ST 516 Final Project
December 12, 2019
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Executive Summary:

An optical fiber manufacturer needed our project team's help to optimize a new design being introduced to minimize signal attenuation. The objectives were to identify any significant main effects and interactions on attenuation, build a model to predict attenuation from the significant factors, and generate a list of optimal settings/characteristics based on that model. Four different data requests were sent, totaling 60 runs and $60,000. The first request was an initial screening design in which the team discovered the significant factors: fiber design, germanium concentration, and furnace temperature. The second request explored the center and high and low points of the significant factors in order to try and find the minimum attenuation possible. The third request was an additional iterative step including axial points for germanium concentration and furnace temperature. The quadratic factors were also included in this iteration's analysis and provided the team with the minimal attenuation required. The list of optimal settings to minimize attenuation are 2 for fiber design, 0.029 for germanium concentration, and 2017 ℃ for furnace temperature. Fiber design 1 also gave minimizing results; however, fiber design 2 was selected for giving slightly better results more frequently. The fourth and final request was a central composite design to verify our chosen optimal settings. Finally, we ran one large model with all run requests to confirm the results and ensure the lack of fit was insignificant.

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1. Introduction

Our project team was working for an optical fiber manufacturer to help minimize signal attenuation in a new design that is being introduced. The optical fiber drawing system consisted of a furnace to melt the end of the preform, sensors to monitor the diameter of the fiber being pulled from the preform, and coating devices to apply protective layers over the outer cladding. The preform first passed through a furnace. Next, a drop of molten glass formed at the end of the preform. The gob then fell away, and the single optical fiber inside was drawn out of the preform through compression on the preform from a feed mechanism at the top of the draw tower and tension provided from a take-up mechanism at the bottom of the draw tower.

The team wanted to run a process experiment to determine the best combination of settings for the fiber drawing process as well as a few other characteristics to minimize attenuation. The following factors were investigated: fiber draw speed (from 20-30 m/s), furnace temperature (from 1800-2200 ℃), draw tension (from 0.5-1.0 N), germanium concentration (from 0.01-0.05), fiber design (1 or 2), draw tower (1 or 2), raw material supplier (1 or 2), and coating type (1 or 2). The objectives were to identify any significant main effects and interactions on attenuation, build a model to predict attenuation from the significant factors, and generate a list of optimal settings/characteristics based on that model. The team had $50,000 for the experimental runs, with each run costing $1,000.

2. Experimental Design

2.1 Data Request 1: Initial Screening Design

The initial screening design was a 2^{8-4} fractional factorial design. Each factor was varied (either high or low value) for 16 runs. This design considered all main effects and some two factor interactions. Figure 1 shows the table of factor values used.

	Pattern	Draw Speed	Furnace Temp	Draw Tension	Germanium Conc	Fiber design	Draw Tower	Material Supplier	Coating	Y
1	--------	20	1800	0.5	0.01	1	1	1	1	2.32372319
2	---++++-	20	1800	0.5	0.05	2	2	2	1	1.16400667
3	--+-++-+	20	1800	1	0.01	2	2	1	2	2.370051525
4	--++--++	20	1800	1	0.05	1	1	2	2	1.815811992
5	-+--+-++	20	2200	0.5	0.01	2	1	2	2	1.00660995
6	-+-+-+-+	20	2200	0.5	0.05	1	2	1	2	2.98148246
7	-++--++-	20	2200	1	0.01	1	2	2	1	0.92552989
8	-++++---	20	2200	1	0.05	2	1	1	1	2.242111823
9	+----+++	30	1800	0.5	0.01	1	2	2	2	2.247303322
10	+--++--+	30	1800	0.5	0.05	2	1	1	2	1.202220427
11	+-+-+-+-	30	1800	1	0.01	2	1	2	1	2.288505634
12	+-++-+--	30	1800	1	0.05	1	2	1	1	1.730257232
13	++--++--	30	2200	0.5	0.01	2	2	1	1	0.969239724
14	++-+--+-	30	2200	0.5	0.05	1	1	2	1	2.982802884
15	+++----+	30	2200	1	0.01	1	1	1	2	0.852368484
16	++++++++	30	2200	1	0.05	2	2	2	2	2.270838756

Figure 1. Initial screening design for all factors with both high and low values.

2.2 Data Request 2: Centerpoints

The second data request was another 2^{8-4} fractional factorial design. In this case the centerpoints and high and low values of germanium concentration and furnace temperature were explored over both fiber designs. All other factors were kept constant at the low value of the provided range.

	Pattern	Fiber Design	Germanium Conc	Furnace Temp	Draw Tower	Material Supplier	Coating	Draw Tension	Draw Speed	Attenuation
1	--------	1	0.01	1800	1	1	1	0.5	20	2.19566983
2	--+-----	1	0.01	2200	1	1	1	0.5	20	0.937662187
3	-+------	1	0.05	1800	1	1	1	0.5	20	1.868694221
4	-++-----	1	0.05	2200	1	1	1	0.5	20	2.992495153
5	-00-----	1	0.03	2000	1	1	1	0.5	20	0.737889537
6	-00-----	1	0.03	2000	1	1	1	0.5	20	0.684299471
7	-00-----	1	0.03	2000	1	1	1	0.5	20	0.669691553
8	-00-----	1	0.03	2000	1	1	1	0.5	20	0.713901716
9	+-------	2	0.01	1800	1	1	1	0.5	20	2.405969537
10	+-+-----	2	0.01	2200	1	1	1	0.5	20	0.999544235
11	++------	2	0.05	1800	1	1	1	0.5	20	1.111047431
12	++-----...	2	0.05	2200	1	1	1	0.5	20	2.321846473
13	+00-----	2	0.03	2000	1	1	1	0.5	20	0.487030456
14	+00-----	2	0.03	2000	1	1	1	0.5	20	0.428685807
15	+00-----	2	0.03	2000	1	1	1	0.5	20	0.335158362
16	+00-----	2	0.03	2000	1	1	1	0.5	20	0.431984245

Figure 2. Second screening design varying the significant factors from screening design 1

2.3 Data Request 3: Incremental Optimization

The third data request was an elaboration on the values of germanium concentration and furnace temperature explored in the centerpoints analysis. Germanium concentration ranged from 0.005 to 0.05 by a step increase of 0.005 while furnace temperature ranged from 2240 ℃ to 2160 ℃ with a decreasing step of 10 ℃. All other factors were again kept constant at the low value of the provided range.

	Pattern	Fiber Design	Germanium Concentration	Furnace Temperature	Draw Tower	Material Supplier	Coating	Draw Tension	Draw Speed	Attenuation
2	++-+--+-	1	0.01	2220	1	1	1	0.5	20	1.063163528
3	-+-+-+-+	1	0.015	2210	1	1	1	0.5	20	0.992636561
4	--++--++	1	0.02	2200	1	1	1	0.5	20	1.129255096
5	+----+++	1	0.025	2190	1	1	1	0.5	20	1.176853261
6	--+-++-+	1	0.03	2180	1	1	1	0.5	20	1.218544089
7	+-+-+-+-	1	0.035	2170	1	1	1	0.5	20	1.538974927
8	++++++++	1	0.04	2160	1	1	1	0.5	20	1.753335858
9	--------	2	0.015	2230	1	1	1	0.5	20	1.268485379
10	-++--++-	2	0.02	2220	1	1	1	0.5	20	1.146936929
11	+-++-+--	2	0.025	2210	1	1	1	0.5	20	1.040767107
12	+--++--+	2	0.03	2200	1	1	1	0.5	20	1.061451763
13	+++----+	2	0.035	2190	1	1	1	0.5	20	1.223184211
14	---++++-	2	0.04	2180	1	1	1	0.5	20	1.478709938
15	-+--+-++	2	0.045	2170	1	1	1	0.5	20	1.595915933
16	++--++--	2	0.05	2160	1	1	1	0.5	20	1.745125709

Figure 3. Third screening design, step increase in germanium and decrease in furnace temperature

2.4 Data Request 4: Central Composite Design

The fourth and final request was a central composite design. This run included four runs of the best values for fiber design, germanium concentration and furnace temperature obtained from data request 3. Additionally, axial points for each continuous factor were calculated using the range of the factor and +/- $\sqrt{k}$. These axial points were run with the centerpoints of the other factor. This data request totalled 12 runs.

	Fiber Design	Germanium Concentration	Furnace Temperature	Draw Tower	Material Supplier	Coating	Draw Tension	Draw Speed	Attenuation
1	2	0.0302439	2000	1	1	1	0.5	20	0.334483083
2	2	0.0302439	2000	1	1	1	0.5	20	0.435272131
3	2	0.0302439	2000	1	1	1	0.5	20	0.42528646
4	2	0.0302439	2000	1	1	1	0.5	20	0.446554621
5	2	0.01	2200	1	1	1	0.5	20	1.014258729
6	2	0.01	1800	1	1	1	0.5	20	2.47977809
7	2	0.05	2200	1	1	1	0.5	20	2.256472396
8	2	0.05	1800	1	1	1	0.5	20	1.18697696
9	2	0.05837	2000	1	1	1	0.5	20	1.439373652
10	2	0.00171	2000	1	1	1	0.5	20	1.349003935
11	2	0.03	2283	1	1	1	0.5	20	1.883384748
12	2	0.03	1717	1	1	1	0.5	20	2.141175523

Figure 4. Central composite design of significant factors from previous analyses

3. Results and Analysis

3.1 Data Request 1: Initial Screening Design

When considering all the factors, the half normal plot (shown in Figure 5a) displayed the following main factors as having an effect: fiber design, furnace temperature, and germanium concentration. Another model was run considering only the main effects and their interactions, and this half normal plot is shown in Figure 5b. The following factors have an effect: fiber design, furnace temperature, germanium concentration*furnace temperature, and germanium concentration*fiber design. Because of aliasing, the interactions that have an effect in Figure 5a are still included in the effects in Figure 5b; draw speed*material supplier was aliased with germanium concentration*furnace temperature and draw speed*coating is aliased with germanium concentration*fiber design. Figure 6 shows the effect summary of the model with the main effects.

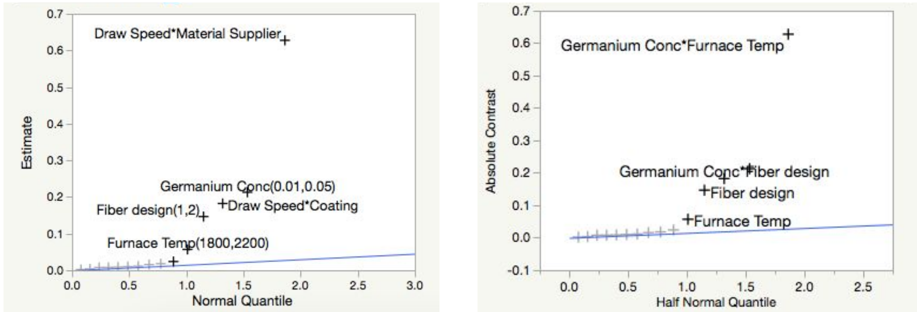


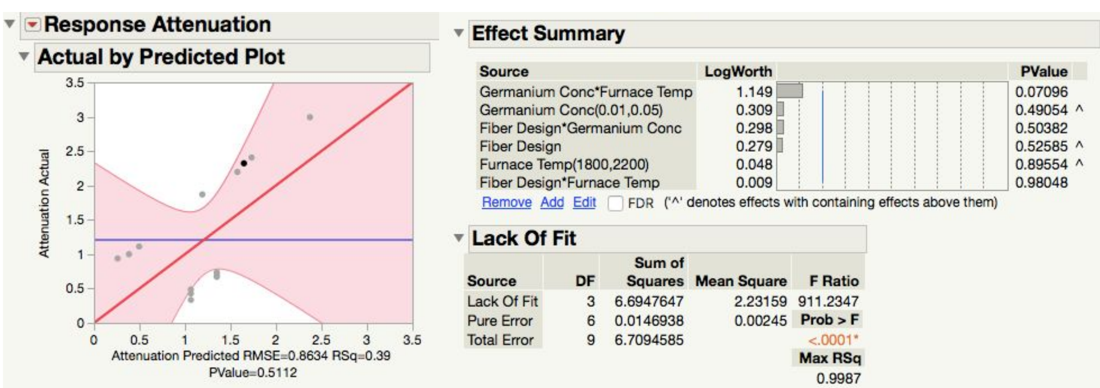
Figure 5. (a) Half normal plot of model considering all factors. (b) Half normal plot of model considering main effects from previous model and their interactions.

Source	LogWorth	PValue
Germanium Conc*Furnace Temp	12.610	0.00000
Germanium Conc(0.01,0.05)	7.975	0.00000 ^
Germanium Conc*Fiber design	7.326	0.00000
Fiber design(1,2)	6.428	0.00000 ^
Furnace Temp(1800,2200)	2.969	0.00107 ^

Figure 6. Effect summary of model with main effects.

3.2 Data Request 2: Centerpoints

After running the data from the second set of runs using the main factors of germanium concentration, furnace temperature, fiber design and their interactions, the lack of fit was significant. This is shown in Figure 7 by the variability in the actual by predicted plot, the lack of significance in the factors, and the significant f value for lack of fit. The conclusion drawn from this data request was that the data had curvature that was not being accounted for by the model.



Source	LogWorth	PValue
Germanium Conc*Furnace Temp	1.149	0.07096
Germanium Conc(0.01,0.05)	0.309	0.49054 ^
Fiber Design*Germanium Conc	0.298	0.50382
Fiber Design	0.279	0.52585 ^
Furnace Temp(1800,2200)	0.048	0.89554 ^
Fiber Design*Furnace Temp	0.009	0.98048

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	3	6.6947647	2.23159	911.2347
Pure Error	6	0.0146938	0.00245	Prob > F
Total Error	9	6.7094585		<.0001*
				Max RSq
				0.9987

Figure 7. Summary of fit for the second set of runs

In order to determine the ranges of germanium concentration and furnace temperature that should be further explored, the prediction profiler was evaluated for the second set of runs. As shown in Figure 8: the desirability is quite high at fiber design 1, germanium concentration of 0.01 and furnace temperature of 2200 ℃. This was verified with the cube plot in Figure 9, where the lowest value was 0.26 at the intersection of the same 3 factors. However, there did not seem to be a large difference between fiber design 1 and 2 so it was decided to move forward with evaluating ranges of germanium concentration (starting low and increasing) and furnace temperature (starting high and decreasing) for both fiber designs.

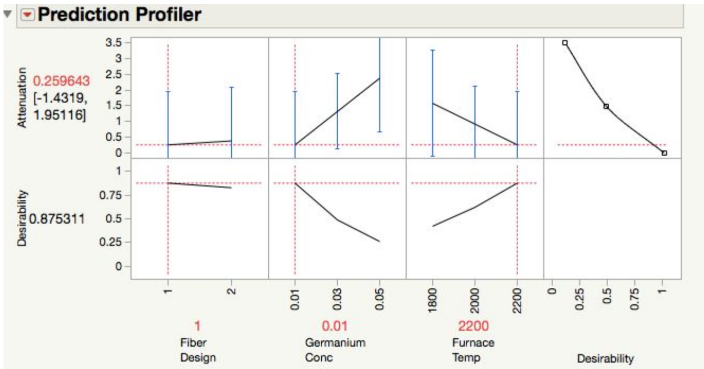


Figure 8. Prediction profiler maximizing the desirability (minimization) for attenuation

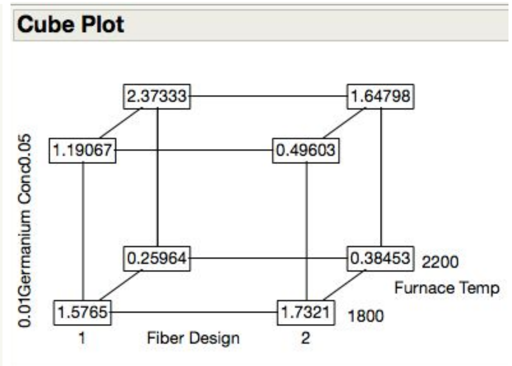
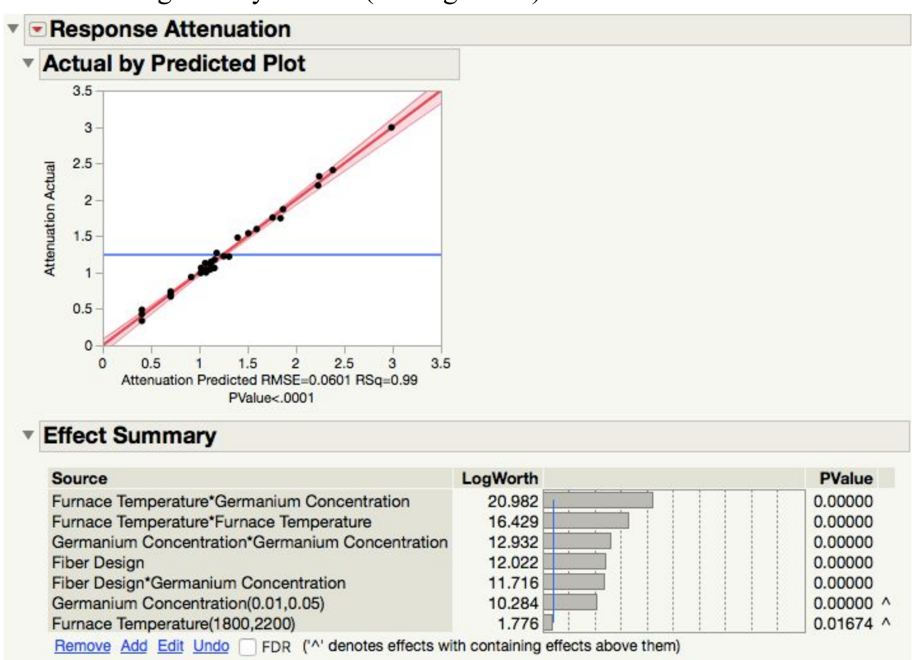


Figure 9. Cube plot maximizing the desirability (minimization) for attenuation

3.3 Data Request 3: Incremental Optimization

After running the third data request with germanium concentration, fiber design, and furnace temperature as the main effects and their interactions, JMP did not render useful results (effects summary and prediction profiler were not interpretable). The lack of fit was still significant, indicating curvature. After adding in quadratic expressions for furnace temperature and germanium concentration, the same issues arose. It was therefore decided to combine the data from the second and third sets of runs, creating a model using germanium concentration, fiber design, furnace temperature, their interactions, and the quadratic for germanium concentration and furnace temperature. Following this model, the interaction between fiber design and furnace temperature was removed due to insignificance. Residual and Q-Q plots were analyzed and deemed generally normal (see Figure 11).



Source	LogWorth	PValue
Furnace Temperature*Germanium Concentration	20.982	0.00000
Furnace Temperature*Furnace Temperature	16.429	0.00000
Germanium Concentration*Germanium Concentration	12.932	0.00000
Fiber Design	12.022	0.00000
Fiber Design*Germanium Concentration	11.716	0.00000
Germanium Concentration(0.01,0.05)	10.284	0.00000 ^
Furnace Temperature(1800,2200)	1.776	0.01674 ^

Figure 10. Actual by predicted plot and the effects summary for the second and third data combined, following the removal of fiber design and furnace temperature interaction.

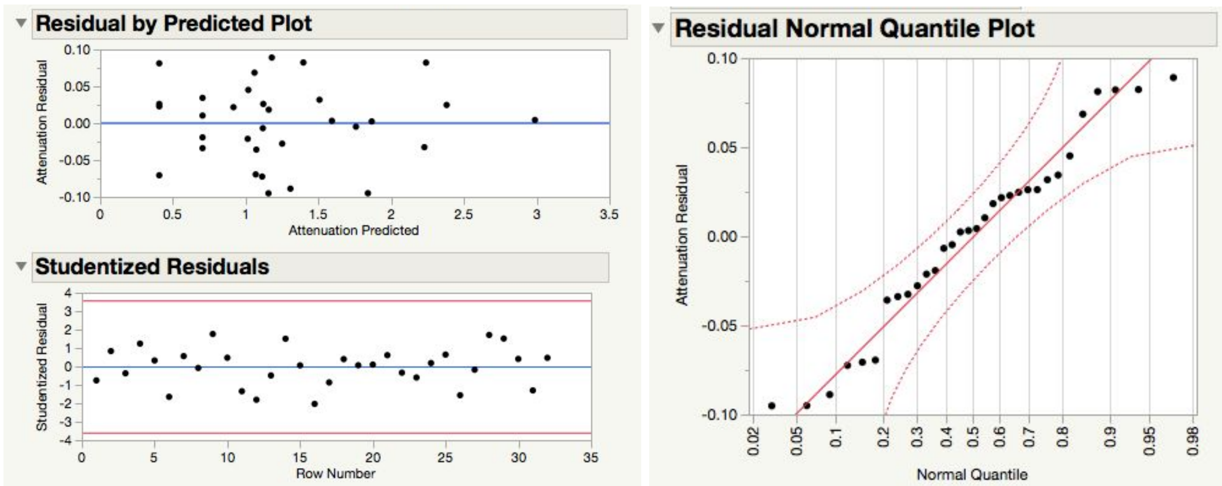


Figure 11. Residual plots and normal quantile plot for second and third data runs combined.

Desirability for attenuation was set to minimize using the prediction profiler, rendering an optimal experimental design of fiber design 2, germanium concentration of 0.030, and a furnace temperature of 2000 ℃. Both values for germanium concentration and fiber design were directly in the middle of the given ranges. The desirability was 0.868 shown in Figure 13, which is relatively high.

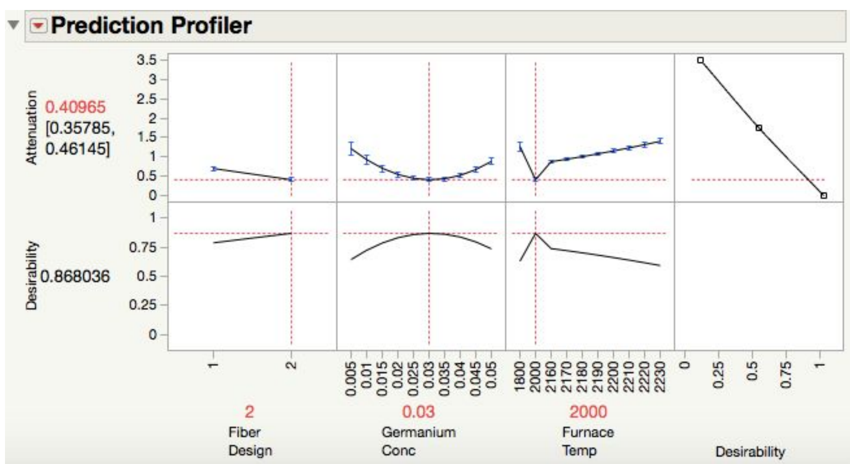


Figure 12. Optimized prediction profiler for combined experimental runs 2 and 3, indicating optimal settings for each of the three main effects.

Analyzing germanium concentration of 0.03 and furnace temperature at 2000 ℃ on the contour profiler showed the values at the center of the contour, indicating a minimum value for attenuation had been reached.

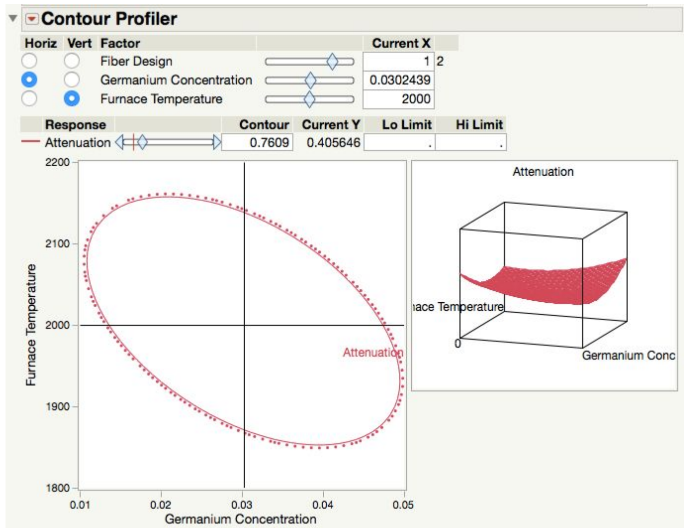


Figure 13. Contour profiler for second and third experimental design results.

3.4 Data Request 4: Central Composite Design

As a fourth data analysis procedure, a central composite design was tested totaling 12 runs. Because fiber design 2 appeared to be the best design in the results from data request 3, fiber design 2 was solely used in the experimental design. As a result, fiber design and all associated interactions did not rear any parameter estimate values. Results from the central composite design indicated that main effects, interactions, and quadratic terms were significant, with the exception of germanium concentration.

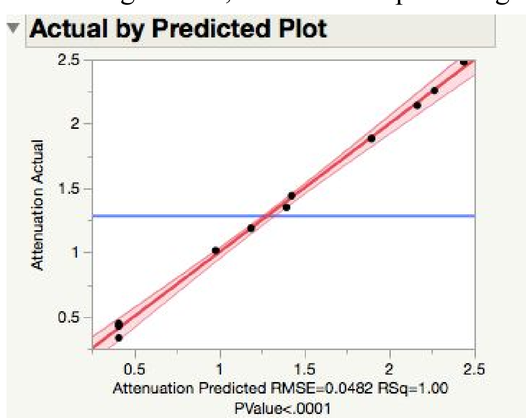


Figure 14. Actual by predicted plot for the central composite design

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.4102134	0.024093	17.03	<.0001*
Germanium Concentration(0.01,0.05)	0.0086544	0.017021	0.51	0.6293
Furnace Temperature(1800,2200)	-0.095047	0.01703	-5.58	0.0014*
Germanium Concentration*Furnace Temperature	0.6337537	0.024091	26.31	<.0001*
Germanium Concentration*Germanium Concentration	0.4987928	0.019002	26.25	<.0001*
Furnace Temperature*Furnace Temperature	0.8085381	0.019033	42.48	<.0001*

Figure 15. Parameter estimates for the central composite design

The prediction profiler for the fourth data request returned values of 0.029 for germanium concentration and a furnace temperature of 2018 ℃.

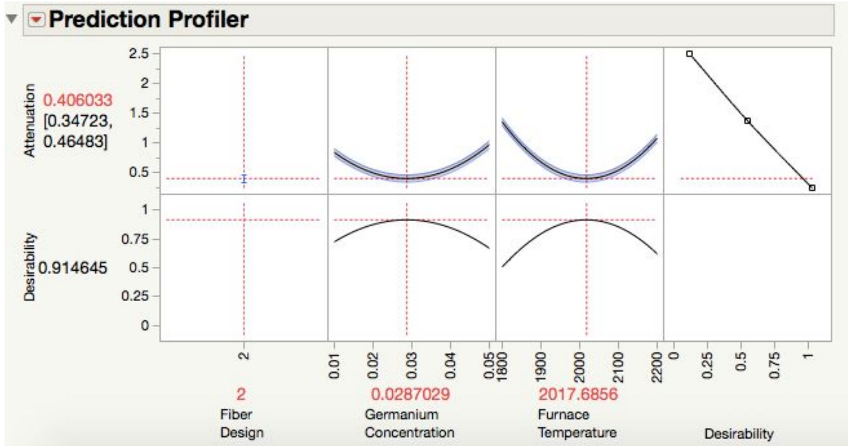


Figure 16. Prediction profiler for the central composite design

The lack of fit for the fourth set of runs is insignificant at a value of 0.5862. This suggests the model is capturing the curvature in the data.

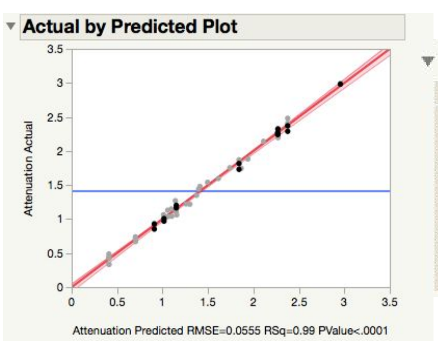
Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	3	0.00601834	0.002006	0.7608
Pure Error	3	0.00791076	0.002637	Prob > F
Total Error	6	0.01392910		0.5862
				Max RSq
				0.9988

Figure 17. Lack of fit summary for the central composite design

Final Results (All runs combined) - deleted furnace temperature*fiber design

All runs were combined and analysis was performed using Germanium Concentration, Fiber Design and Furnace Temperature. Figure 18 shows the actual by predicted plot as a good fit to the data, this is represented by the linear relationship observed. When looking at the parameter estimates, all factors were significant with the exception of the interaction between fiber design and furnace temperature, therefore it was removed.



Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.5561407	0.015068	36.91	<.0001*
Fiber Design[1]	0.1458932	0.007397	19.72	<.0001*
Germanium Concentration(0.01,0.05)	0.2054979	0.00936	21.95	<.0001*
Furnace Temperature(1800,2200)	-0.061266	0.008684	-7.05	<.0001*
Fiber Design[1]*Germanium Concentration	0.1991129	0.009237	21.56	<.0001*
Germanium Concentration*Furnace Temperature	0.6189679	0.009685	63.91	<.0001*
Germanium Concentration*Germanium Concentration	0.4859912	0.014292	34.00	<.0001*
Furnace Temperature*Furnace Temperature	0.8063761	0.015682	51.42	<.0001*

Figure 18. Actual by predicted plot for model with combined runs.

From Figure 19, the lack of fit was not significant, indicating the curvature in the model is accounted for. Additionally, the residual plot and Q-Q plot show normality in the data. Both of these observations imply that the model was a good fit to the dataset and is a good predictor for attenuation.

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	27	0.10629947	0.003937	1.8351
Pure Error	25	0.05363628	0.002145	Prob > F
Total Error	52	0.15993575		0.0656
				Max RSq
				0.9982

Figure 19. Lack of fit for entire dataset model

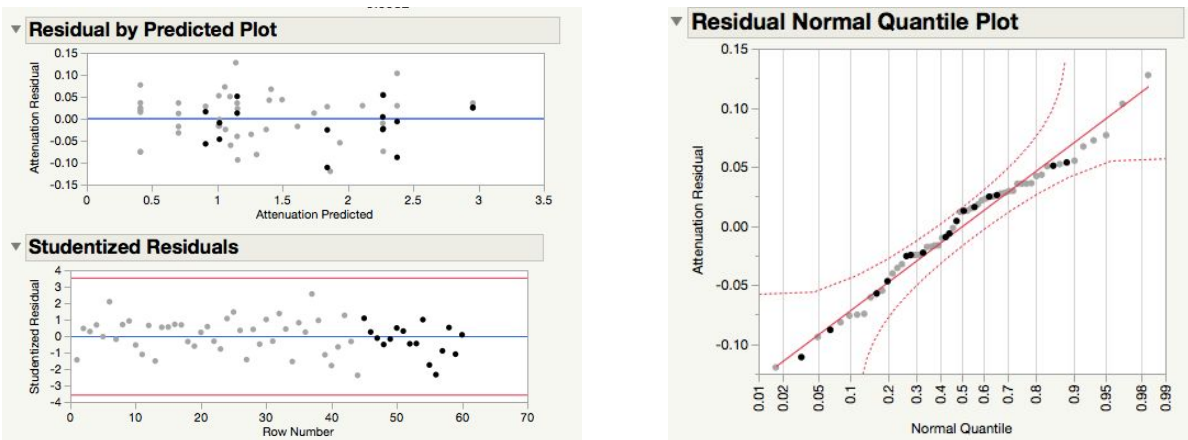


Figure 20. Residual plots for entire dataset and final model

The fourth and final request we added all the runs and came up with a list of optimal settings to minimize attenuation. After selecting maximum desirability and looking at the prediction profiler in Figure 21, the following optimal settings were chosen: fiber design 2, germanium concentration of 0.0288169, and 2016.5 degrees for furnace temperature. These numbers were very close in value to those rendered using the CCD method. Although both fiber designs were rendering similar optimal settings, we selected fiber design 2 due to slightly better results.

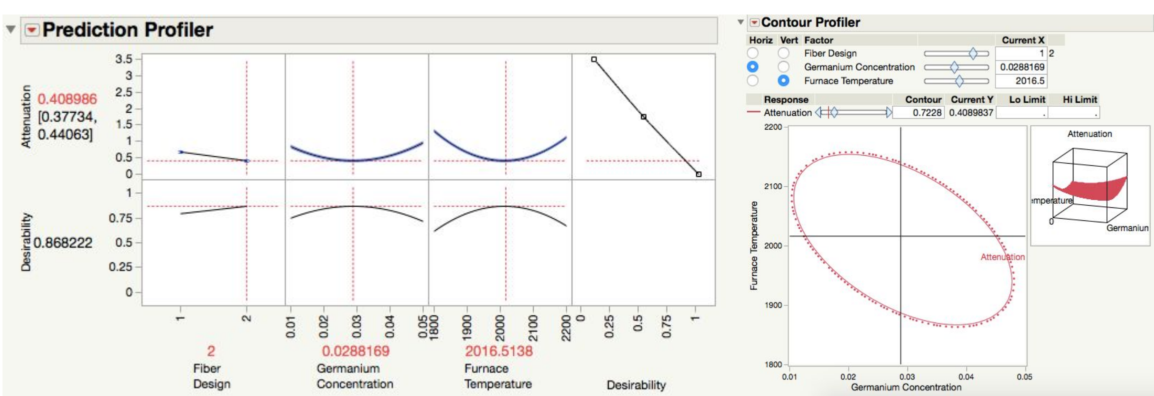


Figure 21: Prediction profiler and contour profiler for entire dataset and final model

Analysis of variance for this model indicates that the variability in attenuation under specified conditions cannot be attributed to randomness due to the significant f value shown in the analysis of variance table in Figure 22. The model had a very high R-squared value as indicated in the summary of fit table also in Figure 22. This indicates and supports that the model was accurately predicting attenuation and was a good fit to the data.

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	30.400295	4.34290	1412.009
Error	52	0.159936	0.00308	Prob > F
C. Total	59	30.560231		<.0001*

Summary of Fit

RSquare	0.994767
RSquare Adj	0.994062
Root Mean Square Error	0.055459
Mean of Response	1.409286
Observations (or Sum Wgts)	60

Figure 22. ANOVA and summary of fit for the entire dataset and final model

4. **Recommendations and Conclusion**

The first objective for the team was to identify any significant main effects and interactions on attenuation. From the initial screening design, the significant main effects were discovered to be fiber design, germanium concentration, and furnace temperature. Additionally, interactions of fiber design and germanium concentration as well as germanium concentration and furnace temperature were determined to be significant. The second objective was to build a model to predict attenuation from the significant factors and generate a list of optimal settings/characteristics based on that model. This objective was achieved by running axial points, an incremental optimization similar to that of steepest ascent/descent, and finally a central composite design. The following is the model that can be used to predict attenuation:

$$\begin{aligned} Attenuation = {} & 0.5561407 + 0.1458932 * Fiber\ Design + 0.2054979 \\ & * Germanium\ Concentration - 0.061266 * Furnace\ Temperature \\ & + 0.1991129 * (Fiber\ Design * Germanium\ Concentration) + 0.6189679 \\ & * (Germanium\ Concentration * Furnace\ Temperature) + 0.4859912 \\ & * Germanium\ Concentration^2 + 0.8063761 * Furnace\ Temperature^2 \end{aligned} \tag{1}$$

The optimal settings that were concluded to minimize fiber optic attenuation are: fiber design 2, a germanium concentration of 0.029, and 2017 ℃ for furnace temperature. All other factors should be chosen as the most cost effective option since they were not significant in the analysis there is not a suggested optimal setting.

While we did go over our $50,000 budget by $10,000, we concluded that the final data request was needed to feel confident in our chosen optimal settings. Unfortunately, our model does have limitations. The desirability is only 0.868 due to added complexity with quadratic terms, which could be improved. Additionally, no dealiasing was performed which could have an effect on our results. It would be helpful in the future to also perform a central composite design with a fiber design of 1 since we only considered fiber design 2 following analysis of results that suggested it was the superior design.