1985 Winner, American Supplier Institute Taguchi Application Award — Product Improvement by Application of Taguchi Methods

Jim Quinlan and Engineering Staff,
Flex Products, Inc., Midvale, OH

As originally written this paper was an exceptionally clear example of an improvement developed through Taguchi experimental design. The original text and figures are essentially unchanged. The italicized captions and comments under the figures assist explanation of the Taguchi method. If readers not yet exposed to Taguchi methodology pick through the article carefully, we think they will grasp the basics of Taguchi experimental design.

However, it is not possible in a brief article to explain a methodology that demands at least a week's instruction to apply in "cookbook" form. Several courses in statistics are assumed for those who debate the merits of the statistical theory applied. All we can do is give the flavor of the method, not profound insight.

This revision was done with the help and permission of Jim Quinlan and the American Supplier Institute. The Institute continues to hold a worldwide competition each fall to determine an annual best case winner.

Editor

THE PRODUCT

Extruded Thermoplastic Speedometer Cable Casing.

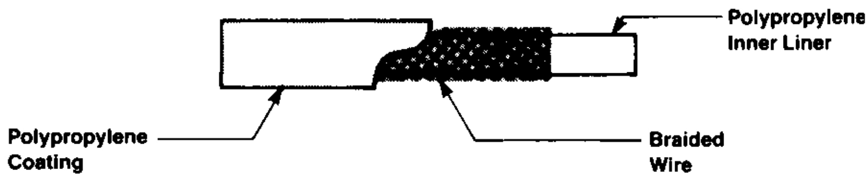
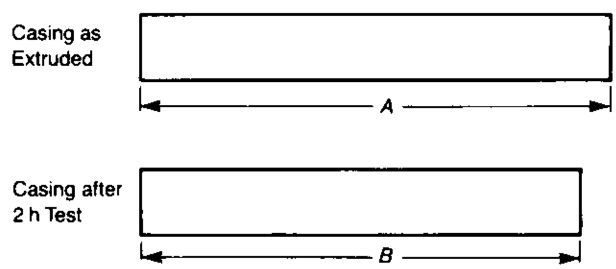


Fig. 1.

THE QUALITY CHARACTERISTIC

Percent Shrinkage after a two hour heat soak test.



$$\text{Shrinkage} = 100 \times \left(\frac{A-B}{A}\right)$$

Fig. 2.

The Product Under Test

The product under test in this experiment was extruded thermoplastic speedometer casing, shown in Fig. 1. This product is used to cover the mechanical speedometer cable on automobiles. The product consists of an extruded polypropylene inner liner, a layer of braided wire, and a coextruded casing.

This product has been produced for over fifteen years. Prior to manufacture by Flex Products, the casing under test had been produced by a division of General Motors Corporation. That division had conducted much one-factor-at-a-time experimentation with high costs and disappointing results.

The Quality Characteristic

The quality characteristic of concern is the post extrusion shrinkage of the casing. Excessive shrinkage can cause noise in the assembly, which has been one of the larger problems with mechanical speedometer cable assemblies. The post extrusion shrinkage is approximated with a two hour heat soak test, as shown in Fig. 2.

The percent shrinkage is obtained by measuring a length of casing that has been properly conditioned, placing that casing in a two hour heat soak in an air circulating oven, reconditioning the sample, and measuring the length. The post test length is then subtracted from the original length, divided by the original length, and then multiplied by 100 to obtain a percent result. The approximate length of the samples is 600 mm.

The Process

The production process for this product is to (1) extrude the polypropylene liner, cool it and coil it, (2) uncoil the liner and braid wire around the liner and recoil it, and (3) uncoil the wire coated liner and extrude the coating onto it and then cut the product to the finished length.

There are three separate operations. Most of the efforts at reducing post extrusion shrinkage had been directed at the final operation, since many of the characteristics were specified by the engineering drawing. In addition, in discussions regarding post extrusion shrinkage, the final operation seemed the most logical operation in which factors that significantly effect shrinkage would exist.

The Cause and Effect Diagram for the Experiment

In the preliminary design of the experiment, cause and effect diagrams are the most useful manner in which to generate a listing of the factors for test. Cause and effect diagrams lend more structure to ideas than the traditional brainstorming methods. Fig. 3 in the text is a greatly abbreviated version of the actual C-E diagram.

In this experiment, we obtained the opinions of our customers, the production personnel, the quality personnel, and the engineers involved in the product and process to develop a list of factors that could contribute to post extrusion shrinkage. By obtaining input from all informed personnel, the probability of conducting a successful experiment is increased dramatically.

This large diagram of potential factors was then reduced to the 15 most likely candidates by a consensus process.

The Factor Listing

The final result was a listing of the fifteen, two level factors shown in Fig. 4. Note that four factors concern the first step of the production process, the next three concern wire braiding, and the final eight concern the coating process.

A number of these factors concern design specified characteristics. Liner outer diameter, liner raw material, wire braid type, wire diameter, and coating raw material are all designed into the product.

The levels of the factors were selected by personnel familiar with the process. This group was essentially the same as that which participated in the cause and effect diagram, with the exception that our customer's personnel were not included.

The Layout and Results Using L16 Orthogonal Array

Fig. 5 shows the L16 array, the four separate shrinkage results, and

THE CAUSE AND EFFECT DIAGRAM FOR THE EXPERIMENT

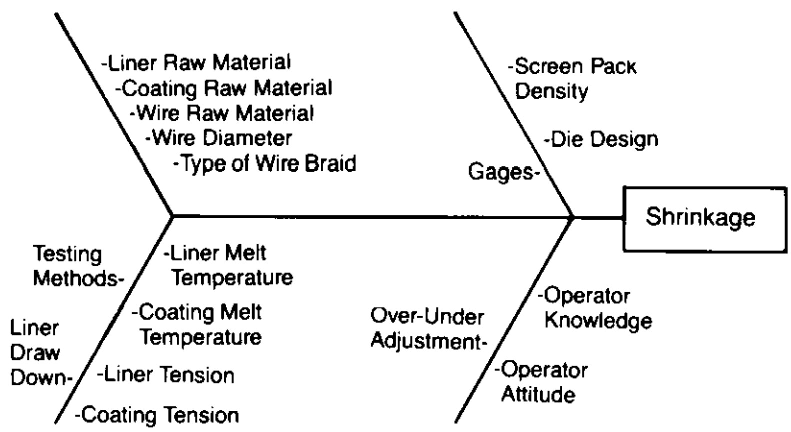


Fig. 3. This is a simplified version of the cause and effect diagram constructed to identify potential causes of the shrinkage problem.

FACTOR LISTING

	A. Liner O.D.	**A1** = *Existing*	**A2** = *Changed*
Liner	**B.** Liner Die	**B1** = *Existing*	**B2** = *Changed*
Process	**C.** Liner Material	**C1** = *Existing*	**C2** = *Changed*
	D. Liner Line Speed	**D1** = *Existing*	**D2** = *80% of Existing*
Wire	**E.** Wire Braid Type	**E1** = *Existing*	**E2** = *Changed*
Braiding	**F.** Braiding Tension	**F1** = *Existing*	**F2** = *Changed*
	G. Wire Diameter	**G1** = *Smaller*	**G2** = *Existing*
	H. Liner Tension	**H1** = *Existing*	**H2** = *More*
	I. Liner Temp.	**I1** = *Ambient*	**I2** = *Preheated*
Coating	**J.** Coating Material	**J1** = *Existing*	**J2** = *Changed*
Process	**K.** Coating Die Type	**K1** = *Existing*	**K2** = *Changed*
	L. Melt Temperature	**L1** = *Existing*	**L2** = *Cooler*
	M. Screen Pack	**M1** = *Existing*	**M2** = *Denser*
	N. Cooling Method	**N1** = *Existing*	**N2** = *Changed*
	O. Line Speed	**O1** = *Existing*	**O2** = *70% of Existing*

***Fig. 4.** Fifteen of the possible causes (variables A through O) were selected as factors in the design of the experiment. Each factor has two different settings, called "levels" in experimental design parlance.*

▷

LAYOUT USING ORTHOGONAL ARRAY L_{16}

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O		TEST1	TEST2	TEST3	TEST4	S/N RATIO
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		0.49..	0.54..	0.46..	0.45..	6.26
1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	....	0.55..	0.60..	0.57..	0.58..	4.80
1	1	1	2	2	2	2	1	1	1	1	2	2	2	2	....	0.07..	0.09..	0.11..	0.08..	21.04
1	1	1	2	2	2	2	2	2	2	2	1	1	1	1	....	0.16..	0.16..	0.19..	0.19..	15.11
1	2	2	1	1	2	2	1	1	2	2	1	1	2	2	....	0.13..	0.22..	0.20..	0.23..	14.03
1	2	2	1	1	2	2	2	2	1	1	2	2	1	1	....	0.16..	0.17..	0.13..	0.12..	16.69
1	2	2	2	2	1	1	1	1	2	2	2	2	1	1	....	0.24..	0.22..	0.19..	0.25..	12.91
1	2	2	2	2	1	1	2	2	1	1	1	1	2	2	....	0.13..	0.19..	0.19..	0.19..	15.05
2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	....	0.08..	0.10..	0.14..	0.18..	17.67
2	1	2	1	2	1	2	2	1	2	1	2	1	2	1	....	0.07..	0.04..	0.19..	0.18..	17.27
2	1	2	2	1	2	1	1	2	1	2	2	1	2	1	....	0.48..	0.49..	0.44..	0.41..	6.82
2	1	2	2	1	2	1	2	1	2	1	1	2	1	2	....	0.54..	0.53..	0.53..	0.54..	5.43
2	2	1	1	2	2	1	1	2	2	1	1	2	2	1	....	0.13..	0.17..	0.21..	0.17..	15.27
2	2	1	1	2	2	1	2	1	1	2	2	1	1	2	....	0.28..	0.26..	0.26..	0.30..	11.20
2	2	1	2	1	1	2	1	2	2	1	2	1	1	2	....	0.34..	0.32..	0.30..	0.41..	9.24
2	2	1	2	1	1	2	2	1	1	2	1	2	2	1	....	0.58..	0.62..	0.59..	0.54..	4.68
																			TOTAL..	**193.47**

__Fig. 5.__ The fifteen factors, A through O, are tested at one of two clearly different values (levels). Sixteen different experimental runs are to be made. Each run is designed with a different combination of values for each factor as represented by each row of the array. Each factor level (indicated as 1 or 2) is present eight times in this design. The design is intended to wring as much information as possible from a few experimental runs.

Four separate shrinkage tests were run on samples of cable from each of the 16 experimental runs; data shown. The S/N ratio is a Signal to Noise ratio recommended by Dr. Taguchi for the analysis of quality characteristics. Since shrinkage is a smaller-is-better quality characteristic, the smaller-is-better variation of Signal-to-Noise ratio is used in this case. A high S/N ratio indicates either 1) a lower average shrinkage rate, 2) less variance within the four shrinkage results, or both 1) and 2).

Subsequent analysis is based on the 16 S/N ratios shown in the right hand column. The sum of all 16 ratios is 193.47, so the average "S/N ratio value" (db) for any factor in a run is 12.1 db (193.47 ÷ 16).

SIGNAL TO NOISE RATIO WHEN SMALLER RESPONSE IS BETTER

Formula:

$$S/N = -10 \times \text{Log}\left[1/n \sum_{i=1}^{n} y_i^2\right]$$

Examples:

Case	Avg.	y_1	y_2	y_3	y_4	S/N
1....	.50	.56	.44	.54	.46	5.94
2....	.15	.21	.09	.19	.11	16.00
3....	.15	.15	.16	.14	.15	16.47

CASE 3 IS BEST—SAME AVERAGE AS CASE 2 BUT LESS VARIABILITY

__Fig. 6.__ This figure illustrates calculation of the S/N ratio using contrived data, not data from Fig. 5, but the S/N ratios in Fig. 5 were calculated the same way. All data are shown, so you can try it if you wish. Higher "y" values increase the value of the sum of squares, and more variance between y's adds slightly to the value of the sum of squares, as shown. Taking the negative logarithm converts smaller results into the larger numbers on a different scale, which are easier in subsequent manipulations.

the signal to noise ratio. The L16 array allows the testing of up to 15, two level factors. Of course, this type of design runs the risk of confounding the interactive effects with the factorial effects. To eliminate this risk entirely is only possible if all of the 32,768 combinations of the factors were tested. To minimize the risk, the experiment must be tested for reproducibility.

Since a minimum of 3000 feet of finished product was the smallest quantity that could be manufactured at a given combination of factors, 48,000 feet of product was committed to this experiment.

The experiment itself was quite complicated to run through our extrusion plant. In an effort to minimize the confusion, summary sheets for each operation were provided to the foremen and operators. These sheets listed the combination of the factors and the orders of production, which were randomized as much as possible.

Even with the use of the summary sheets, the conduct of this experiment was not easy. The management and production operators at our extrusion facility deserve much of the credit for the success of this experiment.

After random samples were selected for each three thousand foot sample, there were then four separate short term heat soak tests performed. One test was performed each day. Shrinkage was calculated from the above formula and recorded.

The Signal to Noise Ratio

Dr. Taguchi has extended the audio concept of signal to noise to multivariate experimentation. The formulae for signal to noise are so designed that the experimentor can always select the highest value to optimize the experiment. Therefore, the method of calculating the signal to noise ratio differs depending on whether a larger response, a smaller response, or an on target response is desirable.

In cases such as this where the smaller amount of shrinkage is better, the formula is shown in Fig. 6. In this case, either a reduction in the mean shrinkage and/or a reduction in the variability will improve the situation. The figure shows the improvement in signal to noise ratio when either of those characteristics improve.

The Totals for Each Factor Level

The first step in the analysis of all multivariate experiments is to sum all the results containing one level of a factor and comparing it to the other level of the factor. If level one of factor A, for example, either decreased the average shrinkage or substantially reduced the variability, then the total signal to noise ratio for A1 would be larger than that for A2.

Since the experiment was conducted using an orthogonal array, each total for a factor level contains eight signal to noise ratios. By definition the totals for both levels of a given factor equal the total of the experimental results, i.e. 193.47. By reviewing the numbers in Fig. 7, a feeling for the effect of each factor can be obtained by noting the difference in signal to noise totals for a given factor level. The greater the difference between level 1 and level 2 for a factor, the greater that factor's effect.

The Analysis of Variance Table

Fig. 8 is the ANOVA table for the experiment. The analysis is performed by noting the sources of variation in the lefthand column, which are, of course, the fifteen factors under test in the experiment. The column labelled df indicates the degrees of freedom for the factor. The next column, labelled S, is the sum of squares for the factor. The column labelled V is the mean sum of squares, i.e. the sum of squares for the factor divided by the degrees of freedom in that factor. The column labelled F is the results of the traditional Fisher test for significance; and an asterisk denotes whether the factor was significant at 95 or 99 percent confidence.

Notice that seven degrees of freedom, seven factorial effects in

S/N TOTALS FOR EACH FACTOR LEVEL

A1 = 105.88	E1 = 67.96	I1 = 92.82	M1 = 94.97
A2 = 87.59	E2 = 125.51	I2 = 100.64	M2 = 98.50
B1 = 94.40	F1 = 87.89	J1 = 99.40	N1 = 94.51
B2 = 99.07	F2 = 105.58	J2 = 94.07	N2 = 98.96
C1 = 87.61	G1 = 77.74	K1 = 106.25	O1 = 95.01
C2 = 105.86	G2 = 115.73	K2 = 87.22	O2 = 98.46
D1 = 103.19	H1 = 103.24	L1 = 93.50	
D2 = 90.28	H2 = 90.22	L2 = 99.97	

THE GREATER THE DIFFERENCE IN LEVEL TOTALS FOR A FACTOR, THE GREATER THE SIGNIFICANCE OF THAT FACTOR

Fig. 7. S/N ratio values from Fig. 5 associated with each of the two levels are summed for all 15 factors. The experimental array in Fig. 5 is designed so that each factor is run eight times at its "1" level and eight times at its "2" level. The average total is 8 × 12.1 db, or 96.7 db, but of most interest is the magnitude of difference **between** *totals for each of the two levels of each factor. A big difference indicates that a factor has important influence on shrinkage even when its effect was smothered in the other changes made in each experimental run.*

ANALYSIS OF VARIANCE TABLE

Source	df	S	V	F	S'	(%)
A	1	20.9128	20.9128	11.87*	19.1513	4.6
B	[1]	[1.3612]	1.3612	Pooled	—	—
C	1	20.8282	20.8282	11.82*	19.0667	4.6
D	1	10.4171	10.4171	5.91*	8.6556	2.1
E	1	207.0275	207.0275	117.53**	205.2660	49.5
F	1	19.5625	19.5625	11.11*	17.8010	4.3
G	1	90.1788	90.1788	51.19**	88.4173	21.3
H	1	10.5963	10.5963	6.02*	8.8348	2.1
I	[1]	[3.8226]	3.8226	Pooled	—	—
J	[1]	[1.7765]	1.7765	Pooled	—	—
K	1	22.6350	22.6350	12.85**	20.8736	5.0
L	[1]	[2.6146]	2.6146	Pooled	—	—
M	[1]	[0.7782]	0.7782	Pooled	—	—
N	[1]	[1.2355]	1.2355	Pooled	—	—
O	[1]	[0.7418]	0.7418	Pooled	—	—
e	7	12.3304	1.7615	—	26.4222	6.4
T	***15***	***414.4886***	—	—	***414.4886***	***100.0***

* = *Significant at 95% Confidence, F(0.05,1,7) = 5.59*
** = *Significant at 99% Confidence, F(0.01,1,7) = 12.20*

Fig. 8. *This is an ANOVA table, the output of a standard analysis-of-variance software package. The table decomposes each factor's contribution to the total variation within the 16 S/N ratios shown in Fig. 5, but calculations are based on the totals by factor level shown in Fig. 7. The "F" column is a standard Fisher F test showing whether variability of results by the two different levels for each factor are significantly different. It is added only for reference.*

This significance key indicates that we are 95 percent sure that factors A, C, D, F, and H explain more variance in results than should occur through randomness of outcomes, and we are 99 percent sure that factors E and G explain more than randomness of outcomes.

Interpretation centers on the S and S' columns, which are indicators of total variance explained by each factor. Almost 50 percent of the total variance among the 16 S/N ratios appears to be due to changing Factor E from level 1 (Existing Wire Braid Type) to level 2 (Changed Wire Braid Type).

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GRAPHS OF SIGNIFICANT EFFECTS

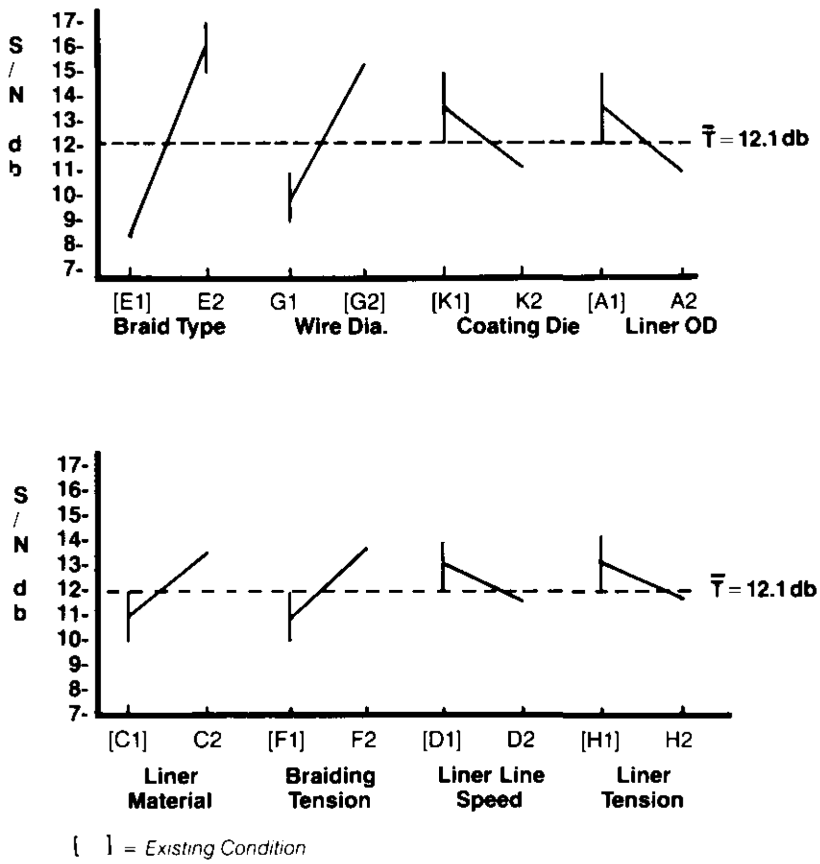

***Fig. 9.** Graphical illustration of the findings from Fig. 5 and Fig. 7. The data point plotted for each factor level is its average S/N ratio (db), which is its total shown for Fig. 7 divided by eight. (Each factor level appears eight times in this experimental design.) The average expected of all factors was 12.1 db.*

Only the big S/N difference, big variance factors are graphed. A higher db level indicates which level of a factor is optimum. The factor levels labeled in brackets are the existing conditions, and several of those are in the optimum combination. The pairs of factor levels are graphed in the order of the largest difference between them. The vertical bar shows a 90 percent confidence interval for estimates of each factor value. Changing braid type (Factor E) and changing wire diameter (Factor G) should have a major impact on shrinkage. We are not quite so sure of the other results.

this case, have been pooled into an estimate of error. This estimate of variance, or mean sum of squares for error, is used as the denominator of the F test.

The column labelled S' is the pure effect of each factor. Since all multivariate experiment designs assume that error is allocated equally over all the degrees of freedom within the experiment, each significant effect contains an amount of error which must be subtracted out. The error is added to our estimate of error in the S' column. Notice that St and S't are equal—the total variation within the experiment is constant. The final column is the S' value for each significant factor divided by the total variation S't. This column indicates the percent of contribution to variance by each factor.

From this table, it is easy to see that Factors E and G are the most important in terms of shrinkage. These two factors account for more than 70 percent of the experimental variance.

The Graphs of Significant Effects

To obtain a clear idea of the experimental results, the effect of each significant factor is graphed. The factors are arranged so that the most significant is on the left. These graphs indicate what was observed in the table of summary results—that the greater the difference between levels, the greater the effect. The points are calculated by taking the total of the factor level shown in Fig. 7 and dividing the number of data points in that total to obtain an average effect. In the case of E1 for example, the average effect is 67.96 divided by 8, or 8.5 db. The experimental average of 12.1 db is obtained by dividing the total for the experiment (193.47) by the number of data points (16).

The vertical bar is the 90 percent confidence range for the estimate of the factor level's mean. This is based on our estimate of error and the degrees of freedom therein.

Since the higher signal to noise ratio is more desirable, it can be seen that the best level of the factors under test were being used in five of the eight significant cases. The most significant factor, however, was specified by the engineering drawing at an undesirable level.

Existing versus Optimum Conditions

If each factor were selected for the best signal to noise ratio, what would be the effect on post extrusion shrinkage as measured by the two hour test? And, since the actual production condition was not tested in this experiment, what does the experiment predict our shrinkage to be in production as it was currently being run?

These questions can be answered using a simple formula for prediction from the experimental results. Since the assumption has been made that each factor is independent, i.e. no significant interactions exist, the factorial effects are assumed to be independent. Fig. 10 shows these calculations and their results.

Note that the term optimum reflects only the optimum levels of the factors as defined by this experiment. The true optimum combination of these factors could be wildly different than the combination shown in Fig. 10. This optimization is based only on the knowledge obtained from the experiment.

A 90 percent confidence band is shown on both estimates—this band again reflects the estimate of error within the experiment and the

CALCULATION OF EXISTING VERSUS OPTIMUM MEAN S/N RATIO.

I. **Existing** = A1 C1 D1 E1 F1 G2 H1 K1

$\hat{u} = A1 + C1 + D1 + E1 + F1 + G2 + H1 + K1 - 7 \times T$

$\hat{u} = 13.24 + 10.95 + 12.90 + 8.50 + 10.99 + 14.47 + 12.91 + 13.28 - 84.64$

$\hat{u} = 12.60 \pm 4.18$

$$\frac{1}{n}\sum_{i=1}^{n} y_i^2 = 0.0595$$

II. **Optimum** = A1 C2 D1 E2 F2 G2 H1 K1

$\hat{u} = A1 + C2 + D1 + E2 + F2 + G2 + H1 + K1 - 7 \times T$

$\hat{u} = 13.24 + 13.23 + 12.90 + 15.69 + 13.20 + 14.47 + 12.91 + 13.28 - 84.64$

$\hat{u} = 24.28 \pm 4.18$

$$\frac{1}{n}\sum_{i=1}^{n} y_i^2 = 0.0037$$

Fig. 10. *The existing-condition factor level combination and the optimal combination are listed. Two calculations are made for each set of conditions.*

For both the existing and optimum sets, the first calculation predicts the S/N ratio of shrinkage tests on cable run under each set of conditions. None of the 16 experimental runs duplicated existing conditions, but since each of the existing factor levels was tested in the overall experimental design, the data can predict the current production S/N ratio (12.60). The optimal condition S/N ratio is likewise predicted. The confidence interval (4.18) is shown for reference.

The purpose of these calculations is validation of the experiment. Finding actual S/N values close to those predicted by experimental data buoys confidence in the conclusions. For both sets, the second calculation is the summation of "y²" based on Dr. Taguchi's "mean squared deviation" formula for a smaller-is-better characteristic. It uses selected experimental shrinkage data back in Fig. 5. Results are used in the Taguchi loss function in Fig. 13.

ACTUAL RESULTS IN THE PROCESS

	$\bar{X}$	S	S/N	Predicted Range
Before	0.26	0.05	11.64	8.42/16.78
After	0.05	0.025	25.05	20.10/28.46

Fig. 11. *The S/N ratios predicted from runs under experimental conditions in Fig. 10 are compared with those from actual production. "Before" production was operated under pre-experiment conditions, and "after" was on the optimum combination conditions established after the experiment. S/N ratio predictions from the orthogonal array experimental data were very close to the actual ratios from routine production which are shown.*

X is the mean shrinkage and S is the standard deviation of shrink tests on results of actual production, not data from experimental runs.

▷

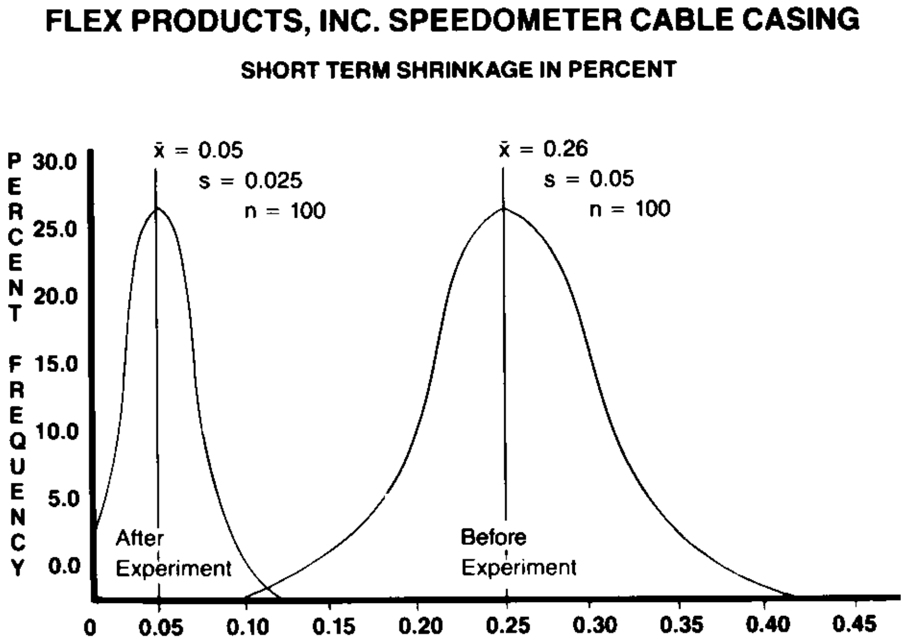

Fig. 12. *This graph of the data in Fig. 11 shows the actual quality improvement obtained as the result of acting on the experimental information. Higher quality at lower cost amply justifies conducting experiments.*

LOSS FUNCTION FOR SPEEDOMETER CASING

If Shrinkage = 1.50%, then Customer Complains.

Warranty Cost to Replace Cable Assembly = $80.

Therefore:

$K = (80/(1.5^2)) = \$35.56$

And:

$L = k\sigma^2$ (For Smaller the Better $\sigma^2 = \bar{y}^2 + s^2$)

Therefore:

Existing Condition $L_e = 35.56 \times 0.0595 = \$2.12$ per unit.

Optimum Condition $L_o = 35.56 \times 0.0037 = \$0.13$ per unit.

Fig. 13. *The Taguchi loss function for this application is the smaller-is-better case. (Closer-to-target and larger-is-better are the other two cases.) The $80 warranty replacement cost is the only number taken from the company's cost system. The estimate is otherwise based on the Taguchi loss function as describing loss somewhere in the chain of ownership and use of the speedometer cable.*

degrees of freedom on which that estimate of mean is based. The term of the sum of squares divided by the number of sample is calculated from the estimated mean as well. Since this is basically an estimate of the average squared plus the square of the standard deviation, it will be used later in our discussion of the loss function.

The Actual Results versus the Prediction

To test the results of our experiment, a comparison was made between the predictions and the actual results. Had these not compared within the 90 percent confidence range, the experimental results would be suspect. Either a significant hidden factor could exist, the conduct of the experiment might be flawed, or a strong interactive effect could exist.

As can be seen in Fig. 11, the experiment successfully predicted the actual signal to noise ratio of the process both at the existing and the optimized condition.

The effect this had on the distribution of post extrusion shrinkage can be seen in Fig. 12. This dramatic improvement, it should be noted, was only achieved by changing one of the design criteria of the product. The control charting efforts that had been assiduously applied to this process and product could not have been successful in reducing the average post extrusion shrinkage by the amount shown.

The Loss Function

One of Dr. Taguchi's concepts that has been gathering slow acceptance is that of the loss function. Since quality is defined by Dr. Taguchi as the loss a product causes to society, both producer and consumer costs must be considered. In most cases, lower producer costs lead to higher consumer costs and the sum of those two costs to society can be approximated by $L = k\sigma^2$.

Using this formula allows reduction in variability to be a quantified gain. This formula is used to calculate the gain to society caused by a process improvement.

LOSS FUNCTION

POST EXTRUSION SHRINKAGE AS A PERCENTAGE OF ORIGINAL CASING LENGTH

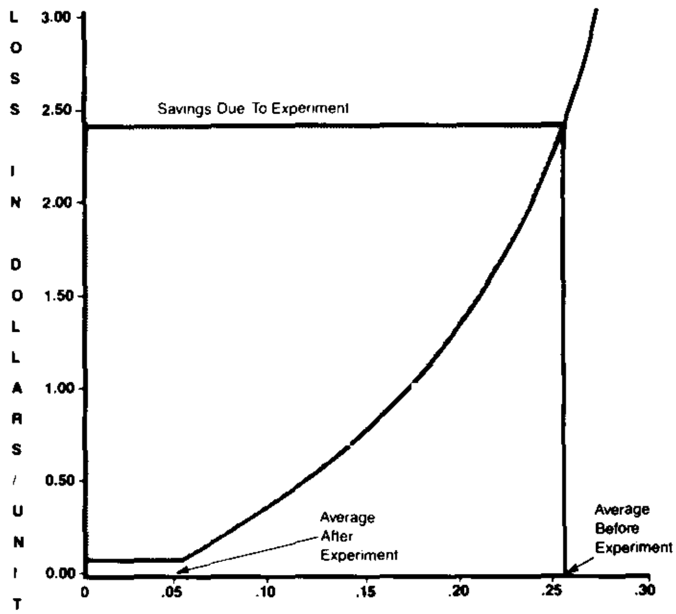

Fig. 14. Graph of the calculations in Fig. 13.

Taguchi Awards

In 1985, the American Supplier Institute initiated an award in Dr. Taguchi's honor. This award is presented to those who have worked to promote the implementation of Taguchi Methods or who have made the most effective application of these techniques.

Awards are based on the following criteria.

1) *Uniqueness* — The engineers ability to apply the techniques to various engineering applications.
2) *Design* — Timely, cost-effective studies which have a high success ratio.
3) *Best Analysis* — The most effective use of analysis techniques for dynamic characteristics.
4) *Economic Outcome* — The most dramatic improvements in quality and cost.

While much of this formula is approximation, I feel more and more comfortable with its use. The savings shown in Fig. 14 go somewhere, either to the producer or to the consumer. By minimizing the cost of our products to society, American manufacturers can continuously improve their competitive position in world markets.

Author's Postscript:

"Reviewing this experiment almost four years after the fact, I still find it a good example of the importance of Dr. Taguchi's parameter design. Factor E, wire braid type, was a design specification. The original design engineer had selected the wire braid type over a decade earlier, thus determining the shrinkage quality of the product. For over ten years the casing delivered exactly the amount of shrinkage originally designed to it. This "specified" quality level contributed to many costly problems in the field. The real solution was altering the nominal value of the wire braid type specification. A decade of process improvement efforts had no effect because of one nominal value of the engineering drawing. The tragedy is that this parameter design experiment was conducted a decade too late."

Jim Quinlan