar. This allows you to choose specific settings. The bars default to the midpoint levels of these non-axes factors. You can change their levels by dragging the bars, or by typing the desired level in the numeric space near the bottom of the Factors Tool. Check this out by grabbing the slide bar for factor **C:Concentration** and moving it to the left. Notice how the interaction graph changes.

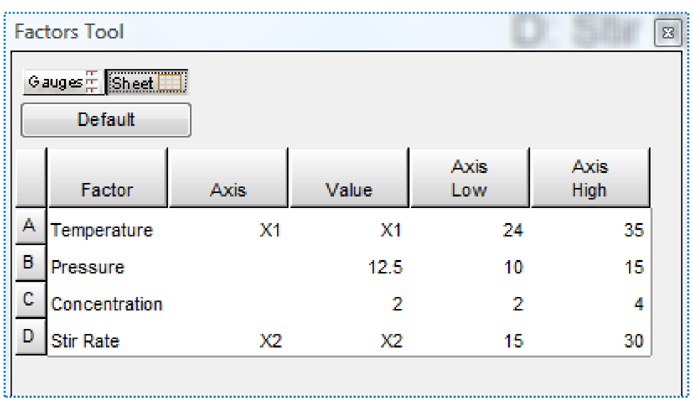


Interaction AD with the slider bar for factor C set far left at its low (–) level

It now becomes clear that a very high filtration rate can be achieved by going to the high stir rate (the red line for factor D). Click this high point to get all the details on its response and factor values. This is the optimum outcome.

To reset the graph to its default concentration, you could type “3”at the bottom of the Factors Tool. (Factor C must be clicked and highlighted for this to take effect.) You can also get the original settings back by pressing the Default button. Give it a try, but remember that going to low concentration of formaldehyde was a primary objective for this process-troubleshooting experiment, so be sure to slide C back to the left again.

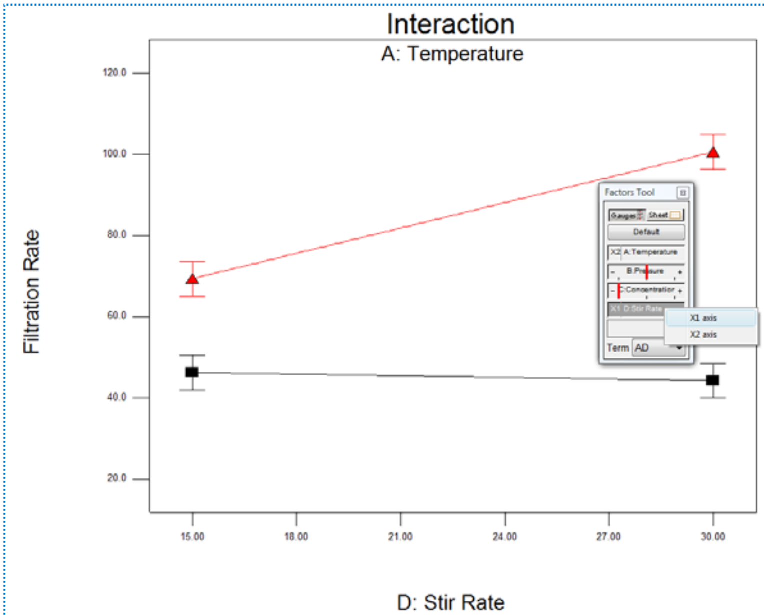
Yet another option is available for setting factor levels, which you can see by going to the **Factors Tool** and clicking the **Sheet** button. This view offers alternative modes for specifying how to set up your plot. In the columns labeled “Axis” and “Value” you can change the axes settings or type in specific values for factors. Don’t bother with this – we just wanted to show it to you because it may come in handy.



	Factor	Axis	Value	Axis Low	Axis High
A	Temperature	X1	X1	24	35
B	Pressure		12.5	10	15
C	Concentration		2	2	4
D	Stir Rate	X2	X2	15	30

Sheet View of Factors Tool

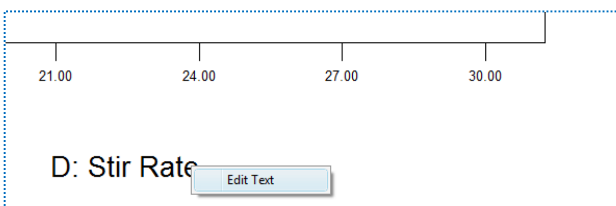
Click back to **Gauges** to return the Factors Tool to its default configuration. You can view the AD interaction with the axes reversed by right-clicking **D:Stir Rate** and changing it to **X1 axis**.



Axes switched

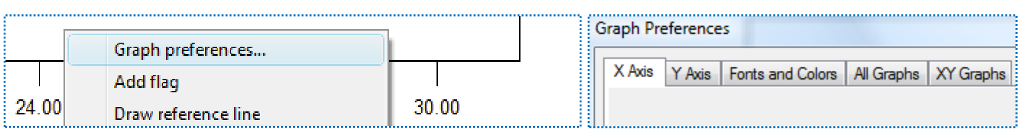
It makes no difference statistically, but it may make more sense this way.

One last thing: You can edit at least some text on many of your graphs by right-clicking your mouse. For example, on the interaction graph you can right-click the X1-axis label. Then choose Edit Text. The program then provides an entry field. Try it!



Edit text capability

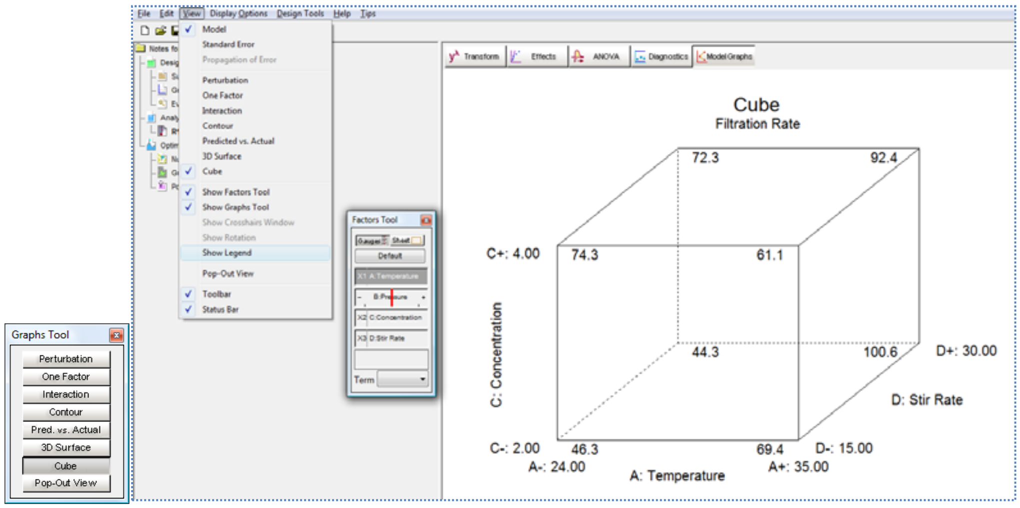
You can also right-click anywhere on the plot to get options for Graph Preferences. There you can change the layout of the X1 or X2 axis, etc. Check this out!



Graph preference option (via right-click of mouse over the graph)

Draw the Cube Plot

Now from the floating **Graphs Tool** select **Cube** to see the predicted response as a function of the three factors that created significant effects: A, C, and D. Turn off the legend via **View**, **Show Legend** (toggle).



Cube plot of A, C, and D, with legend toggled off

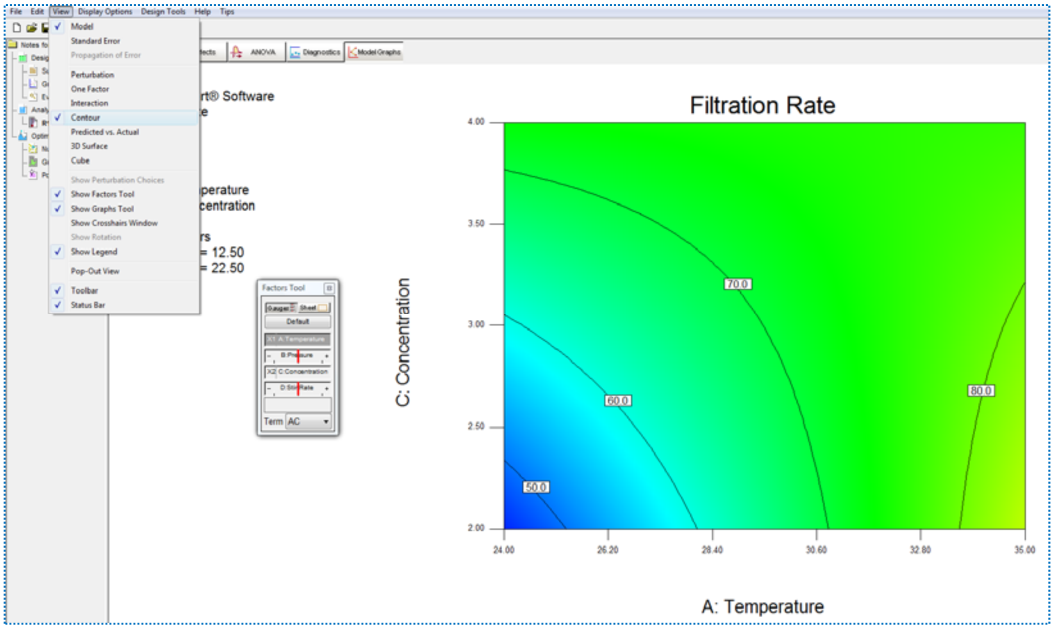
This plot shows how three factors combine to affect the response. All values shown are predicted values, thus allowing plots to be made even with missing actual data. Because the factors of interest here are A, C, and D, the program picked them by default. (You can change axes by right-clicking any factor on the Factors Tool.)

Filtration rate is maximum at settings A+, D+, C- (lower back right corner with predicted response over 100), which also corresponds to the reduced formaldehyde concentration. Fantastic!!

Produce Contour and 3D Plots of the Interaction

An interaction represents a non-linear response of second order. It may be helpful to look at contour and 3D views of the interaction to get a feel for the non-linearity.

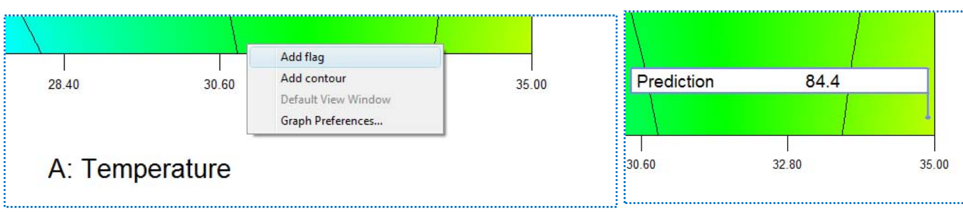
First select **Contour** to get a contour graph. Also, if you haven't done it already, turn the legend back on by choosing **View**, **Show Legend** (the checkmark appears when the legend is on.) The axes should come up as A (Temperature) and C (Concentration). If not, simply right click over the Factor Tool and make the appropriate changes.



Contour graph, legend back on

You may be surprised to see the screen's color shading – graduated from cool blue for lower response levels to warm yellow for higher values.

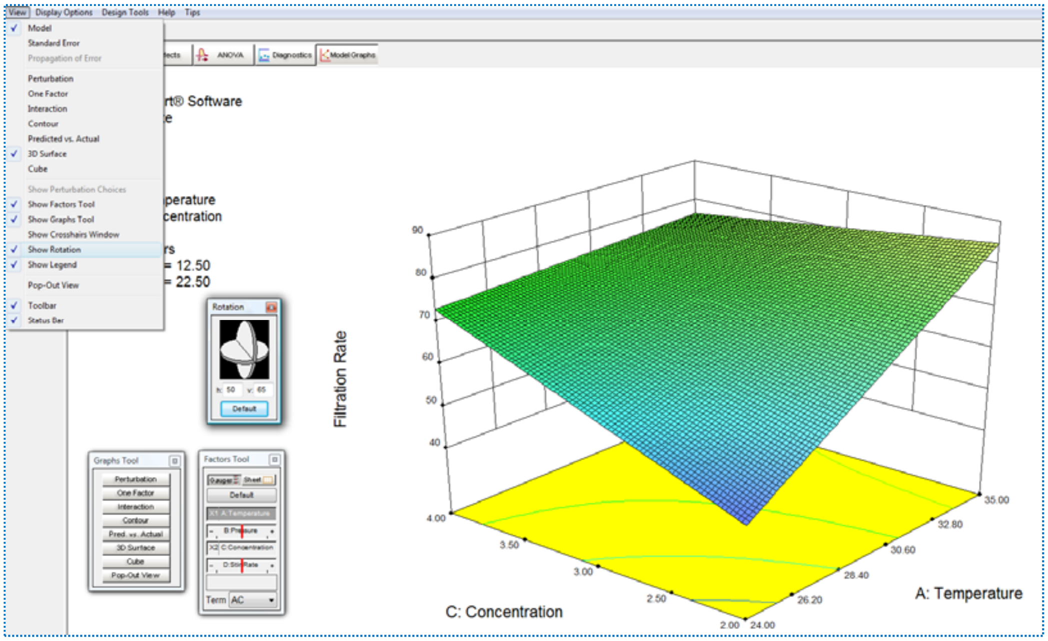
Design-Expert contour plots are highly interactive. For example, you can click on a contour to highlight it. Then you can drag it to a new location. Furthermore, by right-clicking anywhere within the graph you can bring up options to add flags, add contours, or change graph preferences.



Adding a flag (via right-click menu)

If you like, play around a bit with these options. However, these graphs are overkill for such a simple design (remember – the experiment involved only two levels of each factor). Therefore it will be best if you hold off on too much exploration of these advanced features until you can move on to the Response Surface Tutorials.

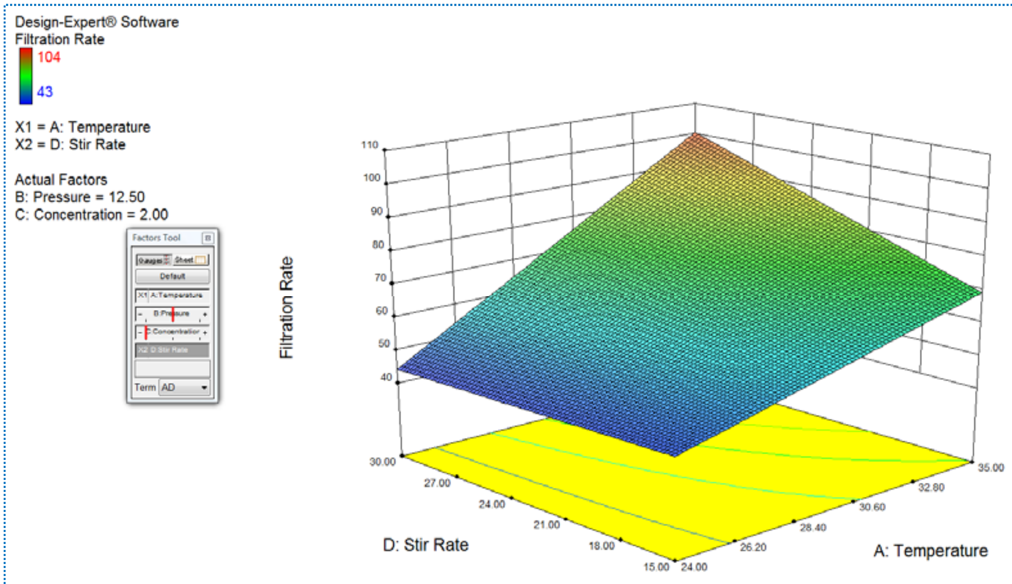
Now, strictly for creating an impressive-looking graph (which may or may not add anything to the story), select **3D Surface**. Also select **View, Show Rotation.**



A 3D view of the AC interaction

Grab the rotation wheel with your mouse and rotate the plot to different angles. It's fun! Press the Default button to re-set the graph to its original coordinates. Now try turning the graph without the wheel. Move your mouse cursor (🡅) over the graph. When it turns into a hand (✋), press down and rotate the view however you like.

Before moving on to the last stage, take a look at the other interaction by going to the **Factors Tool** and from the **Term** list selecting **AD**.



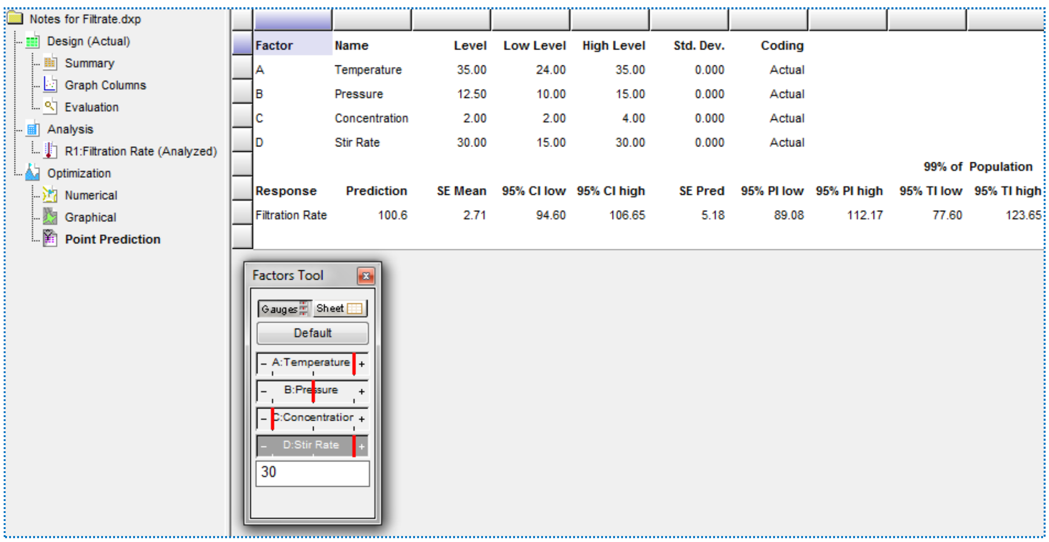
3D plot for second interaction: AD

We have nearly exhausted all the useful tools offered by Design-Expert for such a basic design of experiments, but there's one more tool to try.

Point Prediction

The last feature that we will explore appears at the upper left of the screen under the main branch of **Optimization**: Click the **Point Prediction** node to make response predictions for any set of conditions for the process factors. When you first enter this screen, the floating **Factors Tool** palette defaults to the center points of each factor. Levels are easily adjusted with the red slider bars or more precisely by using the Sheet view. In this case, the analysis suggests that you should slide the factors as follows:

- A (Temperature) right to its high level (+)
- B (Pressure) leave at default level of center point
- C (Concentration) left to its low level (-)
- D (Stir Rate) right to its high level (+)



Point prediction with best factor settings

This will provide the highest predicted filtration rate with the least amount of formaldehyde.

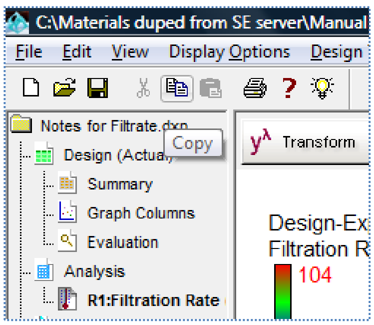
Besides the response prediction value, several other pieces of information are provided. The "SE Mean" is the standard deviation associated with the prediction of an average value at these settings. The "95% CI" is the confidence interval that is calculated to contain the true mean 95% of the time. The "SE Pred" is the standard deviation associated with the prediction of an individual observation. The "95% PI" is the prediction interval calculated to contain the true value of an individual observation 95% of the time. Finally, the 95% TI is the tolerance interval calculated to contain a proportion (P) of the sampled population with a confidence ($1-\alpha$). By default, the interval contains 99% of the sampled population with 95% confidence. Note that the 95% confidence interval on a mean will have the narrowest spread, with the 95% prediction interval for a single observation being wider and the 95% TI which contains 99% of the population being the widest. The most rigorous interval, TI, is often required for setting manufacturing specifications, but most experimenters will settle for the PI as a way to manage expectations.

You've now viewed all the important outputs for analysis of factorials. We suggest you do a **File**, **Save** at this point to preserve your work. Design-Expert will save the model you created so the outputs can be quickly reproduced if necessary. Remember that if you want to write some comments on the file for future identification, you can click the Notes folder node at the top left of the tree structure at the left of your screen and then type in the description. It will be there to see when you re-open the file in the future.

Prepare Final Report

Now all that remains is to prepare and print the final reports. If you haven't already done so, just click the appropriate icon(s) and/or buttons to bring the information back up on your screen, and click the print icon (or use the **File, Print** command).

You can also copy graphs to other applications: Use **Edit, Copy** or press the copy icon (📋).



Copy icon

For ANOVA or other reports be sure to do a **Select All** first, or highlight the text you wish to copy.

This completes the basic tutorial on factorial design. Move on to the tutorials on advanced topics and features if you like, or exit from Design-Expert by choosing **File, Exit** from the menu. If you have not stored your data, or you made changes since the last save, a warning message will appear. Exit only when you are sure that your data and results have been stored.