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Statistical process control: Learning by doing

Statistical process control works for everybody, if everybody works for statistical process control. This Consumer Electronics manufacturing unit has proof!

Virtually everyone in industry is familiar with the term statistical process control (SPC) and the great success the Japanese and U.S. companies such as Chrysler Corporation have had following implementation of such a program. However, little is written on how such a system is implemented. This paper shows how SPC was put into practice at RCA. Commitment to SPC requires a change in philosophy by management, an investment in training the entire organization top to bottom, and time to realize the potential benefits of improved quality and increased productivity in manufacturing, warranty costs, and product share.

Getting started

As a result of attending a workshop at the David Sarnoff Research Center in Princeton, N.J., on "Applications of Statistics to Manufacturing," the operations staff of the VideoDisc Stylus/Cartridge Manufacturing Operations (RCA Consumer Electronics Division) located in Indianapolis, Indiana, at the Rockville Road plant, decided to embark upon a program of SPC in early 1983.

Kickoff training was provided by the Productivity and Quality Assurance group from DSRC and involved key manufacturing, engineering, and quality personnel. The Basic Statistical Toolkit training included discussions of variability, histograms and simple plots, control-charting techniques, and process-capability studies. A commitment of 44 person-days was required for the training of all 22 participants involved over a 4-week period.

Abstract: *Stylus/Cartridge Manufacturing Operations at RCA Consumer Electronics in Indianapolis, Indiana, trained in Statistical Process Control procedures in early 1983. They began applying their education almost immediately and have found several suitable projects since then. One such successful venture is described in this paper. The manufacturing results: a better cartridge at significant cost savings.*

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After completion of the course, there still remained the task of making SPC a part of our everyday worklife. There existed a basic, underlying commitment to understanding and achieving the benefits that were felt possible with SPC. The first step was to choose a problem area in cartridge manufacture that was ripe for initial success. This was important to maintain the momentum towards a change in manufacturing philosophy.

First success

A task force was formed consisting of the manufacturing supervisor, the hourly production group leader, manufacturing engineer, manufacturing technicians, quality control supervisor, quality control technicians, and the Purchased Material Inspection (PMI) supervisor. In a brainstorming session, the group selected the number one quality-related problem at assembly and final audit: rejection because of incorrect force and bias (vertical and lateral tracking force).

At the time of the study, the manufacturing process consisted of a cartridge assembly "build" operation, where the initial force and bias were established, followed by combined 100 percent inspection for force and bias, and a repair operation. The force-and-bias inspection in manufacturing was performed on an optical comparator. The quality inspections, however, were performed on an electronic gauge. The manufacturing inspection equipment had been set to agree on the average with the electronic quality control fixture, but there was not one-to-one correspondence on individual cartridges.

Prior to the task-force meeting, it was agreed to keep control charts of the process—shown by operator—after the assembly "build" and repair operations. A meeting was held to explain the charts to operators to relieve their anxiety. After one week, there was a noticeable improvement on the charts from the assembly fixtures. This could be attributed to the performance feedback given to the operators.

At the first meeting, participants reviewed the control charts, developed a cause-and-effect diagram, ranked the causes, and selected the number one item, staking force, for further study and control charting. The PMI supervisor provided information that showed that the flylead (signal conductor and force spring) had variations in thickness that affected the final force of the assembly. What started out as an assembly issue became a material issue.

The control charting of the assembly and repair operations was continued. Histograms (Fig. 1) and box plots (Fig. 2) of the force and bias were prepared for each operation. The information from the histograms was the most revealing. After assembly, bias was normally distributed and had a tighter range than after repair. This was sufficient evidence to justify elimination of the bias-repair operation—it had become part of the problem. Similar analysis of the force data, however, showed that the repair operation degraded the product distribution.

A process capability study was now performed on force. The results of the capability study showed that it was not possible to manufacture the product to the existing specifications.

This data was shared at a joint meeting with the cartridge management and the design engineering personnel. Analysis by the design engineer found that the VideoDisc player was able to accept the cartridge force at its natural process capability. It was concluded at the meeting to eliminate the inspection and repair operations and to control the process average within one standard deviation of the nominal force specification.

An off-shoot of the above findings was our increased awareness of the real impact of material upon the performance of the cartridge. Purchasing had previously arranged the bulk rolling of the flylead material. Our data clearly showed the effect of the flylead materials's thickness on performance of the cartridge. This led the plant QC Manager to contact the material vendor and, with purchasing, negotiate for process control of the vendor's milling operation—at a cost reduction. The savings to RCA resulting from the implementation of process control at the cartridge assembly operation showed up as direct labor reduction, material cost savings, and improved yields that facilitated further savings at subsequent operations because of the improved process.

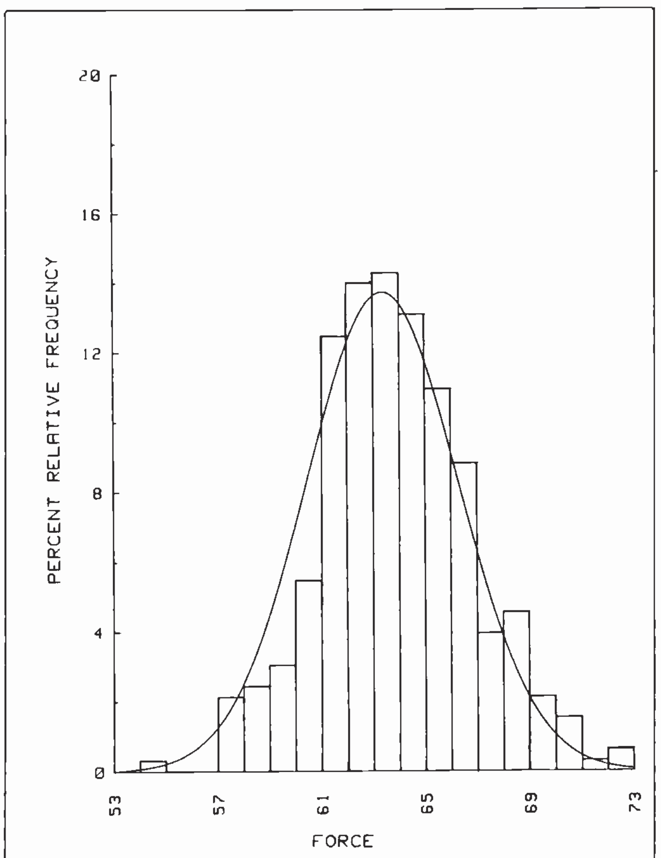

Fig. 1. *Histogram of flylead force, measured after the cartridge is assembled. The process is a normal distribution, but exceeds the design specification of 65 mg. ±7. The specification was changed to control the process within 3 σ limits.*

Success breeds success

After the success with the force and bias problems, several members of the organization enrolled in the RCA Corporate Engineering Education (CEE) course offered on "Design of Experiments." There emerged a small group of highly committed members of the organization who, on their own energies, have spread the "gospel of statistical process control." Although feeling persecuted at times, they have persevered. The support of management and the consultants at RCA Laboratories helped, but ultimately their efforts cannot compare to the personal, day-to-day commitment of the individuals directly involved in manufacture.

In the short time since the first success, there have been many other studies and designed experiments. Problem analysis, through designed experiments, is gradually being recognized as the surest path to permanent solutions, rather than the "band-aid" fixes that are often a temptation during crises. The basic truth of controlling the natural manufacturing process cannot be denied.

Lessons learned

The incorporation of statistical process control in the manufacturing operation has generated a better understanding of what

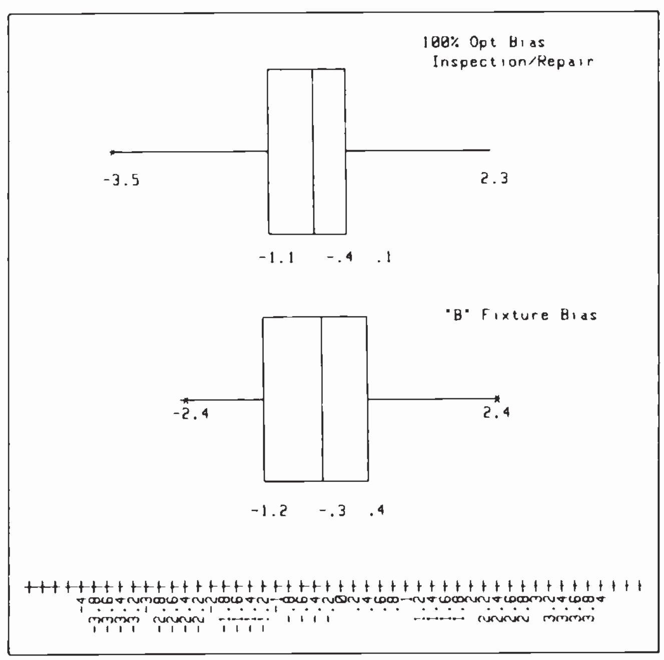

Fig. 2. *Box plots of before-and-after bias repair. Although 50 percent of product is more tightly distributed, the overall distribution is larger. Conclusion—stop the repair, and control the process.*

makes the product work. The necessary change in philosophy involves the commitment of management and the whole organization to SPC. The transition period can be frustrating until it is complete. Those frustrations are eased by the realization that we are making progress and doing what is right.

With the advantage of 20/20 hindsight, there are several things that participants should keep in mind when an organization embarks upon statistical process control. The following list is certainly not complete—but then we have not finished our trip.

- Control charting can only be used to improve the product if one understands the underlying distribution.
- Control charts do provide an excellent historical record of the process. Control charts can also be invaluable in solving problems not directly related to the factor being charted.
- It is critical to know and recognize the capability of the measuring system being used. It is fruitful to do measurement capability studies early—an inadequate measurement system can only obscure problems.
- Progress in a single organization can be frustrated if related organizations are not commited to SPC. Include such organiza-

What is Statistical Process Control?

- Putting a process in pictures—histograms, control charts, graphs for understanding variability.
- Analyzing pictures for deviate behavior—looking at the shape of the distribution and the activity of the mean and range.
- Reacting to warnings given by analysis—doing corrections according to control-chart rules and distribution abnormalities.
- Blending mathematical interpretations with technical awareness of the process.

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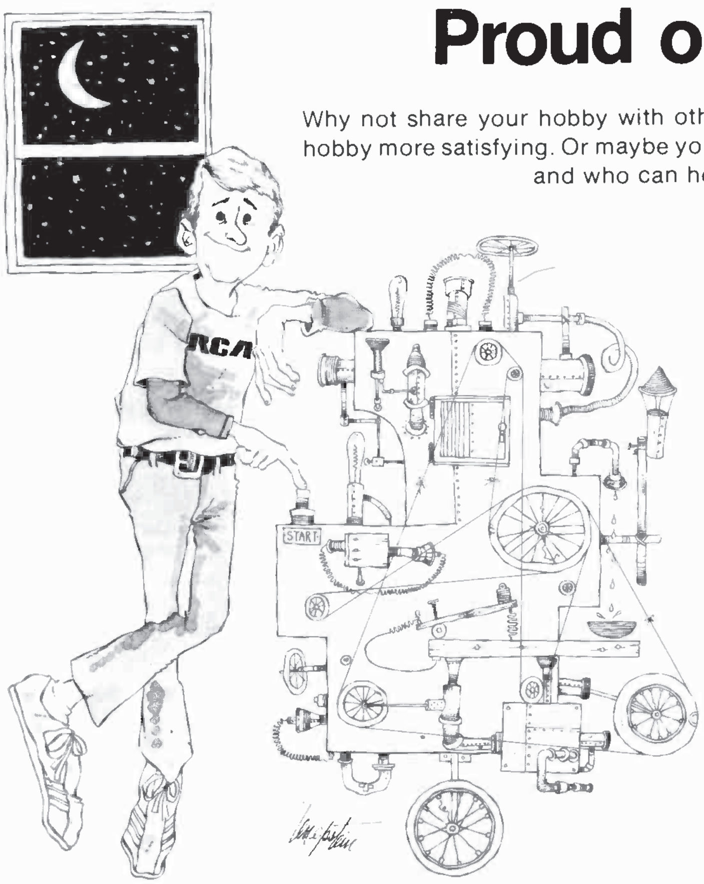
tions in the training sessions along with frequent explanations at meetings of the basic principles being applied. This process is important in building a solid base of support.

- The use of "package" computer-analysis programs by the inexperienced can lead to incorrect solutions. Although the best solution is to have individuals knowledgeable about statistics in the organization, access to strong statistical strengths from consulting groups, such as those at RCA Laboratories, is important.
- Patience, of course, is a virtue. This is the biggest challenge to operating management who are used to making quick decisions. Initially, designed experiments seem to take forever. Once the value of the results becomes evident, the little extra time to get results is worth the wait. As greater knowledge is gained about the process and the product, simpler experiments can be designed that are easier and quicker.
- Believe in SPC. SPC can point out problems even before there are rejects. Ignoring such advance warnings has been adequately demonstrated to be costly.
- The importance of material characteristics on the process cannot be understated. Failure to appreciate this impact can hide or divert attention away from the real causes of process or performance problems.
- It is important that SPC not be viewed as a "Quality Control program." It requires the total organization involvement and commitment to accept the responsibility of reacting to changes in the process without the "crises" of rejects.

Conclusion

The gains possible through statistical process control are real but they do not come without cost. The cost is minor when considering the alternatives. Changes in philosophy and operating style do not come easily. They require commitment, understanding, and patience. The long-term rewards are great and are worth the extra effort.



D.E. Coleman | P.G. Stein

Better yields, better understanding: An example of statistical production engineering

When looking for machining defects in VideoDisc styli, measured at the limits of light microscopy, RCA engineers depended on statistical production engineering to ferret out some of the hidden causes.

Statistical production engineering is an interdisciplinary procedure by which manufacturing processes may be simultaneously improved in both yield and product quality. This is accomplished through studies that increase our basic understanding of how a process works. When we have this understanding, the day-to-day operation of the process becomes more consistent because the effects of adverse changes that occur in any manufacturing process can be corrected.

At RCA's VideoDisc cartridge plant at Rockville Road, Indianapolis, the diamond stylus that reads the video signal from a CED VideoDisc is plated, faceted, assembled into a plastic and metal cartridge, and machined. A recent statistical production engineering effort was successful in helping to improve this manufacturing process, reducing rejects at one near-final step of the process from 15 percent to 2 percent. This effort represented a cooperation between VideoDisc cartridge personnel and statisticians from the David Sarnoff Research Center. Some details of this effort are presented here. They emphasize the concepts and strategy used, so that application of the same techniques to other processes may be easily understood.

The stylus and v-to-p

The cartridge is about the size of a box of paper clips, and one is installed in each VideoDisc player manufactured by RCA in Bloomington, Indiana. Cartridges are also distributed to be sold as replacement parts. The process used to manufacture a stylus is unique, and is particularly hard to understand and control because of the stylus's physical dimensions.

Abstract: *Working as a member of a team of engineers and other technical people, an industrial statistician can help solve production problems. He or she does this by increasing the understanding of cause-and-effect relationships between process steps and product characteristics. This was done recently in RCA's VideoDisc cartridge plant, with some significant results.*

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A stylus must be machined with tolerances of fractions of a micrometer (one micrometer is 1/1,000,000 meter, or 0.00003937 inches). It is very difficult to see and measure fractions of a micrometer, even with a good optical microscope or shadowgraph. A micrometer is only as long as two wavelengths of yellow light, and therefore perilously close to the ultimate limits of light microscopy. Similarly, the actual processes used by RCA to machine ("micromachine") the styli are impossible to watch. Only snapshot views can be obtained by aborting the micromachining process to take measurements—and this runs the risk of introducing additional (and uncharacteristic) variation in the process and product.

One problem that has concerned personnel at RCA's VideoDisc cartridge plant involves the faceting and micromachining of two geometric features of the VideoDisc stylus that are supposed to be in the same spatial plane. One of them is called the "v line," and the other is the "prow"—from an analogy to boating (Fig. 1, next page).

The "v line" starts at the back of the bottom part of the stylus which, seen from the rear (the electrode side), is shaped like a "v." It continues forward for the entire length of the shoe (that part of the stylus which rides in the VideoDisc groove.) The prow is the lower front part of the stylus. It steers the stylus along the groove.

The distance between the plane of the v line and the plane of the prow, as optically measured at the apex, or lowest point of the prow, is referred to as "v-to-prow off-center," or simply, "v-to-p." In a geometrically perfect stylus, the v line should end at the prow; a v-to-p of zero is best. V-to-p was one of the major defect classes found at the visual inspection station following final micromachining. It had been responsible for a cartridge reject rate of about 15 percent at that station.

Strategy for tracking down v-to-p

Members of the RCA Laboratories Productivity and Quality Assurance Research group were teamed with staff from the

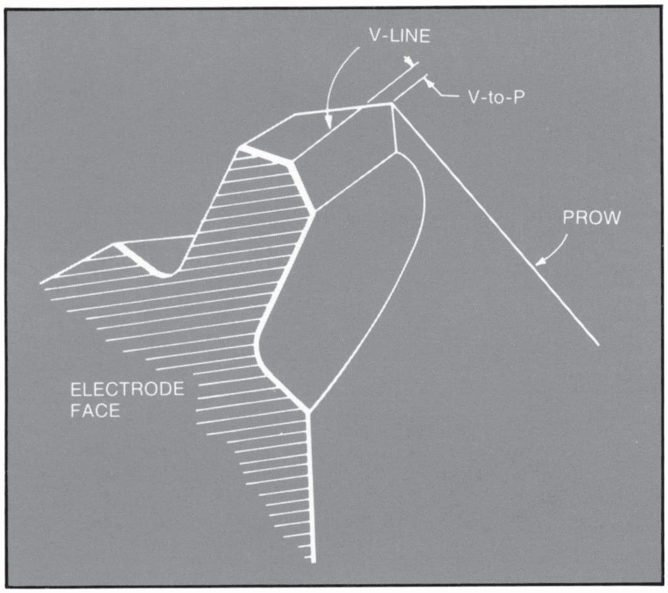

Fig. 1. *The VideoDisc cartridge stylus, with geometric features noted. The "shoe" makes contact with the bottom of the groove. The prow is the leading edge of the stylus. The "v line" runs along the bottom center of the shoe. In a perfect stylus, the "v line" intersects the prow.*

VideoDisc stylus terminology

The following terms are used in the article and describe the different alignment directions of the VideoDisc stylus with respect to the VideoDisc groove.

Lean: angle of the stylus as measured in line with the disc groove.

Azimuth: rotational angle of the stylus as measured between the disc groove line and the normal to the electrode surface. The electrode surface should be perpendicular (90°) to the side of the disc groove, which corresponds to an azimuth of 0°.

Tilt: angle of the stylus to the side of disc groove.

Electrode facet angle: angle on the electrode face from the prow facet to the vertical plane perpendicular to the electrode face.

Prow heading: angle of the heading of the line formed by the intersection of the two prow facets with respect to the disc groove centerline.

Shoulder-height induced angle: v-p offcenter that occurs at setdown on the micromachining tool. It is caused by the different shoulder heights of the tool grooves.

VideoDisc cartridge plant to track down the causes of v-to-p. The ultimate goal was gaining a better understanding of these causes so they could be reduced or eliminated. A number of possible causes of v-to-p had been proposed and, through the use of engineering judgment, partially ranked lists of these proposed causes had been produced. There was general agreement that v-to-p and its causes were poorly understood. Because of the small dimensions and difficult measurements involved, though, it was not clear that the rankings were correct, or that the lists even contained the most important causes!

Divide and conquer

The strategy was to take a methodical and disciplined approach. This was unlikely to find a quick solution to the problem, but would guarantee that at each stage of investigation some knowledge would be gained, thus shrinking the list of possible causes. This "divide-and-conquer" strategy differs from the troubleshooting often seen in manufacturing, which uses a mixture of engineering judgment and experience. In general, the statistical production engineering approach does not promise immediate results. It is therefore inappropriate to expect "quick fixes," but rather to look for an evolutionary improvement due to deeper understanding of the process. These results, though slower, can still be dramatic.

The first step in this divide-and-conquer approach was to determine the primary source (*not* cause) of v-to-p variability. Was it due to v-to-p measurement variation (lack of repeatability)? Stylus variation? Cartridge assembly variation? There are four separate stations of micromachining equipment. Was there variation among them, or were they all performing alike? There are two micromachining media, types N and R, and different micromachining tools are used. Did media or tools contribute variation? Nobody knew for sure. The data available did not point in a clear direction. To answer these questions, a hierarchical, or "nested," study was proposed based on the hierarchy of the micromachining process. This "process capability study" focused on the capability of the existing process to make cartridges free of v-to-p problems, to measure the variability of the existing process, and to split this variability up into its separate sources.

Process capability study

The hierarchy was natural, at least on a gross scale. First, there were four micromachining stations. Second, on each station either of two types of media could be used. These two parameters could be chosen at will for the study. Third, for each type of medium we had some sample micromachining tools all from the same tool production run. Fourth, for each tool we had some typical cartridges. These latter two parameters were sources of variation that were taken as given, and were truly "nested." Calling this situation nested means that while medium N could be run on station 1 or on station 3, the medium of tool 37 could not be changed, nor could we try tool 37 on different stations. Similarly, we could micromachine a cartridge on only one tool—hence on only one medium and on only one station. The structure of the study is shown in Fig. 2. Additionally, some cartridges were measured twice to give an estimate of the measurement error.

Before the study was carried out, some technical staff and some managers were asked to estimate the sources of variation and their relative proportions. This was done in order to get everyone to think in quantitative terms, to see a variety of ideas about the variability, and to enable us to later measure what we had learned from the study. The estimates from this exercise are shown in Fig. 3.

The study was carried out in April, 1983. As the study results in Fig. 3 illustrate, most (71 percent) of the v-to-p problem had its source in cartridge-to-cartridge variability. In other

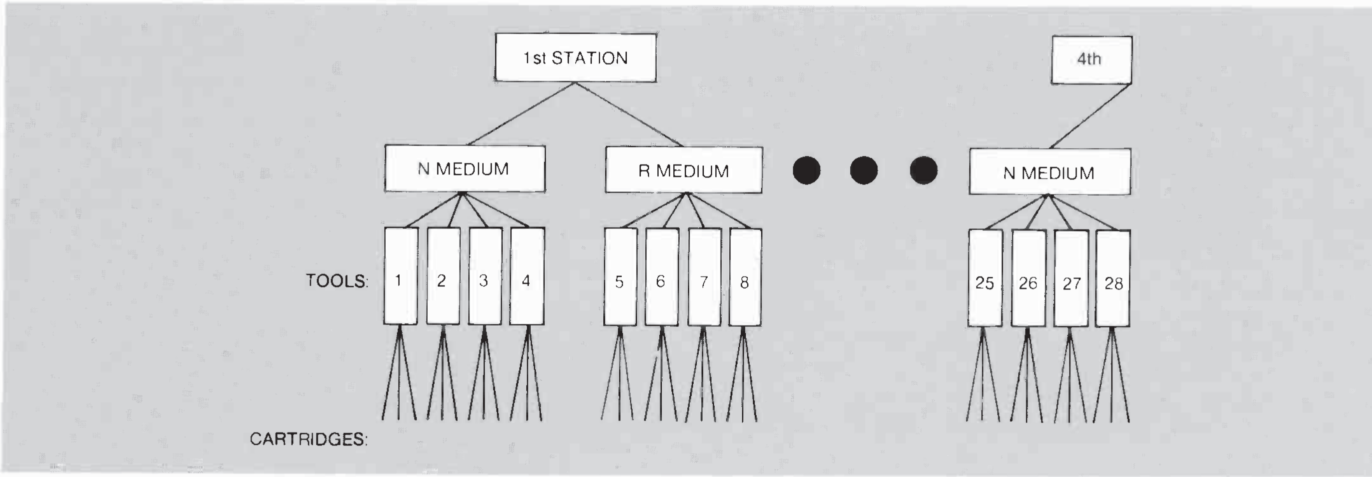

Fig. 2. *Design of the process capability study. The natural hierarchy of the micromachining process is reflected in this designed study. The specific details of how many media per station were used, how many tools per medium type were used, etc. directly entered into the analysis of variance done on the data obtained.*

Source of variability	***Estimated total % of variance***	***Percentage variance predictions and (% off from study)***				
		Person 1	*Person 2*	*Person 3*	*Person 4*	*Person 5*
Station	9	5 (– 4)	5 (– 4)	5 (– 4)	15 (+ 6)	13 (+ 4)
Medium	0	20 (+20)	20 (+20)	30 (+30)	25 (+25)	0 (0)
Tool	18	5 (–13)	40 (+22)	5 (–13)	15 (– 3)	12 (– 6)
Cartridge	71	60 (–11)	30 (–41)	40 (–31)	50 (–21)	50 (–21)
Measurement error	2	10 (+ 8)	5 (+ 3)	5 (+ 3)	5 (+ 3)	25 (+23)

Fig. 3. *What we have learned from the study (4/7/83). Five people in the cartridge manufacturing plant can quantify what they learned from this study. These five gave predictions of variance components for each of the sources of variability identified in the study: station, medium on tool, tool, cartridge, and measurement error. Here are the results in percent of total variability.*

words, the cartridges were different from one another *before micromachining* in an important (and unknown) way. This unknown difference accounted for 71 percent of the variation seen in the v-to-p measurement, while the differences among stations, in the media, in the tools, and in the measurements accounted for only 29%. That this cartridge-to-cartridge difference was the main source of variability was not a great surprise (see Fig. 3), but the extent to which it accounted for v-to-p was new information. This conclusion indicated that efforts should be focused on cartridge-to-cartridge variation first.

To study cartridge-to-cartridge variation, a list of possible causes of v-to-p was needed that indicated what could vary from cartridge to cartridge. To generate this list, some information from the cartridge plant was obtained and, in addition, a modeling technique was used.

Finding an ideal model

Independent of this Statistical Production Engineering effort, Dr. A. Moldovan of the Princeton Labs had developed an "ideal geometric micromachining" model that used a trigonometric formula to compute what machining would occur when a stylus with six specific geometric characteristics came into contact with a tool with one specific geometric characteristic. The model intentionally ignored such phenomena as resonances between stylus and tool, changes in any part of the cartridge other than the stylus during micromachining, nonuniformities in the machining medium, and the crystallographic orientation of the stylus. Moldovan had integrated into the model those characteristics of the stylus and tool that he thought were important and that he thought could be modeled reasonably easily.

Previously, Moldovan had used his model for Monte Carlo computer studies. He made distributional assumptions of interest for the seven geometric variables, and essentially drew values for these variables from the distributions for many thousands of simulated cartridges. His formula gave a predicted v-to-p for each group of seven variable settings. For any choice of distributions of the seven variables—each chosen to represent a manufacturing situation—an approximate distribution of v-to-p could be computed. Additionally, since Moldovan's model includes an

VARIABLE SETTING								V—TO—P THAT RESULTS
VAR:	1	2	3	4	5	6	7	
	1	1	1	1	1	1	1	—0.3846
	1	1	1	1	1	1	2	—0.2192
	1	1	1	1	1	1	3	—0.1140
				.				.
				.				.
				.				.
	5	5	5	5	5	5	4	1.0012
	5	5	5	5	5	5	5	1.0034

Fig. 4. *Design of the simulation experiment. A 5-to-the-7th full factorial "experiment" was run using Dr. A. Moldovan's "ideal micromachining" model. The data produced by the model took this form.*

T-Ratio	
624	(1) Electrode Facet Right
622	(2) Electrode Facet Left
2205	(3) Tilt
1081	(4) Shoulder Height Induced Angle
3966	(5) Azimuth
3966	(6) Prow Heading
0	(7) Prow to (Normal—to—Disc)
298	(3) & (7) Interaction

The greater the T-ratio, the greater the statistical significance. Greater than 4 is very significant.

Fig. 5. *Results of the simulation experiment. A quantitative ranking of the significance (and impact) of the control variables is given here, based on the regression analysis of the 2187-observation subset of the 15625 observations.*

analytic expression for v-to-p, the importance of the variables could be roughly ranked.

The designed experiment

The approach taken for this study, however, was a little different. In addition to providing some validation for the model, we wanted to rank the importance of the variables, and to quantify their relative importance in manufacturing. At the same time, it was possible to investigate the impact of interaction and quadratic effects as well as the linear effects. This would serve to guide the effort in the next stage of tracking down v-to-p: the performance of a designed experiment in the factory to identify specific cartridge sources of v-to-p problems. To reach this objective, a simple designed experiment was planned for computer simulation: a 5-to-the-7th "full" factorial experimental design, with every possible combination of five settings for each of the seven variables. The five settings were:

(1) low end of spec;

(5) high end of spec;

(3) nominal (spec midpoint);

(2) midway between (1) and (3); and

(4) midway between (3) and (5).

Moldovan's model was used to get all the v-to-p estimates, as shown in Fig. 4.

Since there were no random effects, including measurement error, in this simulation experiment, no repeated estimates were made for any combination of the settings. This design gave us $5 \times 5 \times 5 \times 5 \times 5 \times 5 \times 5 = 15625$ v-to-p estimates. Settings (2) and (4) were dropped, leaving $3 \times 3 \times 3 \times 3 \times 3 \times 3 \times 3 = 2187$ v-to-p estimates from which to make estimates of the linear, interaction, and quadratic terms, using regression analysis. The rest of the v-to-p estimates were used as a cross-validation, to "check the fit" of the mathematical expression obtained from the regression on the 2187 estimates.

The experimental results

The results of this experiment on simulated data are shown in Fig. 5. In summary, the model had a good fit, good validation, and the variables with the most statistically significant contributions to v-to-p were azimuth and prow-heading, tilt (half as significant as azimuth and prow heading), shoulder-height induced angle (half as significant as tilt), electrode facet angles (60 percent as significant as shoulder-height induced angle) and the rest. Quadratic terms were not important, but interactions were somewhat so—the most important of which (tilt and prow-to-normal-to-disc) occurred seventh on the ranked list of effects from the regression analysis.

The next stage of investigation was to statistically design an experiment that would give us estimates of the same terms, but from "real" data—that is, cartridges produced in the VideoDisc cartridge plant. It was impractical to consider actually setting all seven of the simulation variables in the production environment. Selection was made from the most important variables as identified by the simulation experiment, and an experiment was designed using them. Making this choice is not as straightforward as it may seem. In order to use variables that conform to the structure of the designed experiment, the variables had to be able to be set to predetermined values in the factory. The problem of "setting error" was not commonly appreciated in the manufacturing situation. Processes designed to manufacture parts to a nominal value cannot always specifically be changed to be able to set a variable at a predetermined value other than the nominal. In addition, it was now necessary to address the problem of measurement error in v-to-p, and in the variables themselves. The process capability study had, fortunately, shown the measurement error of v-to-p to be relatively small. If the measurement error were unknown, it would be impossible to determine the setting error of the variables.

After considerable discussion about the logistics, priorities, and design, an experiment and a plan for carrying it out were agreed upon. The key variables chosen were azimuth, prow heading, and tilt. The design chosen was a two-cubed full factor-

Setting or selecting? Which is better for a designed experiment?

Should an attempt be made to build samples of a product so as to set control variables at the levels called for by the design, or can the output of routine production generate the range of values required by the design? To answer this question requires judgment and experience on the part of the statistician and the engineer, because there are tradeoffs to be made.

On the one hand, if design points are chosen that are somewhat moderate—that deviate only slightly from the nominal—there will be a risk of seeing only local behavior or noise. This is analogous to looking at a small slice of data that shows roughly linear behavior. The advantage of choosing small deviations is that it will be relatively simple to get samples of the product that have the values required by the design. This can be done either by slight process modifications to set the control variables, or by selecting from existing production.

On the other hand, if more extreme design points are chosen, the study is more likely to see causal behavior through the noise, at the risk of detecting behavior uncharacteristic of possible control variable settings in production.

Setting control variables by modifying the process runs two risks. First, modifying the process will likely change more than just the control variable intended. Second, it is impossible to modify the process to obtain precisely the desired setting. This is due both to setting error and measurement error.

Selection from current product to find samples that conform to the design points runs three risks. First, measurement error prevents us from obtaining precisely the desired setting. Second, a selection of product that has the desired characteristics may be different from nominal product in other, unknown ways. Third it may also be impractical to select from current product. This is often the case for complex designs.

For example, with a 2-to-the-4th factorial experiment design, with settings at the plus/minus two standard deviations from the (nominal) mean, and given that the control variables have a Gaussian distribution, there is a chance of 0.00000057 that any given sample would meet a given design point.

The complexity of these issues and their implications for both statistician and engineer means that it is important to address them early in the process of planning a designed experiment.

ial with eight replicates to protect against setting error, and to help estimate unexplained variability. This design is shown schematically in Fig. 6. Each variable was planned to be set at two settings, its specification low, and its specification high.

The data and results

In August of 1983 the experiment was conducted over a week's period. After all the data had been collected, the results were analyzed. Additional measurements were taken on the styli made with synthetic diamonds, and these were also analyzed. The results of the experiment are summarized in Fig. 7. In brief, it was found that:

1. Setting error was serious—cartridges could not be specially built as desired.
2. Right electrode facet angle, tilt, and azimuth were statistically significant causes of v-to-p for synthetic diamonds.
3. Synthetic diamonds differed greatly from natural diamonds.
4. Right electrode facet angle and left electrode facet angle did not behave with the same degree of importance in affecting v-to-p.

The results of the analysis prompted the cartridge plant people to

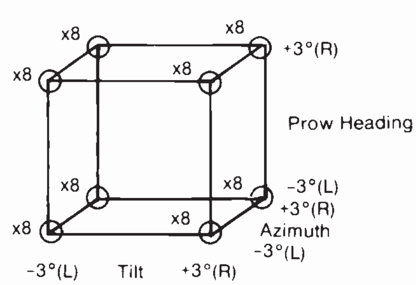

Fig. 6. *Design of the v-to-p experiment. The design of the v-to-p experiment called for eight cartridges to be built for each of the eight possible combinations of tilt (3° L/ 3° R), azimuth (3° L/ 3° R), and prow heading (3° L/ 3° R), totaling 8 × 8 = 64 cartridges for each type of diamond stylus, natural and synthetic.*

T-Ratio	
3.78	(1) Electrode Facet Right
2.15	(2) Electrode Facet Left
2.02	(3) Tilt
3.13	(5) Azimuth
1.52	(6) Prow Heading
1.21	(7) Prow to (Normal—to—Disc)
1.91	(8) Force
1.65	(9) Bias

The greater the T-ratio, the greater the statistical significance. Greater than 2 is probably significant.

Fig. 7. *Results of v-to-p experiment. A quantitative ranking of the significance and impact of both control variables and other variables (measured on the cartridges after the experiment was conducted) is shown here for the synthetic diamond stylus.*

reexamine the faceting and assembly operations, where two of the key variables, tilt and electrode facet angles, were set during stylus manufacturing. These were of particular interest because they were identified as the most important variables by the in-plant experiment, because of the unequal magnitudes of the left and right facet angles, and because of the interaction term of tilt and prow-to-(normal-to-disc).

During this reexamination, it was discovered that the first alignment fixture for prow faceting was skewed. This caused a fixed shift away from the nominal. In order to produce acceptable cartridges further on in the assembly process, the rest of the faceting equipment had been set up to compensate for the hidden shift. Although this appeared to correct a problem, it actually compounded the problem and obscured the fact that there was a problem. The compounding effect was a result of nonlinearities in the impact of one variable on another. Specifically, when the tilt was not zero, the electrode facet angles could not be properly set and measured. This in turn meant that the prow angle could not be correctly set and measured.

Prompt effort went towards correcting not only the primary problem on the first faceting fixture, but the "cascade" of problems that had been introduced because of the first problem. The immediate impact of making these corrections was a reduction of v-to-p rejects from the 15-percent level to the 5-percent level. Subsequent improvements of this sort have reduced the reject level to about 2 percent. This reduction, coupled with the fact that v-to-p causes only a soft failure (over the long term it leads to an increase in noise in one of the stereo channels), means that v-to-p alone no longer justifies an inspection after micromachining.

It is anticipated that other problems, some which now do justify inspection, will be discovered and solved using the systematic methodology of statistical production engineering.

Summary

The reduction of the v-to-p problem in the VideoDisc cartridge plant from about 15 percent to about 2 percent was the result of a cooperative effort between Labs industrial statisticians and the managers and technical people at the plant. The contribution of the statisticians was an unbiased, statistically sound, and effective collection of methodologies for investigating the problem. The contribution of the VideoDisc cartridge plant people was commitment to carry out the project at the risk of short-term production losses, technical (especially engineering) expertise, and refreshing candor to keep the statisticians on a path that made sound engineering sense.

The systematic investigation described appears easy. In fact, it was not as simple as it appears. The process capability study turned out different from the way it had been designed. Geometric variables were frequently confused, since they are conceptually difficult to envision and can't be seen directly. Forty percent of the data used in the first computer simulation experiment were discovered to be incorrect. The design of the experiment to study cartridge-to-cartridge variability was completely revised four times.

The activities and benefits described here are but a fraction of the successful work carried out by the people at RCA's VideoDisc cartridge plant, in which statistical production engineering techniques are used.

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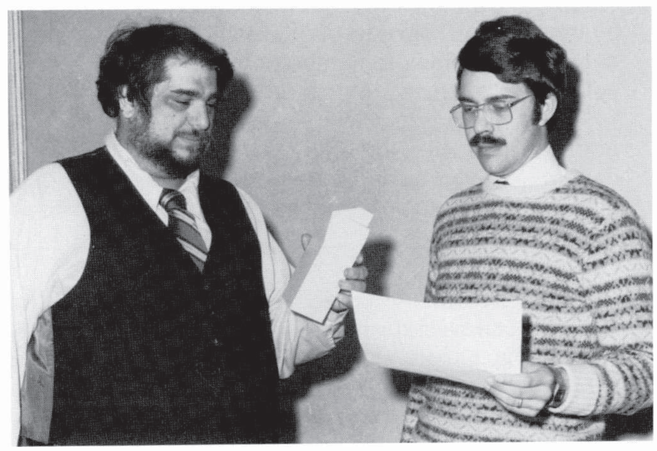

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