Working up a match load using Design of Experiments (DOE)

By Dan Rorabaugh © 2001

Safety and disclaimer: The reader is advised that the loads tested in this article were safe in the rifle used in this article. The author makes no representation of safety for the loads, procedures, or methods reported herein.

I loaded additional rounds of combinations and checked for excessive velocity and other pressure signs prior to shooting the experiment and used these to zero the scope.

Summary: Wouldn't it be nice if you could find a method to work up a match load without having to adjust one variable (like bullet seating depth or powder weight) at a time? Design of Experiments (DOE) allows the advanced reloader to vary more than one quantitative and qualitative variable at the same time in a controlled manner and to determine which components yield the highest accuracy.

This article describes several experiments conducted by the author in the spring of 2001 to work up an accurate match load for a Remington 700 VS (1x12 twist) in .223 caliber. Five variables: brass, primer, bullet, powder weight and bullet seating depth were all varied at the same time in an experiment defined using DOE.

The Average Group Radius (AGR) of each target was determined by scanning the targets into a graphics program on a Windows 98 personal computer and using a Microsoft Excel spreadsheet to do the calculations. A second spreadsheet generated graphs showing the effect each variable had on the AGR.

A load capable of 0.25 moa and an unexpected component interaction resulted from these experiments.

What is Design of Experiments? DOE is a rigorous statistically based methodology that allows the user to put together experiments with multiple variables (inputs) and determine how they affect one or more outputs (in this case, the average group radius - AGR). It is used in agriculture, the semiconductor industry, automotive, pharmaceutical and other manufacturing sectors to optimize yields and improve designs. DOE helps companies in these industries improve quality, time to market and identify those factors that have the greatest impact on the manufacturing process. DOE gives the engineers using this tool a far more fundamental understanding of the entire system and how the underlying input variables affect one or more measurable outputs. The shooter, rifle and reloaded ammunition are a system of a sort.

A chief advantage DOE has over the "change one variable at a time" approach is to let the user find interactions between two or more variables and see how they affect the output. If you change one at a time you might overlook these interactions. DOE lets the user explore these potential interactions easily.

As I was interested in making very small groups, I needed an "output" to measure. Average Group Radius (AGR) was chosen, as it is an excellent way of representing the size of a group on a target. AGR is the average of the distances each shot is from the calculated center of the group. AGR can be determined with a ruler and handheld calculator, but would be very time consuming if examining numerous targets.

How do I figure out the Average Group Radius? I wrote a Microsoft Excel spreadsheet to do all the calculations. I use 5 shot groups on each target. The targets are scanned into Jasc's Paint Shop Pro. The center of each shot measured by reading it off the screen. All five are entered into the spreadsheet and it automatically calculates the AGR. See Figure 1.

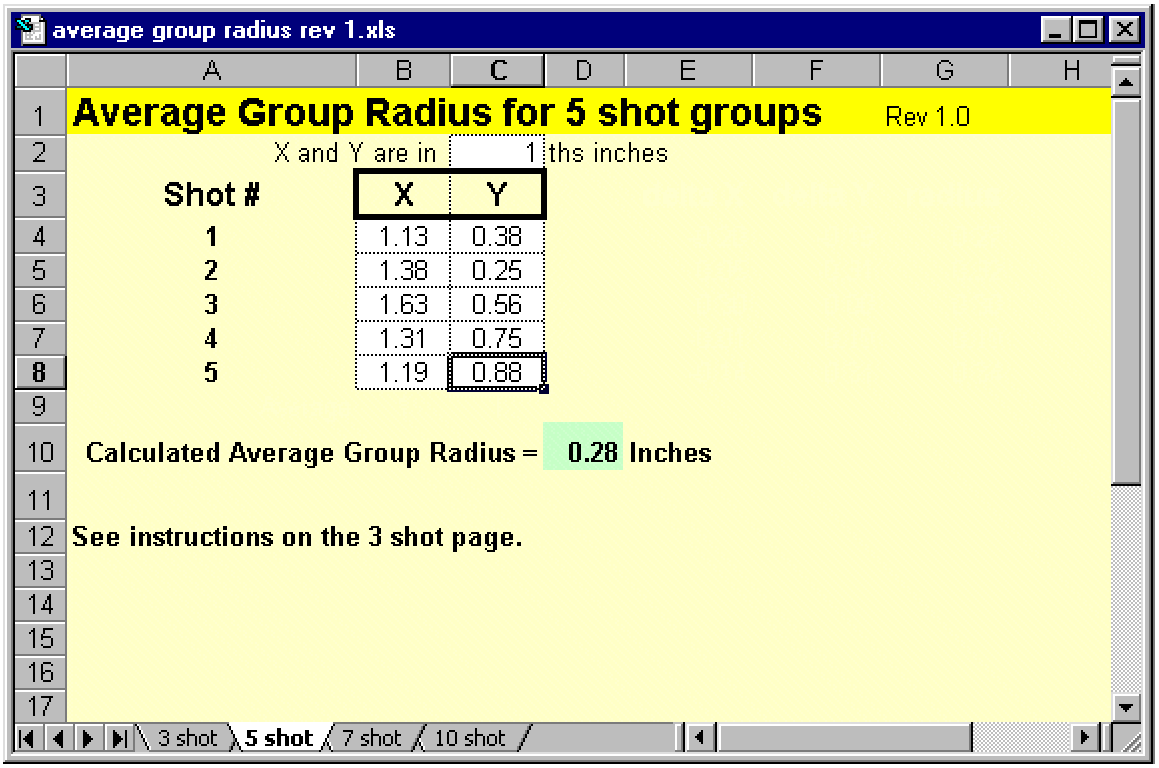

Figure 1

Rather than going into great detail on how this is done, the reader can download a copy of the spreadsheet and instructions from the San Jose Zouaves High Power Rifle Club website. The spreadsheet can handle 3, 5, 7 and 10 shot groups. As a sanity check, I measured a target using the computer and scanner and also using a ruler and came up with the exact same AGR.

http://www.zouaves.org/agr

Brass preparation: All brass used was fireformed in the Remington 700. They were then neck resized only using an RCBS competition die set. I have found I can minimize the runout by indexing each piece of brass with a felt pen and running it once through the resizing die, then turning it 180 degrees and running it through a second time. The primer pockets were uniformed using the Sinclair tool, and the flash holes were deburred with the RCBS tool. The necks were measured for uniformity using a Sinclair tool and brass with more than 1.5 mils worth of runout set aside. All brass was trimmed to 1.750 inches. All brass was then weighed. The Winchester brass was 92.3 +/- 1.0 grains. The Federal brass was 95.0 +/- 1.0 grains.

Defining the experiment: Variables come in two kinds: quantitative and qualitative. Quantitative variables are the kind you can measure incrementally, i.e. the amount of powder or seating depth off the rifling. You can vary it in small increments. Qualitative variables on the other hand are not measured in small increments. The color of an item is an example of a qualitative variable. The selection of different makes of bullets, choice of which company manufactured the brass or different types of primers are also good examples.

I chose to vary five different factors (inputs) that would be common in working up an accurate match load. There are two levels (Federal or Winchester) to the brass variable. There are three levels (three choices) to each of the balance of the variables. W748 was chosen as the propellant as it is a good choice for .223. I could have easily chosen a different powder and had done a similar experiment last year using H335. I consulted three or four reloading manuals and decided to try between 26 and 28 grains of W748.

Qualitative Variables:

Brass

Federal
Winchester

Primer

Federal 205M
Federal 205
CCI BR-4

Bullet (all 52 grain HPBT)

Sierra #1410
Speer #1036
Hornady #2249

Quantitative Variables

Amount of Winchester W748

26 grains
27 grains
28 grains

Bullet seating depth off the rifling (in thousandths of inches)

5
15
25

We cannot load every possible combination of all five variables. That would be 162 (2x3x3x3x3) combinations. Shooting 5 rounds per group and shooting each group 3 times would be 2,430 (162x5x3) rounds! We would wear out the barrel, our wallet and our patience. Fortunately, DOE comes to our rescue with very cleverly designed combinations that will allow us to find out the influence each variable has on the accuracy of our load with far fewer rounds.

I use an Excel add-on called DOE KISS 97 from Air Academy Associates to handle the experiment design and data analysis. With 5 variables (4 – 3 level and 1 – 2 level) DOE KISS 97 recommended I use a Taguchi L18 matrix for my experiment design. See Table 1.

Run	1	2	3	4	5	6	7	8
1	-1	-1	-1	-1	-1	-1	-1	-1
2	-1	-1	0	0	0	0	0	0
3	-1	-1	+1	+1	+1	+1	+1	+1
4	-1	0	-1	-1	0	0	+1	+1
5	-1	0	0	0	+1	+1	-1	-1
6	-1	0	+1	+1	-1	-1	0	0
7	-1	+1	-1	0	-1	+1	0	+1
8	-1	+1	0	+1	0	-1	+1	-1
9	-1	+1	+1	-1	+1	0	-1	0
10	+1	-1	-1	+1	+1	0	0	-1
11	+1	-1	0	-1	-1	+1	+1	0
12	+1	-1	+1	0	0	-1	-1	+1
13	+1	0	-1	0	+1	-1	+1	0
14	+1	0	0	+1	-1	0	-1	+1
15	+1	0	+1	-1	0	+1	0	-1
16	+1	+1	-1	+1	0	+1	-1	0
17	+1	+1	0	-1	+1	-1	0	+1
18	+1	+1	+1	0	-1	0	+1	-1

Table 1 (Taguchi L18 matrix)

The Taguchi L18 matrix (also called a screening matrix) allows us to examine up to eight different qualitative or quantitative variables simultaneously. Each vertical column of Table 1 represents a variable. Each horizontal row represents a "run" or what combination of variables that "load" will be made. As I am only examining 5 variables I will only need the first 5 columns. The variables are entered into the DOE program and the Excel spreadsheet and a table generated. See Figure 2. I will reload the combinations defined in each row.

Book2

	A	B	C	D	E	F	G	H	I	J
1	Factor	A	B	C	D	E				
2	*Row #*	Brass	Primer	Bullet	Powder Qty	Seating Depth		Y1	Y2	Y3
3	1	-1	-1	-1	26	5				
4	2	-1	-1	0	27	15				
5	3	-1	-1	1	28	25				
6	4	-1	0	-1	26	15				
7	5	-1	0	0	27	25				
8	6	-1	0	1	28	5				
9	7	-1	1	-1	27	5				
10	8	-1	1	0	28	15				
11	9	-1	1	1	26	25				
12	10	1	-1	-1	28	25				
13	11	1	-1	0	26	5				
14	12	1	-1	1	27	15				
15	13	1	0	-1	27	25				
16	14	1	0	0	28	5				
17	15	1	0	1	26	15				
18	16	1	1	-1	28	15				
19	17	1	1	0	26	25				
20	18	1	1	1	27	5				
21										

Figure 2

The quantitative variables (factors D and E) have a "quantity" assigned to them, the qualitative variables (factors A, B and C) a value of –1, 0 or 1.

Variable	Table value
Brass	
Federal	-1
Winchester	1
Primer	
Federal 205M	-1
Federal 205	0
CCI BR-4	1
Bullet	
Sierra #1410	-1
Speer #1036	0
Hornady #2249	1

Table 2

Figure 2 shows us how to load each combination, which component to use and the amount of W748 and bullet seating depth. Columns Y1, Y2 and Y3 are the AGR values from the targets that we will add later. For this experiment we are expending 5 rounds per group with 3 repetitions (Y1 – Y3) and 18 different combinations – the 18 rows.

5 x 3 x 18 = 270 rounds total. Far fewer than the 2,430 we would have had to fire if we tried every possible combination.

Loading the experiment: Loading 270 rounds in 18 different combinations (defined in Figure 2) took careful planning. The brass was primed using a RCBS hand priming tool and placed 15 each in 18 separate plastic ammo boxes. Each box was marked with a sticker identifying the row and load. The Winchester W748 was thrown with a Redding BR-30 and each throw individually weighed on a RCBS 505 balance beam scale. Correct bullet seating depth was measured using the Stoney Point gauge and adjusted accordingly for each of the three different types of bullets.

Shooting the experiment: The experiment was shot in a single morning and afternoon at a local 100-yard range. The velocities were captured using an Oehler 35P chronograph placed about eight feet in front of the muzzle. I mounted my Weaver 16T scope using Leupold mounts and shot with the scope set at 16X. Mirage was not too bad as the day was not hot. The front rest was the simple bright orange Hoppe's with rear bag with bunny ears.

The rows were shot in a random order created by the DOE program. I went through all 18 rows and started again for three full repetitions eventually finishing all 270 rounds. The rifle was cleaned about every 50 shots as we shoot 50 rounds for record during a match. The targets had been carefully serialized and a notebook record kept for each target and row fired.

Crunching the data: The AGR of each target was determined by scanning each target into my PC using a Hewlett Packard ScanJet 4200C scanner. The scanner software lets me then send each image into the Jasc Paint Shop Pro graphics program where the center of each bullet hole is identified and the X and Y coordinates read directly from Paint Shop Pro. These coordinates were then written onto each target. After all 54 targets had been scanned the X and Y coordinates were entered into the "5 shot" page of the AGR Excel spreadsheet to calculate the AGR. The AGR for each target was written on each target next to the group.

All 54 AGR measurements were then entered into the DOE spreadsheet under the Y1, Y2 and Y3 columns noted in Figure 2. See Figure 3 for the complete spreadsheet.

Book2

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Factor	A	B	C	D	E							
2	Row #	Brass	Primer	Bullet	Powder Qty	Seating Depth		Y1	Y2	Y3		Y bar	S
3	1	-1	-1	-1	26	5		0.25	0.45	0.27		0.323333	0.110151
4	2	-1	-1	0	27	15		0.27	0.26	0.35		0.293333	0.049329
5	3	-1	-1	1	28	25		0.36	0.44	0.26		0.353333	0.090185
6	4	-1	0	-1	26	15		0.13	0.27	0.3		0.233333	0.090738
7	5	-1	0	0	27	25		0.31	0.33	0.23		0.29	0.052915
8	6	-1	0	1	28	5		0.13	0.22	0.28		0.21	0.075498
9	7	-1	1	-1	27	5		0.21	0.22	0.19		0.206667	0.015275
10	8	-1	1	0	28	15		0.37	0.29	0.44		0.366667	0.075056
11	9	-1	1	1	26	25		0.4	0.51	0.21		0.373333	0.151767
12	10	1	-1	-1	28	25		0.29	0.34	0.26		0.296667	0.040415
13	11	1	-1	0	26	5		0.22	0.51	0.44		0.39	0.151327
14	12	1	-1	1	27	15		0.33	0.37	0.4		0.366667	0.035119
15	13	1	0	-1	27	25		0.13	0.14	0.15		0.14	0.01
16	14	1	0	0	28	5		0.32	0.21	0.31		0.28	0.060828
17	15	1	0	1	26	15		0.25	0.27	0.19		0.236667	0.041633
18	16	1	1	-1	28	15		0.28	0.28	0.2		0.253333	0.046188
19	17	1	1	0	26	25		0.24	0.25	0.32		0.27	0.043589
20	18	1	1	1	27	5		0.29	0.28	0.31		0.293333	0.015275
21													

Figure 3

Column L (Y bar) gives the average AGR of the three measurements in the same row. Column M (S) gives the standard deviation of the three AGR measurements in the same row. A quick glance at the data shows us Row 13 is very promising. However, we won't stop here. The DOE program will now show us how each component in each variable effect AGR.

Interpreting the data: The DOE software allows us to generate what are known as **Marginal Means Plots** for the impact each variable has on AGR (**Y-hat marginal means plot**) and the standard deviation (**S-hat marginal means plot**). The DOE program automatically averages the output values (Y-hat and S) associated with each level of each factor and creates the marginal means plots. This is significant as the marginal means plots tell us the impact each variable and each level of variable has on our AGR and STD Dev. This quickly tells us what components, powder levels and seating depth will yield the smallest group sizes. Marginal means plots can be done using a calculator and graph paper. It is beyond the scope of this article to show how this is done. Perhaps this can be done in a future "how-to" article.

Figure 4 is the Y-hat Marginal Means Plot. It shows the effect each variable and each component have on the AGR. The Y-axis is AGR in inches. The X-axis shows the five variables. By referring to Table 2 we can read Figure 4. It shows us:

Brass - Winchester brass (1) has slightly smaller AGR's on average than Federal (-1) brass.
Primer – Federal 205 (0) primers have smaller AGR's than Federal 205M (-1) or CCI BR-4 (1).
Bullet – Sierra #1410 (-1) has smaller AGR's than Speer #1036 (0) or Hornady #2249 (1).
Powder Qty – 27 grains has smaller AGR's than 26 or 28 grains of W748.
Seating Depth – Seating depth does not have a large effect on AGR.

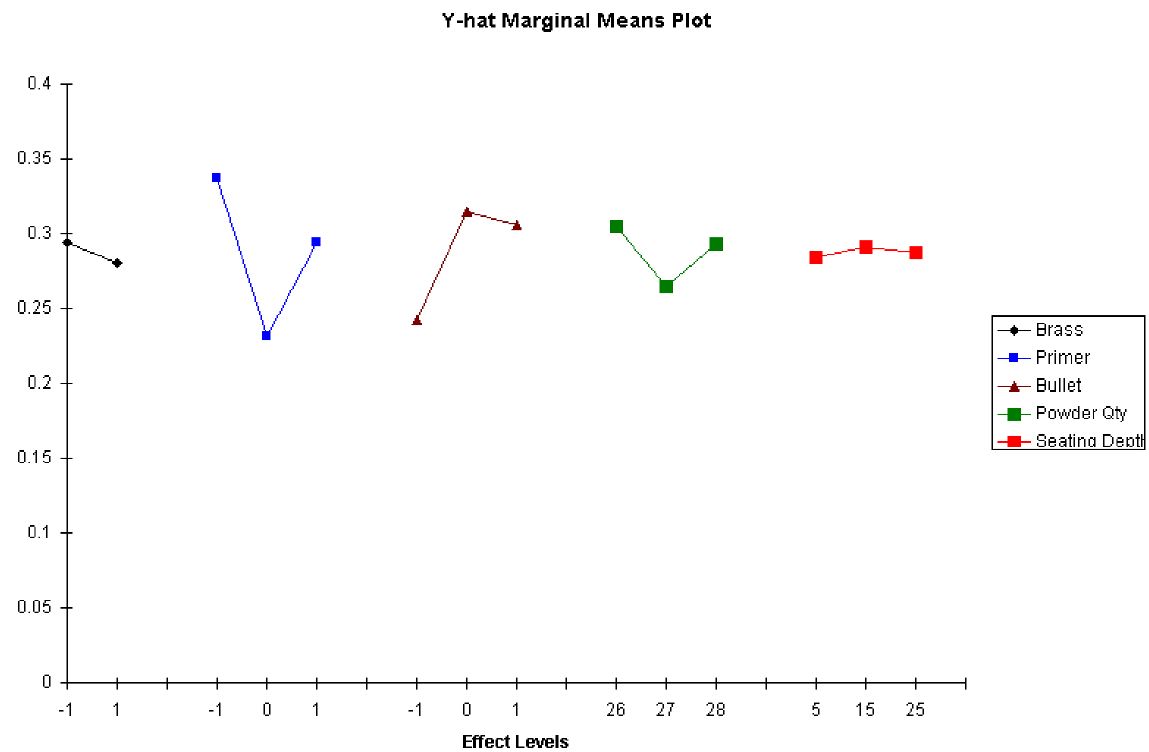

Figure 4

Figure 5 is the S-hat Marginal Means Plot. It shows the effect each variable and each component have on the Standard Deviation (STD Dev) of the AGR. The Y-axis is the Standard Deviation. The X-axis shows the five variables. By referring to Table 2 we can read Figure 5. It shows us:

Brass - Winchester brass (1) has smaller STD Dev on average than Federal (-1) brass.
Primer – Federal 205 (0) primers have smaller STD Dev than Federal 205M (-1) and slightly smaller than CCI BR-4 (1).
Bullet – Sierra #1410 (-1) has smaller STD Dev than Speer #1036 (0) or Hornady #2249 (1).
Powder Qty – 27 grains has smaller STD Dev than 26 or 28 grains of W748 by quite a bit.
Seating Depth – 15 thousandths off the rifling has the smallest STD Dev.

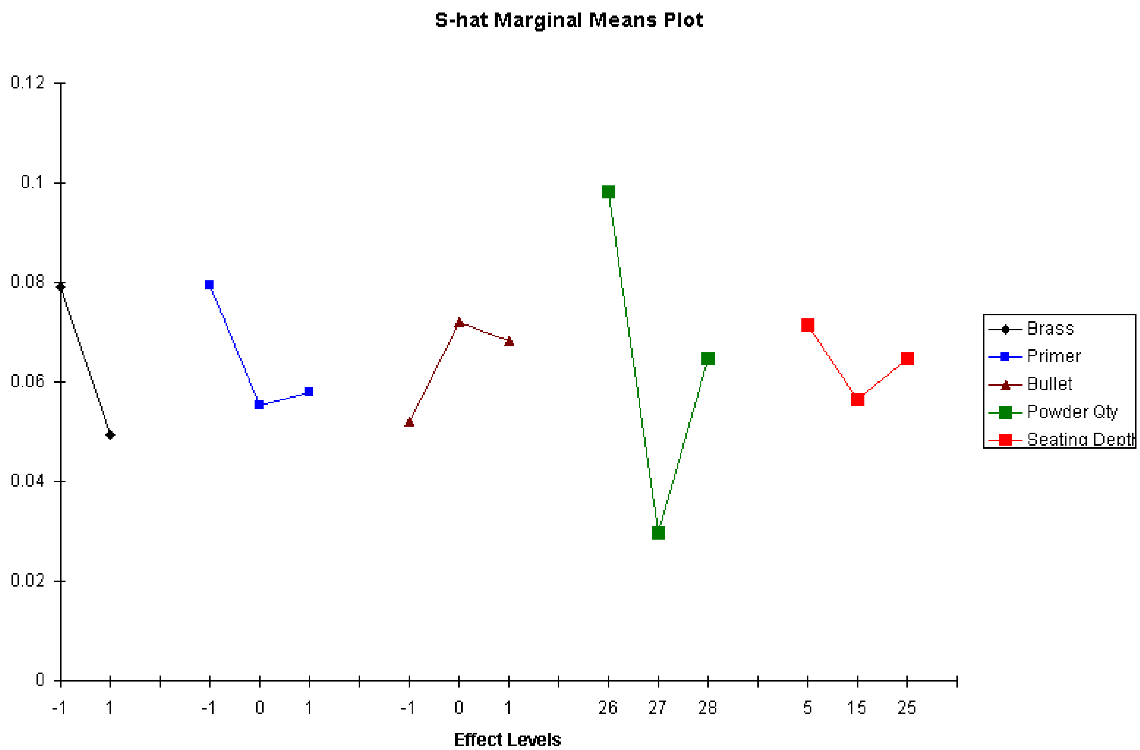

Figure 5

Defining the follow up experiment: We are not done yet. The DOE program has told us the qualitative variables to go with:

Winchester brass
Federal 205 primers
Sierra #1410 bullet

It has also told us about where to examine the quantitative variables:

About 27 grains of W748, and due to low STD Dev, about 15 thousandths off the rifling.

When I looked at the results in Figure 3 I saw row 13 was unusually accurate. One cannot ignore 0.13", 0.14" and 0.15" AGR. This was with Winchester brass, Fed 205 primer, Sierra #1410, 27 grains of W748 and 25 thousandths off the rifling. I think it is surprising that the standard Fed 205 primers would perform better than the Fed 205M match primers. I don't know what criteria Federal uses to sort the match primers from the regular primers, but it's worth looking at the match primers a second time to see if this was a fluke.

For the follow up experiment, I will go with Winchester brass and Sierra #1410 bullets and the following:

Primer:

Federal 205 (-1)
Federal 205M (1)

Powder Qty:

27.0 grains
27.5 grains

Seating Depth:

15 thousandths
25 thousandths

I decided to use 27.0 grains and 27.5 grains of W748 as the graphs showed there might be something gained with a little more powder. Row 13 used 25 thousandths and the S-hat graph liked 15 thousandths off the rifling so I would look at those again.

For experiment #2 the DOE program recommended a full factorial matrix with 5 replications. Full factorial means I am looking at all combinations of all three variables. The rounds were loaded and fired at the same range as before. The targets were measured and entered into the spreadsheet. See Figure 6.

experiment 2.xls

	A	B	C	D	F	G	H	I	J	L	M
1	**Factor**	**A**	**B**	**C**							
2	***Row #***	Primer	Powder Qty	Seating Depth	Y1	Y2	Y3	Y4	Y5	Y bar	S
3	***1***	-1	27.0	15	0.31	0.27	0.33	0.41	0.35	0.334	0.051769
4	***2***	-1	27.0	25	0.13	0.13	0.38	0.13	0.14	0.182	0.11077
5	***3***	-1	27.5	15	0.23	0.34	0.27	0.23	0.25	0.264	0.045607
6	***4***	-1	27.5	25	0.32	0.24	0.13	0.2	0.09	0.196	0.090719
7	***5***	1	27.0	15	0.19	0.23	0.32	0.25	0.28	0.254	0.049295
8	***6***	1	27.0	25	0.31	0.34	0.21	0.29	0.39	0.308	0.066483
9	***7***	1	27.5	15	0.32	0.47	0.19	0.25	0.29	0.304	0.104785
10	***8***	1	27.5	25	0.21	0.22	0.45	0.33	0.28	0.298	0.097826
11											
12											
13	Random Order = 5 ,8 ,3 ,2 ,1 ,4 ,6 ,7										
14											
15	Primer	-1	Fed 205								
16		1	Fed 205M								
17											

Figure 6

Row 2 is the same "recipe" as Row 13 from the first experiment. You cannot argue with the numbers. The third replication (Y3) of 0.38 might be "operator error". There is something very good about this combination.

Crunching the data: Once again an Y-hat and S-hat marginal means plots were generated. See Figures 7 and 8.

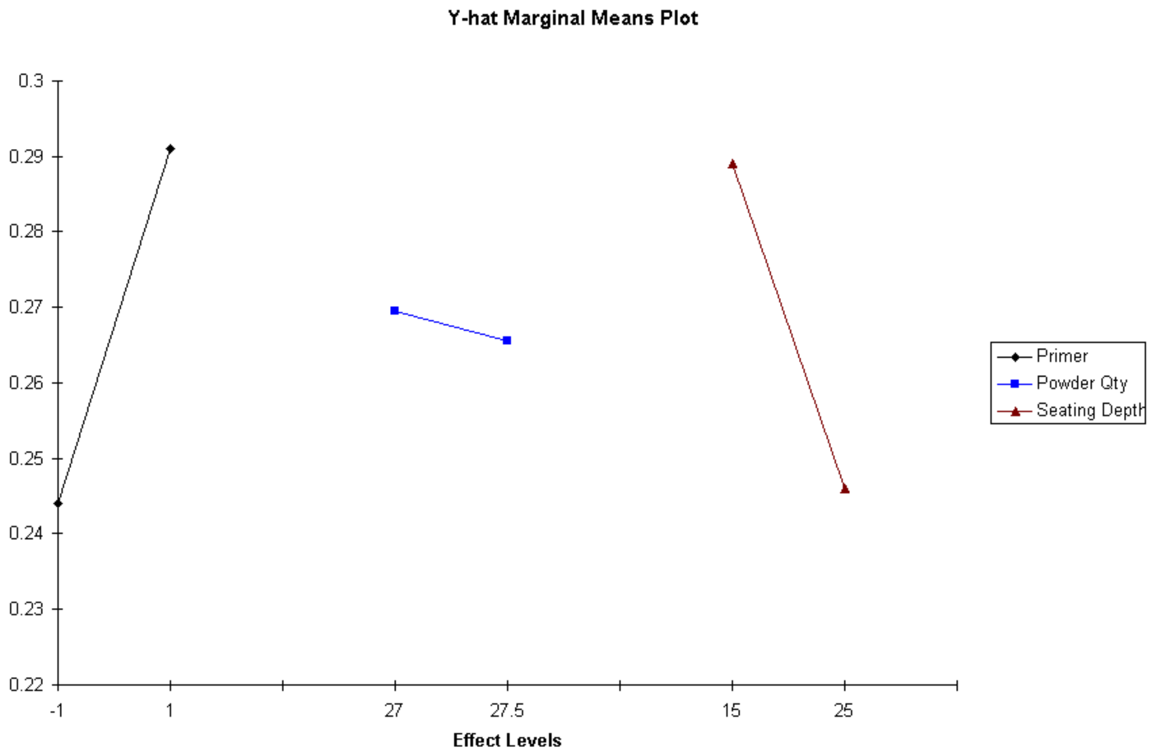

Figure 7

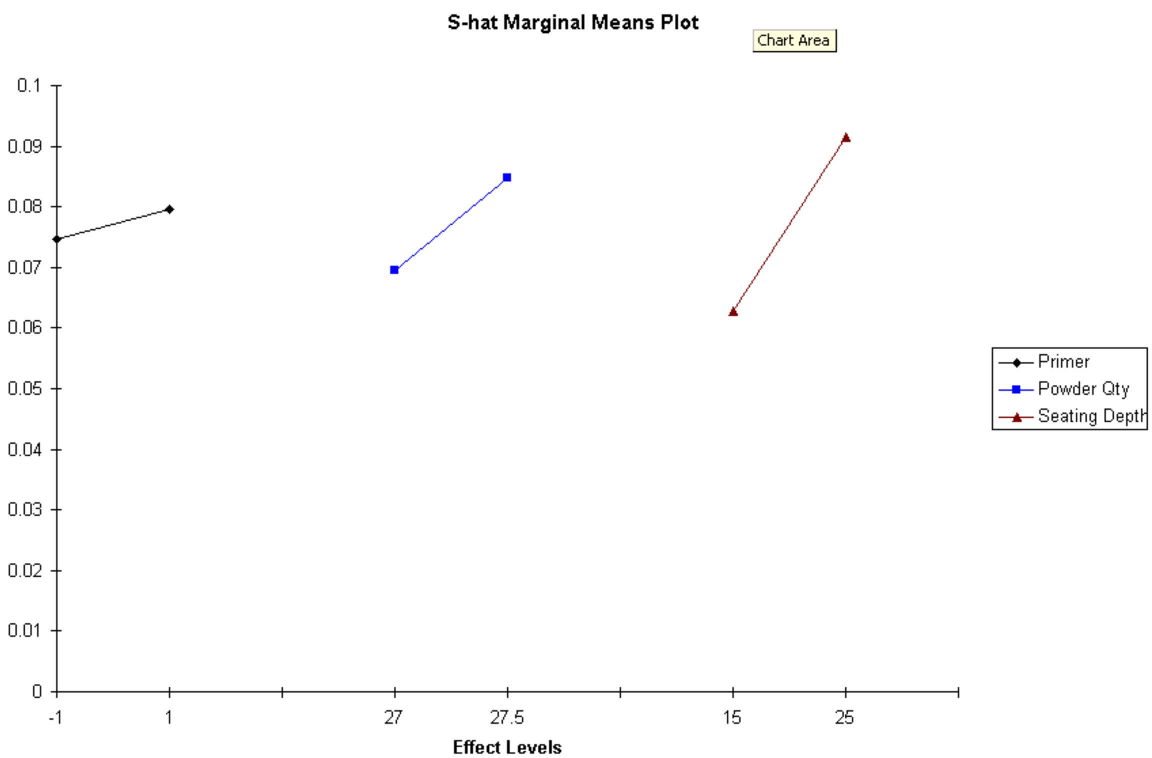

Figure 8

Interpreting the data for the follow up experiment: The Y-hat marginal means plot once again shows the Federal 205 (-1) has smaller AGR's than the match primer. There is very little difference in AGR between 27.0 and 27.5 grains of W748 and that 25 thousandths off the rifling has smaller AGR's than 15 thousandths.

I will go with the experiment's recommendation of:

Winchester brass
Federal 205 primer
Sierra #1410 bullet
27.0 grains of W748
25 thousandths off the rifling

The chronograph noted this combination had an average muzzle velocity of about 3,175 fps.

This combination resulted in AGR's of 0.13, 0.14, 0.15, 0.13, 0.13, 0.38, 0.13 0.14 inches over two experiments. If I can be permitted to throw out a high and low value, the average AGR is approximately 0.14 inches. Double that and you get a 0.28-inch average group diameter. Close enough to a 0.25 moa group in my book.

Next experiment: The DOE program also allows one to do **Regressive Analysis** on the data. This means the program attempts to come up with a mathematical model taking into account all the variables. Through extensive playing with it using the data from the follow up experiment, it showed the most important variables affecting AGR were the choice of primer and bullet seating depth. What was more important, it noted the *interaction* between the two was more important than either primer or seating depth by itself. I found this to be surprising. I don't know why this is important in my rifle.

This does beg another experiment for another day and perhaps another article. I wonder if I have an extra good lot of Federal 205 primers and a so-so lot of Federal 205M primers. So to investigate this I picked up 3 different lots each of Federal 205 and 205M primers. Later this summer I hope to try all 6 lots and vary the seating depth 20, 25 and 30 thousandths to better study and verify this interaction between primer and seating depth.

Conclusion: DOE allows us to look at many different variables. We are not limited to just those I used here. We can also vary brass preparation techniques or trigger pull. We can change how we use the front rest and use different scopes or other bench techniques. There is an old engineering adage, "If it can be measured, it can be optimized". DOE is a tool to that end. It gives the match shooter and reloader an extremely powerful tool that when used properly can move you closer (with certainty) to smaller group sizes.

Appendix: If you are interested in learning more about Design of Experiments I would recommend:

"Understanding Industrial Designed Experiments" by Stephen R. Schmidt and Robert G. Launsby
published by Air Academy Press in Colorado Springs, Colorado ISBN 1-880156-03-2

Software

DOE KISS 97 by Air Academy Associates, website: www.airacad.com
(719) 531-0777

Paint Shop Pro by Jasc Software, website: www.jasc.com

Excel by Microsoft, website: www.microsoft.com

Author Bio: I am an electrical engineer at a large Silicon Valley semiconductor company involved in bringing new products to market. Part of the job involves characterizing the devices to insure they meet spec. I took a four-day class in Design of Experiments in 1999 and saw how it could be applied to reloading. I also shoot High Power rifle with the San Jose Zouaves (www.zouaves.org) and am webmaster of their homepage.