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Real Experiments, Real Mistakes, Real Learning!

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Abstract

Experimental design case studies typically document a successful application of the technique. Successful case studies are valuable in broadening the perspective of the industrial experimenter and are useful in teaching. In this paper we explore, through the use of case studies, the lessons that can be learned from cases which were not successful or where problems were encountered. All data have been disguised to protect proprietary interests without compromising the learning value of the case.

1. INTRODUCTION

Experimental design has demonstrated its value as an effective process learning and problem solving tool. Many case studies have been written publicizing the broad range of application and impressive results, Bisgaard (1992). Cases have proven themselves to be a valuable tool for teaching and broadening perspective

In general, published case studies can be categorized into two main groups. The first type is case studies that detail a specific application, for example injection moulding. These types of cases are of interest to others involved in injection moulding, particularly when common problems such as "sink", "short shots", or excessive shrinkage are involved.

It is very difficult to teach the application of experimental design to engineers in a foundry using such case studies. This has given rise to specialized courses sponsored by groups such as the American Foundrymen's Association. The second type of case study is concerned with documenting the approach used to solve a problem rather than the nature of the problem. Common examples of this approach are case studies which discuss techniques such as Taguchi methods or response surface methodology.

A third type of case study that is seldom published and rarely discussed, documents experiments which were not successful for a variety of reasons. This is a difficult area to gather any kind of information, since failure is stigmatized both in academia and in industry. Symposium organizers are generally more interested in projects which were successful and saved hundreds of thousands of dollars than a project that was a "failure", but in which valuable lessons were learned.

Learning from a Mistake

In an experiment that has gone well, it is difficult to communicate the importance of the planning that led to the success. These details, if they are documented, are often overlooked in favour of the impressive results that have been achieved.

For the student, learning from a mistake, changes the focus of learning. Some of the questions that arise in the mind of the student are: "What happened to cause the experiment to fail?", "Why did the event happen?", "Could I make the same mistake?" and "What are the implications of the mistake?" In the world of medicine, hospitals set up committees to review the way patients are treated. Mistakes are viewed as an educational opportunity not just for the person that made the mistake, but also for other professional staff. This same philosophy can and should be carried over to the practice of experimental design.

There is also an element of psychology present in learning from a mistake. This element is called a "psychological anchor". An "anchor", in psychology, is an event that triggers a whole set of related emotions, feelings, or memories. In teaching experimental design, it is difficult to get students to remember the steps of systematic experimentation. One model of systematic experimentation is shown in Figure 5. Montgomery and Coleman (1993) discuss the need for a systematic approach and suggest the use of questions on check sheets to guide the experimental process. In industry, where experimenters are also involved in short term "fire-fighting", some steps in the process of experimentation may be skipped due to time pressures. A case study that illustrates a mistake can create a "psychological anchor" in the mind of the experimenter. For example, in consulting with students after they have been exposed to case studies where errors have been made, the consultant only needs to state: "Remember the case of the crazing tail light." The main issues in the tail light case will immediately come to mind. This is much easier and considerably more effective than saying, "Remember the fourth step of the fourteen step problem solving model for experimental design".

The case studies that we have chosen to discuss effectively complement the teaching of a structured approach to design of experiments. They also reiterate the importance of the following:

(i) utilizing existing data before the design of an experiment,
(ii) paying attention to setting levels for a factor
(iii) conducting trial runs
(iv) having good communication among the team.

The cases have been integrated into teaching in both industrial and academic settings. We have found that students are interested and motivated to learn from these case studies.

2. THE CASE OF THE CRAZING TAIL-LIGHT

Background and Review of Process:

A tail-light consists of two portions, the clear back-up lens and the surrounding red lens. In the process under investigation, the back-up lens is moulded first, then inserted into another mould where the red lens polycarbonate is injected around the clear lens. The problem in this case was "crazing" of the back-up lens. Crazing consists of fine cracks that can affect the translucency of the part. The typical discrepancy rate for crazing was 2-3%, which was easily managed. The rate, for no apparent reason, increased dramatically to 20-30% and remained high.

Other relevant background information that influenced this case is detailed below:

(i) The plant was on a three shift operation thereby compounding communication difficulties.
(ii) Experimental design was new to the organization and was viewed as a panacea.

(iii) Engineers from the plant had just completed a ten day Design of Experiments course and were eager to put into practice what they had learned.

Figure 1 is a flow chart of the process to produce taillights. Two moulds 88A and 88B produce one right side and one left side clear polycarbonate lens. The clear lens is then inserted into another moulding machine. The red polycarbonate is then injected around the clear lens. The three moulds, 7A, 7B, and 7C produce one complete assembly per cycle. The parts are then put into a basket for baking in an oven. Baking is necessary to relieve the high internal stresses that occur during the process of moulding the red lens around the clear insert. After leaving the oven, the parts are sprayed with a protectant to avoid ultra violet degradation of the polycarbonate.

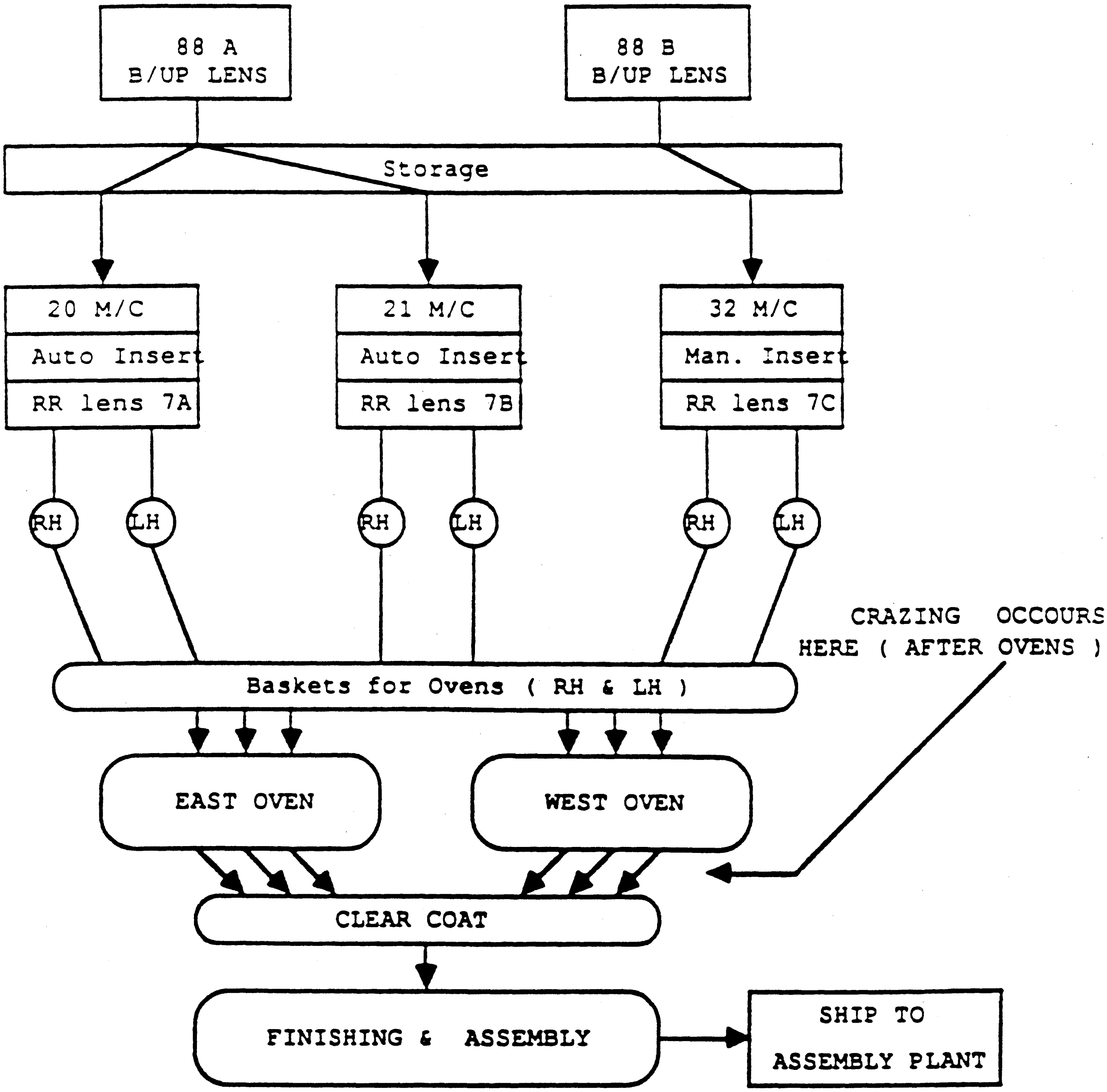
Crazing was not noticeable until after the parts left the oven. This was frustrating for the team since a great deal of value added time and material was lost when a part was scrapped.

Cause and Effect Diagram

An extensive cause and effect diagram was constructed (Figure 2). Input from a number of operators and engineers was obtained in constructing the diagram. The team also decided to list a number of response variables. The reason for this is that the team did not want to eliminate crazing only to have another problem occur. Listing multiple responses on the cause and effect diagram helped to keep this issue in mind.

Two experiments were conducted. The first experiment focused on injection moulding machine factors such as "screw speed", "clamp time", etc. The second experiment focused on factors involving the oven and moulds.

Figure 1
Tail Light Manufacturing Process



Experimental Design Layout and Results

The experiment consisted of 11 factors, 16 runs, "blocked " over two types of base material. In effect, a 32 run experiment--something that is not trivial in a manufacturing environment.

After the first experiment, very little was learned that could reduce the scrap rate of the lenses. A second experiment was planned to focus on differences in moulds. This second experiment clearly demonstrated that most of the scrap produced during the experiment came from one mould.

A search for a special cause was made and it was discovered that during routine preventive maintenance some minor changes were made to one of the moulds. Unfortunately, these changes were the source of the problem.

What Was Learned

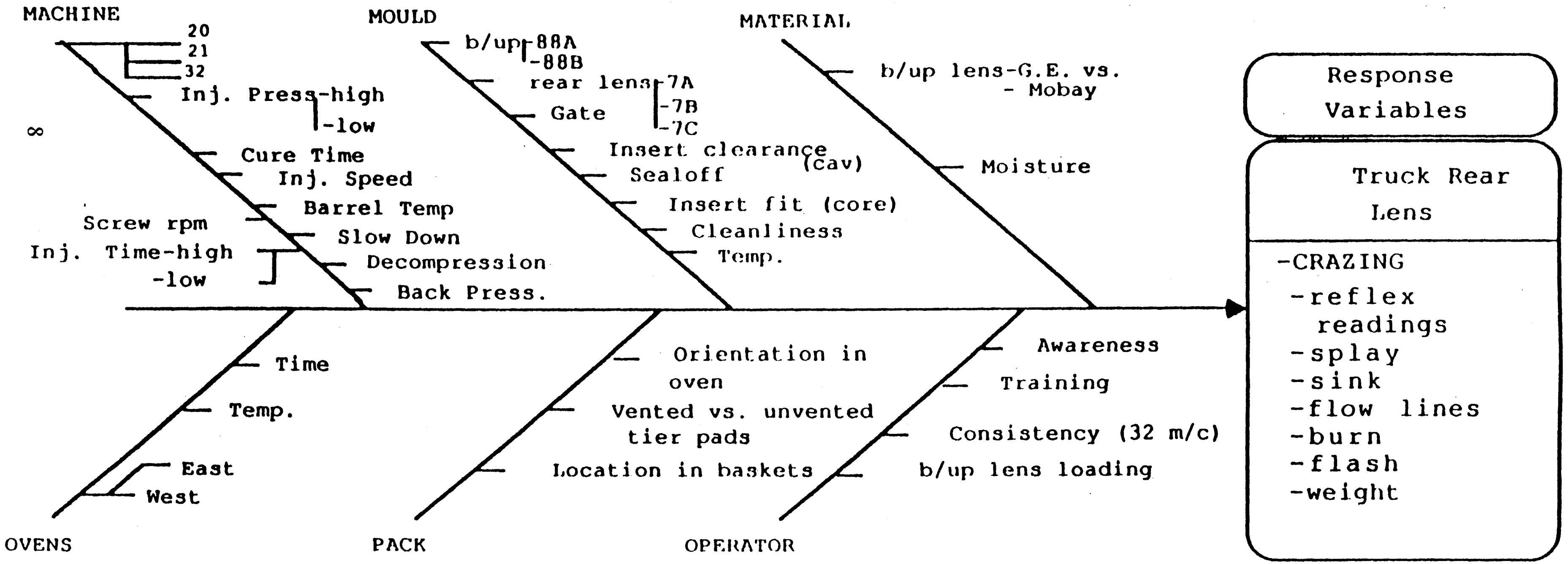
In this case the second experiment was successful in finding the cause of the problem. Beginning industrial experimenters are often disappointed after a first experiment that does not find the answer. In some situations, management loses patience and concludes, "We tried experimental design here and it does not work". In this case, the experimental design team and management of the plant deserve credit for their persistence in sequential experimentation.

After the team completed the second experiment and discovered that one particular mould was causing the problem, a valuable lesson in experimental design practice was learned.

The mould and the point where the crazing was first observable were separated in time and space. Thus a cause and effect relationship was not readily observable. However, each taillight carries a "witness mark" that indicates which mould produced the part. Since the plant was having high rates of scrap, it would have been a relatively easy matter to stratify scrap by mould.

Figure 2

CAUSE and EFFECT DIAGRAM



Histograms of scrap by mould would easily have isolated the source of the problem.

In the eagerness of the team and the consultants working with them to perform an experiment, the power of the "seven basic tools" was overlooked, Ishikawa (1976). The parallel streams in this process strongly suggested that stratification would be a meaningful analytical tool.

3. LEARNING FROM TRIAL RUNS

Background

Trial runs are recommended for a number of reasons. Some of which are:

- (i) An opportunity to evaluate potential problem treatment combinations before proceeding with the experiment.
- (ii) Trial runs provide a final chance to fine tune levels of a factor.
- (iii) As the word "trial" suggests it is a test of the system that will be engaged during the course of an experiment. This is important in a production environment where the experimenter may only have one chance to obtain the needed data. Trial runs provide a chance to make any needed changes in the experimental plan before an experiment begins.
- (iv) Trial runs can help considerably in estimating the time to complete a run, logistical support required for level changes, and total time needed to complete the experiment.
- (v) Finally a trial run is also an excellent communications vehicle. Any breakdown in communications will likely be apparent during trial runs. Trial runs also provide an opportunity to remedy the situation before proceeding with the experiment.

We will review two cases to discuss trial runs. The first case deals with measuring engine performance in a research and development project. The second case deals with evaluating the size of a new dip tank in a paint shop.

Situation 1 -- Engine Performance Experiment

In this situation the experimenters were interested in evaluating the effect of a number of factors on engine performance. Due to the need for specialized test equipment, the experiment was contracted to an outside laboratory. The lab had an excellent reputation for research. However, lab engineers had very little exposure to experimental design. Facilities at the lab were in great demand and expensive, consequently the need by everyone involved to minimize the amount of test cell time.

The process of experimental design was reviewed with the team that would be conducting the experiment. Equipment and materials were ordered and the experiment was planned. The test cell was very complex, and four trial runs were suggested to evaluate the operation of the whole system as well as a potentially sensitive level setting.

Data collection in the test cell was automated. It was possible to collect numerous observations and have the data automatically logged in a computer. The engineers at the lab decided that they would "spot check" key values from the trial to make sure everything was running properly. The laboratory informed the engineers at the company that requested the experiment that the engine horsepower and some other responses were not performing as specified. They also indicated that the discrepancy must be due to the engine supplied. The laboratory was requested to supply the complete data set for the trial runs.

While data from the trial runs were being formatted and sent to the customer's engineers, the laboratory engineers decided to immediately begin the experiment after the trial runs. After three or four runs the laboratory engineers commented again on the fact that the engine was not performing as specified. Since the customer had supplied the engine, it was assumed it must be the customer's problem.

After receipt of the data at the customer's location, plots were made of a number of observations. Although there were only four runs, a degrading pattern from run to run was apparent. (See Figure 3) Not only was the engine not performing as specified, it was getting worse from run to run. This was an important clue. The engine, by itself, was not likely to have this type of degradation. The equipment for measurement, which was calibrated and checked frequently, was not likely to be at fault. The problem must be the result of some interaction between the engine and the measurement equipment.

After about the tenth run the performance of the engine had degraded to the point that the test could no longer be continued. The lab engineers did not have any idea on what caused the degradation. Since the lab was experiencing pressure from other customers for use of the test cell, the test was halted and equipment was dismantled. During dismantling, a failure related to improper heat dissipation in the test cell was discovered. This type of failure was consistent with a degradation in performance. Since the failure was a result of an interaction between the lab equipment and the engine, neither side was willing to accept full responsibility.

The most important lesson from this experiment was the importance of communication. Even though the protocol for the experiment was explained to the lab personnel, the importance of examining the data from the trial runs was lost.

The planning and sequence of steps in an experiment need to be discussed and negotiated with the team prior to conducting the experiment. Other valuable lessons that can be gained from studying this experiment are:

(i) Ensure that the whole team understands the importance of trial runs and why they are being run.

(ii) Establish conscious "buy-off" points during the process of the experiment. Before proceeding the team must make an informed decision.

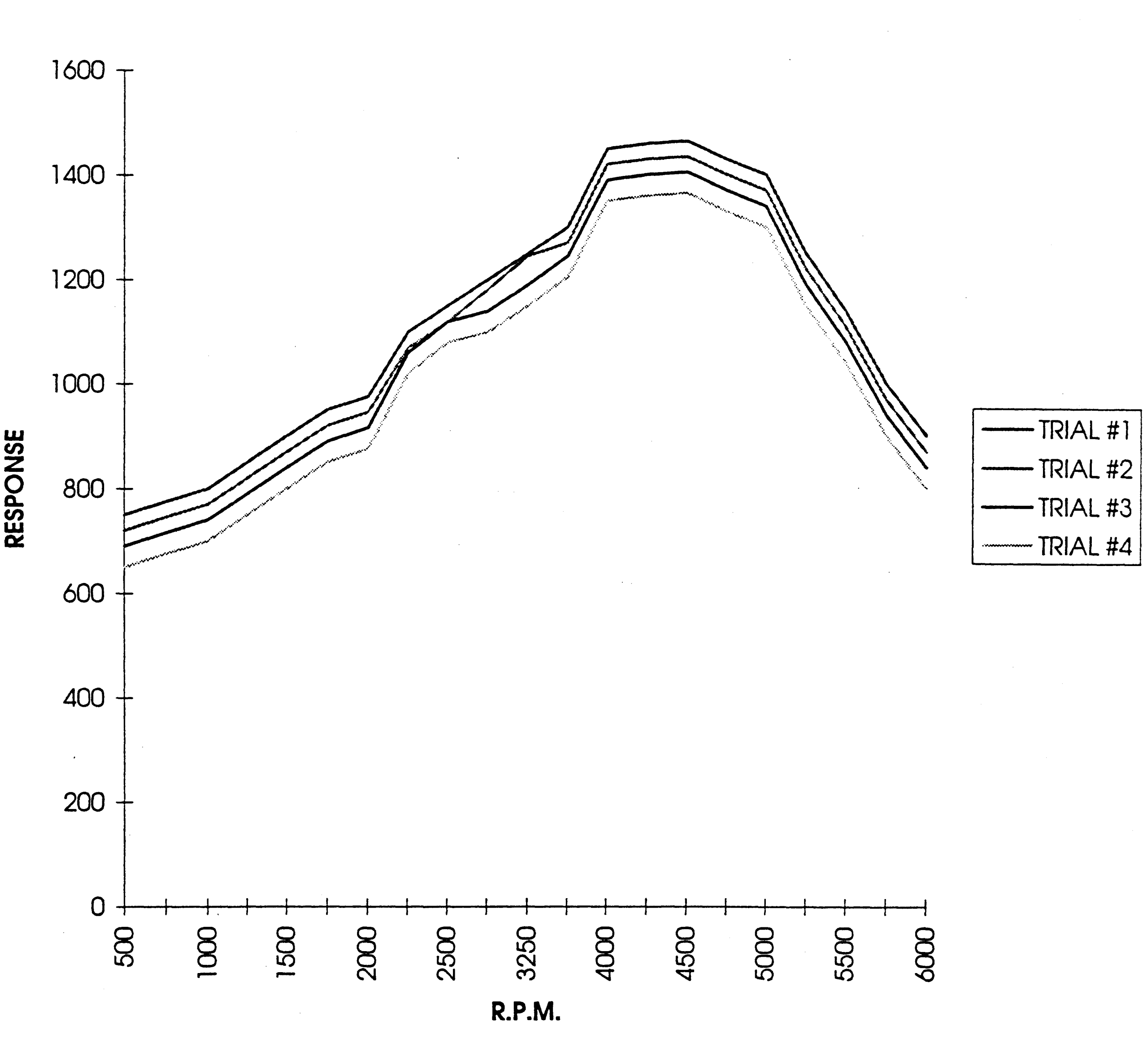


Figure 3

ENGINE PERFORMANCE

(iii) Hold a debriefing session after the trial run to review any problem areas and make required changes before proceeding.

Situation 2 -- Priming Experiment

An experiment was planned for an automotive paint shop. The plant was planning a major paint shop re-tooling for the next model year. One of the processes before the final paint coat is applied involves dipping the parts in a primer tank. The primer is applied to the parts through the process of electro-deposition. This process ensures a uniform coating of primer. One of the questions that the experimenters wanted to answer, was "What is the best size for the paint dip tank?". The speed through the tank is typically controlled by the output requirements of the paint shop. Consequently, the longer the tank, the longer the time the part spends in the primer.

In addition to investigating the size of the tank, some other factors such as primer composition and electrical current were also studied. The engineers had planned to experiment during the "build-out" process just prior to the re-tooling. If anything that was not expected happened, the impact on production would be minimized. To simulate the longer tank, the engineers obtained permission to alter the line speed through the current tank. Slowing the line speed would increase the amount of time the parts spent in the tank, thereby simulating a longer tank. The ability to alter line speed was a key factor in the experiment.

In this experiment, no trial runs were performed. When the engineers were questioned by a consultant on their ability to change line speed, the reply was, "No problem, we have to make occasional changes to line speed through the model year, we should be able to handle this without any difficulty."

The team recognized the difficulty of making frequent line speed changes. As a result, randomization was restricted such that all of the runs at the current line speed would be completed first. After eight runs were completed of a sixteen run experiment, the time came to change the level of the factor "line speed". There was little time left to complete the experiment due to the strategy of conducting the experiment during build-out. Consequently, there was no room for error. Unfortunately, the team discovered that adjusting the conveyors to the new line speed would take over one day. The team ran out of time and the experiment could not be completed. How could this situation have been avoided? Simply by conducting a trial run and discovering the amount of time required to change line speed.

This case points out another reason for trial runs, discovery of the amount of time required to change levels for a factor. Often the amount of time required to complete an experiment is underestimated. Engineers typically have been trained to change one variable at a time holding all others constant. Similarly, when adjustments are made in the plant, engineers are used to estimating the time to change one variable. To change several variables for every run is considerably different from most engineers' mental model of how to run an experiment or to make process changes.

4. UTILIZATION OF EXISTING DATA AND SETTING LEVELS

The task of setting levels for factors often does not receive the attention that is required. A great deal of thought is often given to choosing factors. Selecting levels often does not receive the same degree of attention.

A manufacturer of rubber products was conducting an experiment in their rubber compounding process. The purpose of this experiment was to identify the factors which were important in controlling the process so that the plant could implement more effective process control plans. The company had assembled a multi-disciplinary team that included, chemists, engineers, quality assurance, and the operators of the process. Often operators are not included in the planning stages of an experiment. People who work with a process every day are valuable sources of information for planning an experiment and their input should be sought at the earliest stages of an experiment.

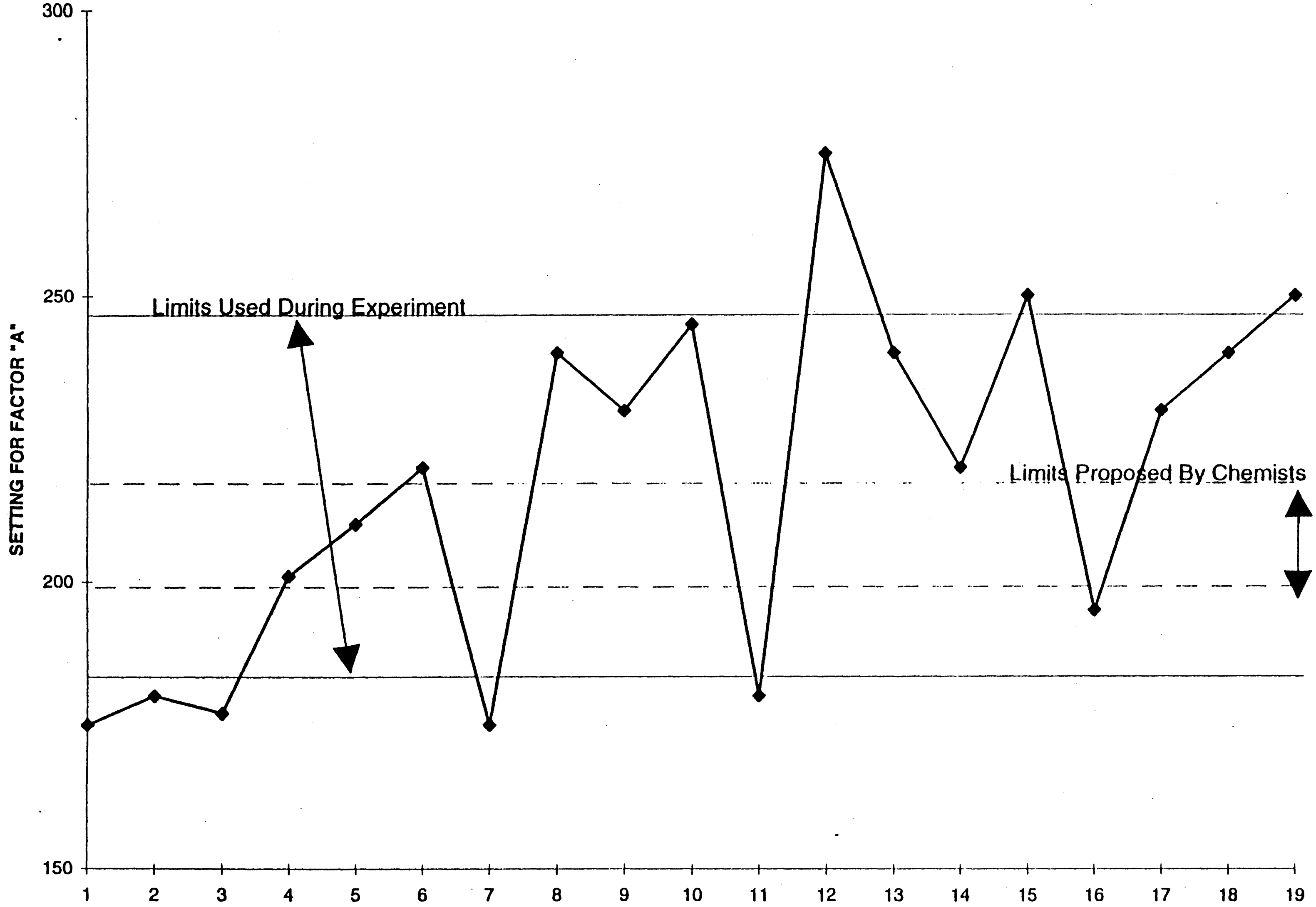
The chemists were not convinced of the experimental design approach and appeared to be somewhat threatened by the process. They insisted on what appeared to be a very narrow range for the levels. One of the chemists even suggested that the corresponding factor should be left out of the experiment.

The remainder of the team insisted that the factor was important and should be included in the experiment. Some members of the team felt the range for the level proposed by the chemists was too narrow. The team became deadlocked and turned to the consultants working with them for help. The consultants also felt that the range was too narrow, but lacked supporting data. Fortunately, the company was rich in data and poor in information. The consultants reviewed process history data and found that there was a great deal of variation in the level of the factor.

A chart was prepared of the setting of the factor over the past year and was presented to the team. (See Figure 4) This chart clearly demonstrated to the chemists that the range they were proposing was too narrow. After examining the chart, the chemists relented and more reasonable levels were chosen.

This case demonstrates the power of substituting facts for emotions. This has to be done in a non-threatening manner and is best handled by keeping issues within the team. Often political motivations will manifest themselves during the planning of an experimental design, particularly with respect to factors and levels. The consultant and team leader should be aware of the potential for this to happen and to be prepared to handle the situation in an objective (facts based) manner.

Figure 4
OPERATIONAL RANGE OF FACTOR "A" OVER TIME



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5. COMMUNICATION BEFORE THE EXPERIMENT

A manufacturer of rubber bushings was planning an experiment for improvement of cosmetic and functional problems encountered with inserting rubber into a metal sleeve. An experiment was planned to investigate the effect of a number of different process settings on the finished bushing.

Running the experiment involved interfering with regular production. Consequently, the management of the plant granted permission to run the plan on a Saturday solely for the purpose of the experiment. Further, the plant management pledged that the "best" operators would be made available to come in and assist with running the equipment.

The team gathered on a Saturday morning. A few trial runs were planned to ensure that no changes would be needed prior to running the actual experiment. During the first trial, some scrap started to be produced by one of the machines. The operator immediately noticed the problem and started to make adjustments to the settings. When questioned why he was doing this the natural reply was "Surely you do not want to make scrap during your experiment!". The situation was immediately noticed by the consultant who asked if the operators had been exposed to any experimental design concepts. The reply was, "I am just here to do my job and my job is not to make scrap". The conflict in this situation is that if the operator had changed settings during the middle of a treatment, the results for the treatment would be confounded. The purpose and essence of the experiment was to evaluate specific level settings that had been determined beforehand.

The experiment was halted for thirty minutes while the experimental design process was explained to the operator. Specifically, the operator was told that, "In order to understand how to make good product, we must learn how bad product is made." The remainder of the experiment was completed without incident. The experiment was successful in significantly reducing scrap.

In this case, the experiment was salvaged.

The team had held planning meetings but had neglected to make the operator a part of the team. The issue was compounded by the fact that the operator had specific tasks to do and was not aware of the conditions needed to run a successful experiment. The contribution that an operator can make to the experimental design process is often overlooked and crowded out by technical discussion.

6. CONCLUSIONS

To summarize, it is important that a structured approach be applied to the process of experimental design. Organizations should also document experiments that did not work out as planned in order that the lessons learned from these situations may be added to the corporate technical memory.

There are several different flowcharts and models for the process of experimental design. Figure 5 is one example that has been found to be a useful model. The case studies previously discussed have been listed on this chart next to the relevant process step. Notice from the chart, that most of the activities are in the planning stages of the experiment. Budgeting time for these activities can often avoid costly, time consuming mistakes during the running of an experiment.

Figure 5

EXPERIMENTAL DESIGN PROCESS

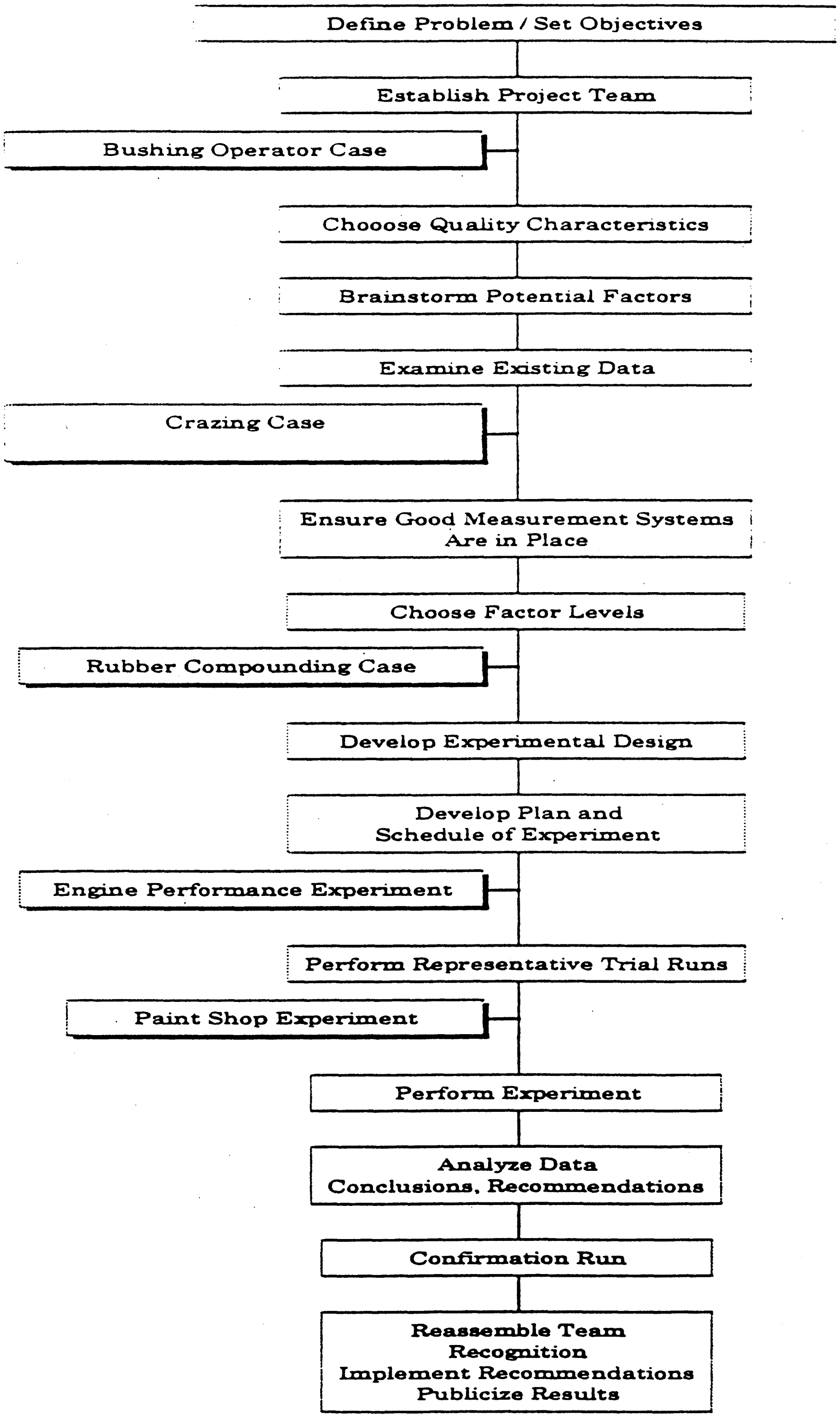

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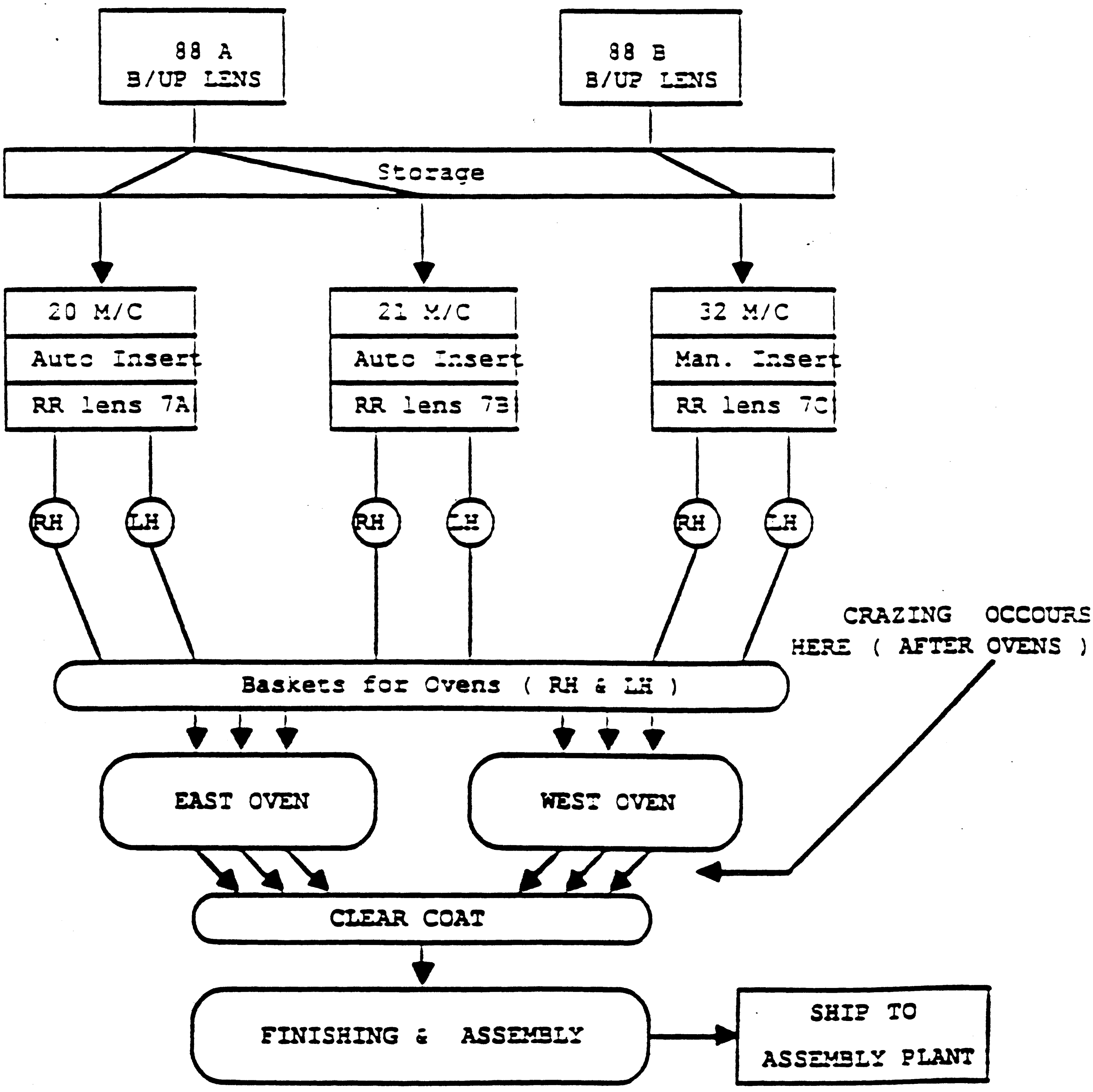
Figure 1

PROCESS FLOWCHART



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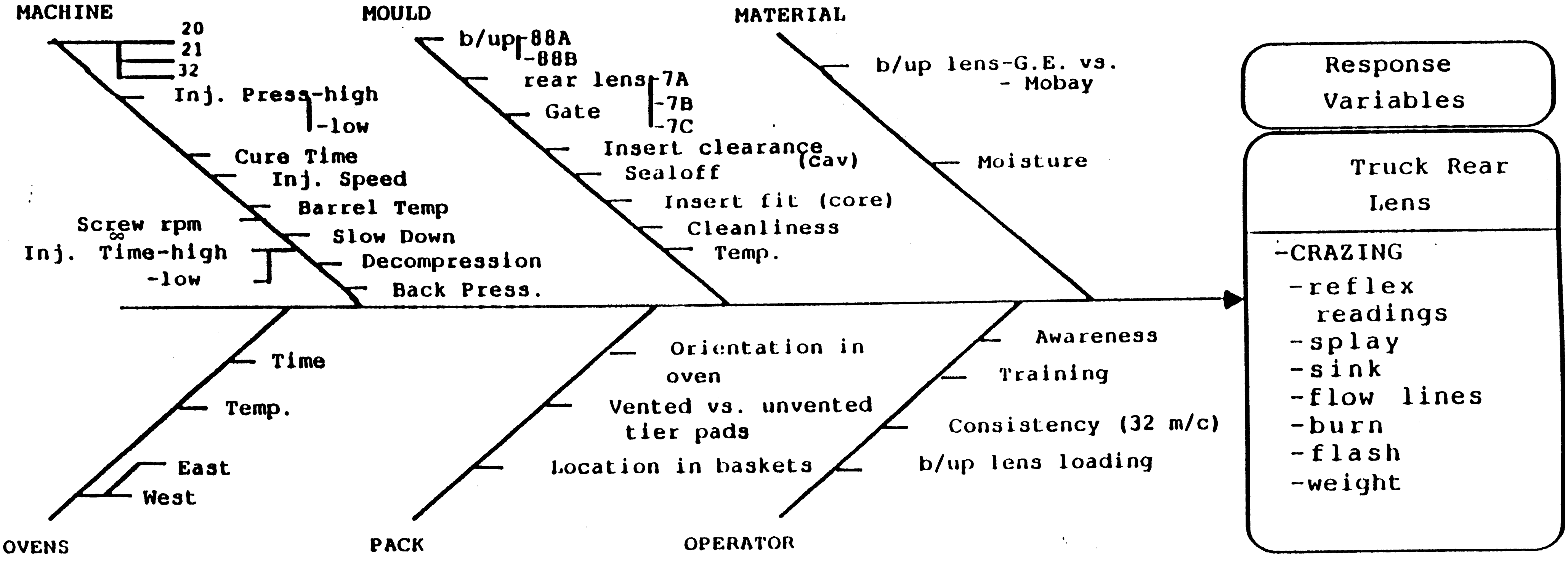
Experimental Design and Results

Two experiments with the same response variables were conducted. The first experiment focussed on typical factors for an injection moulding machine such as injection pressure, screw speed and clamp time. This experiment consisted

Figure 2

CAUSE and EFFECT DIAGRAM



of 11 factors, 16 runs, "blocked " over two types of base material. In effect, a 32 run experiment--something that is not trivial in a manufacturing environment. After the first experiment, very little was learned that could reduce the scrap rate of the lenses.

The second experiment focused on process factors external to the moulding machines such as moulds, machines, ovens and locations in the baking basket. These were more difficult to adjust and were not typically investigated in past problem solving efforts. This experiment clearly demonstrated that most of the scrap produced during the experiment came from one mould.

A search for a special cause was made and it was discovered that during routine preventive maintenance some minor changes were made to one of the moulds. Unfortunately, these changes were the source of the problem.

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Background

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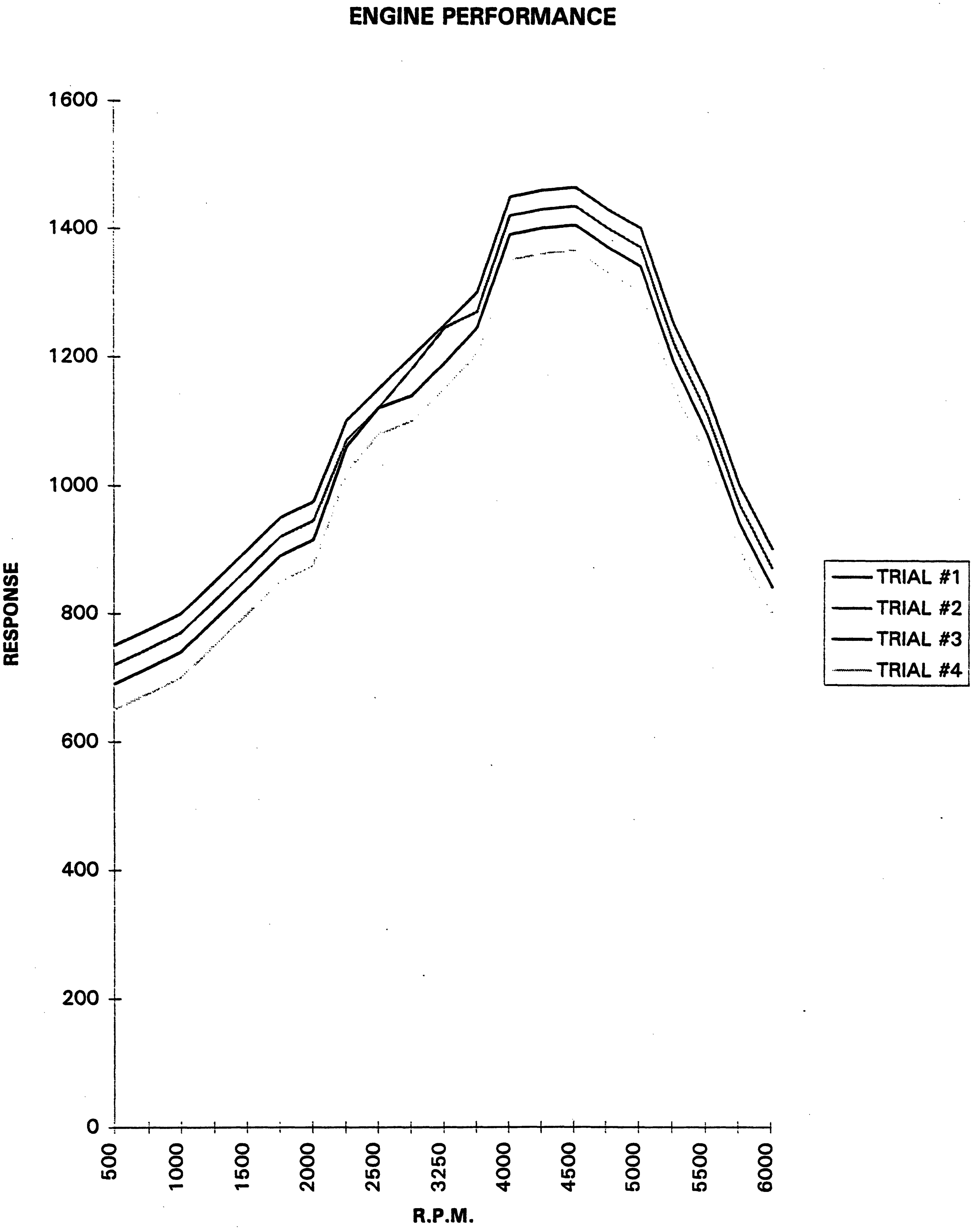

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After about the tenth run the performance of the engine had degraded to the point that the test could no longer be continued. The lab engineers did not have any idea on what caused the degradation. Since the lab was experiencing pressure from other customers for use of the test cell, the test was halted and equipment was dismantled. During dismantling, a failure related to improper heat dissipation in the test cell was discovered. This type of failure was consistent with a degradation in performance. Since the failure was a result of an interaction between the lab equipment and the engine, neither side was willing to accept full responsibility.

The most important lesson from this experiment was the importance of communication. Even though the protocol for the experiment was explained to the lab personnel, the importance of examining the data from the trial runs was lost.

The planning and sequence of steps in an experiment need to be discussed and negotiated with the team prior to conducting the experiment. Other valuable lessons that can be gained from studying this experiment are:

(i) Ensure that the whole team understands the importance of trial runs and why they are being run.

(ii) Establish conscious "buy-off" points during the process of the experiment. Before proceeding the team must make an informed decision.

(iii) Hold a debriefing session after the trial run to review any problem areas and make required changes before proceeding.

Situation 2 -- Priming Experiment

An experiment was planned for an automotive paint shop. The plant was planning a major paint shop re-tooling for the next model year. One of the processes before the final paint coat is applied involves dipping the parts in a primer tank. The primer is applied to the parts through the process of electro-deposition. This process ensures a uniform coating of primer. One of the questions that the experimenters wanted to answer, was "What is the best size for the paint dip tank?". The speed through the tank is typically controlled by the output requirements of the paint shop. Consequently, the longer the tank, the longer the time the part spends in the primer.

In addition to investigating the size of the tank, some other factors such as primer composition and electrical current were also studied. The engineers had planned to experiment during the “build-out” process just prior to the re-tooling. If anything that was not expected happened, the impact on production would be minimized. To simulate the longer tank, the engineers obtained permission to alter the line speed through the current tank. Slowing the line speed would increase the amount of time the parts spent in the tank, thereby simulating a longer tank. The ability to alter line speed was a key factor in the experiment.

In this experiment, no trial runs were performed. When the engineers were questioned by a consultant on their ability to change line speed, the reply was, "No problem, we have to make occasional changes to line speed through the model year, we should be able to handle this without any difficulty."

The team recognized the difficulty of making frequent line speed changes. As a result, randomization was restricted such that all of the runs at the current line speed would be completed first. After eight runs were completed of a sixteen run experiment, the time came to change the level of the factor "line speed". There was little time left to complete the experiment due to the strategy of conducting the experiment during build-out. Consequently, there was no room for error. Unfortunately, the team discovered that adjusting the conveyors to the new line speed would take over one day. The team ran out of time and the experiment could not be completed. How could this situation have been avoided? Simply by conducting a trial run and discovering the amount of time required to change line speed.

This case points out another reason for trial runs, discovery of the amount of time required to change levels for a factor. Often the amount of time required to complete an experiment is underestimated. Engineers typically have been trained to change one variable at a time holding all others constant. Similarly, when adjustments are made in the plant, engineers are used to estimating the time to *change one variable. To change several variables for every run is considerably different from most engineers' mental model of how to run an experiment or to make process changes.*

4. UTILIZATION OF EXISTING DATA AND SETTING LEVELS

The task of setting levels for factors often does not receive the attention that is required. A great deal of thought is often given to choosing factors. Selecting levels often does not receive the same degree of attention. Level changes can induce variation and care must be taken to insure that the induced variation is within the "operational range" for the process. Subject matter expertise combined with historical data can be very useful in the selection of levels. If the difference in levels is too large, the factor will prove to be statistically significant, but this may result in undesireable variation in the process losing all the practical value.

A manufacturer of rubber products was conducting an experiment in their rubber compounding process. The purpose of this experiment was to identify the factors which were important in controlling the process so that the plant could implement more effective process control plans. The company had assembled a multi-disciplinary team that included, chemists, engineers, quality assurance, and the operators of the process. Often operators are not included in the planning stages of an experiment. People who work with a process every day are valuable sources of information for planning an experiment and their input should be sought at the earliest stages of an experiment.

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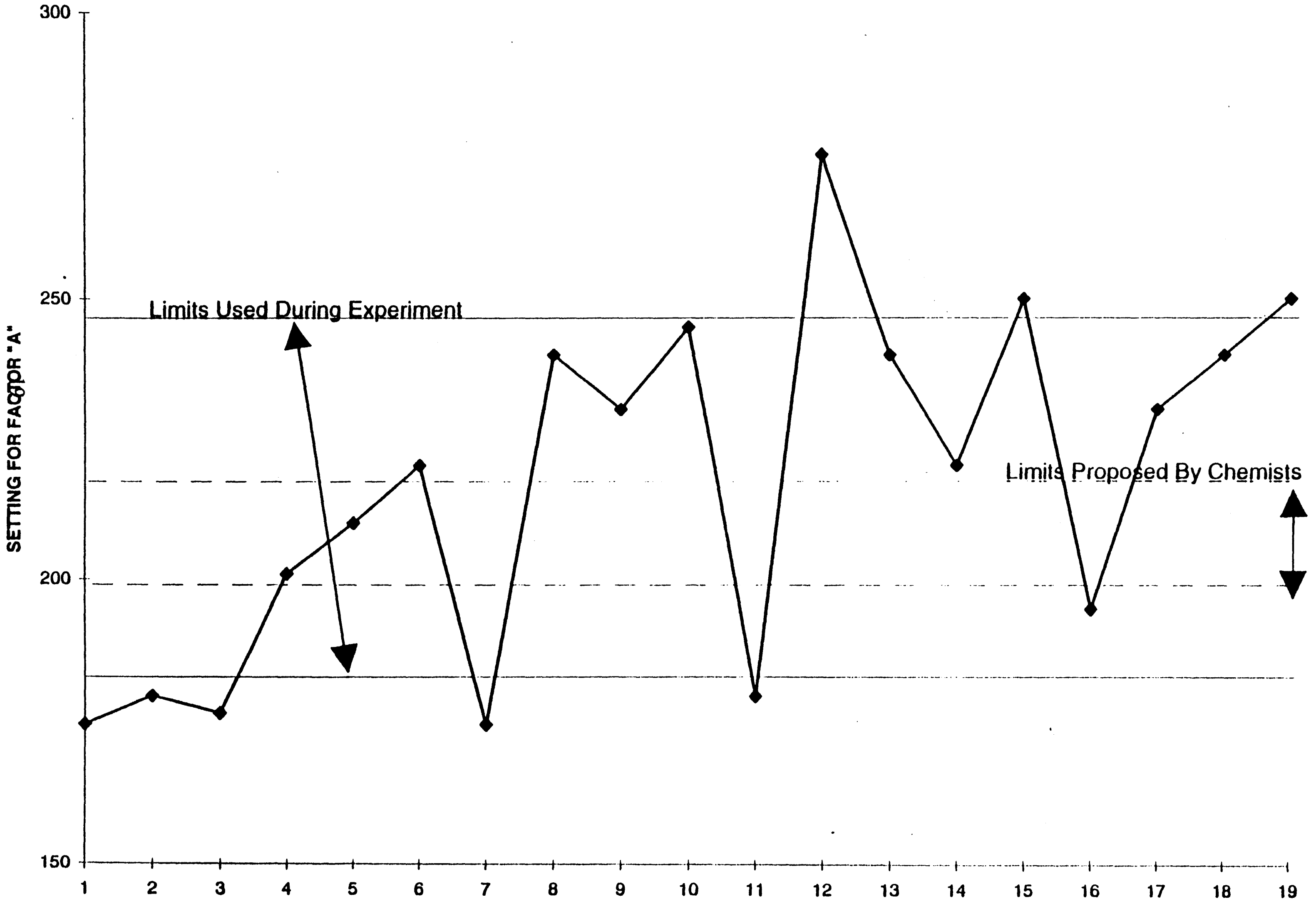
A chart was prepared of the setting of the factor over the past year and was presented to the team. (See Figure 4) This chart clearly demonstrated to the chemists that the range they were proposing was too narrow. After examining the chart, the chemists relented and more reasonable levels were chosen.

This case demonstrates the power of substituting facts for emotions. This has to be done in a non-threatening manner and is best handled by keeping issues within the team. Often political motivations will manifest themselves during the planning of an experimental design, particularly with respect to factors and levels. The consultant and team leader should be aware of the potential for this to happen and to be prepared to handle the situation in an objective (facts based) manner.

Figure 4
OPERATIONAL RANGE OF FACTOR "A" OVER TIME



5. COMMUNICATION BEFORE THE EXPERIMENT

A manufacturer of rubber bushings was planning an experiment for improvement of cosmetic and functional problems encountered with inserting rubber into a metal sleeve. An experiment was planned to investigate the effect of a number of different process settings on the finished bushing.

Running the experiment involved interfering with regular production. Consequently, the management of the plant granted permission to run the plan on a Saturday solely for the purpose of the experiment. Further, the plant management pledged that the "best" operators would be made available to come in and assist with running the equipment.

The team gathered on a Saturday morning. A few trial runs were planned to ensure that no changes would be needed prior to running the actual experiment. During the first trial, some scrap started to be produced by one of the machines. The operator immediately noticed the problem and started to make adjustments to the settings. When questioned why he was doing this the natural reply was "Surely you do not want to make scrap during your experiment!". The situation was immediately noticed by the consultant who asked if the operators had been exposed to any experimental design concepts. The reply was, "I am just here to do my job and my job is not to make scrap". The conflict in this situation is that if the operator had changed settings during the middle of a treatment, the results for the treatment would be confounded. The purpose and essence of the experiment was to evaluate specific level settings that had been determined beforehand. The experiment was halted for thirty minutes while the experimental design process was explained to the operator. Specifically, the operator was told that, "In order to understand how to make good product, we must learn how bad product is made." The remainder of the experiment was completed without incident. The experiment was successful in significantly reducing scrap.

In this case, the experiment was salvaged. *The team had held planning meetings but had neglected to make the operator a part of the team. The issue was compounded by the fact that the operator had specific tasks to do and was not aware of the conditions needed to run a successful experiment. The contribution that an operator can make to the experimental design process is often overlooked and crowded out by technical discussion.*

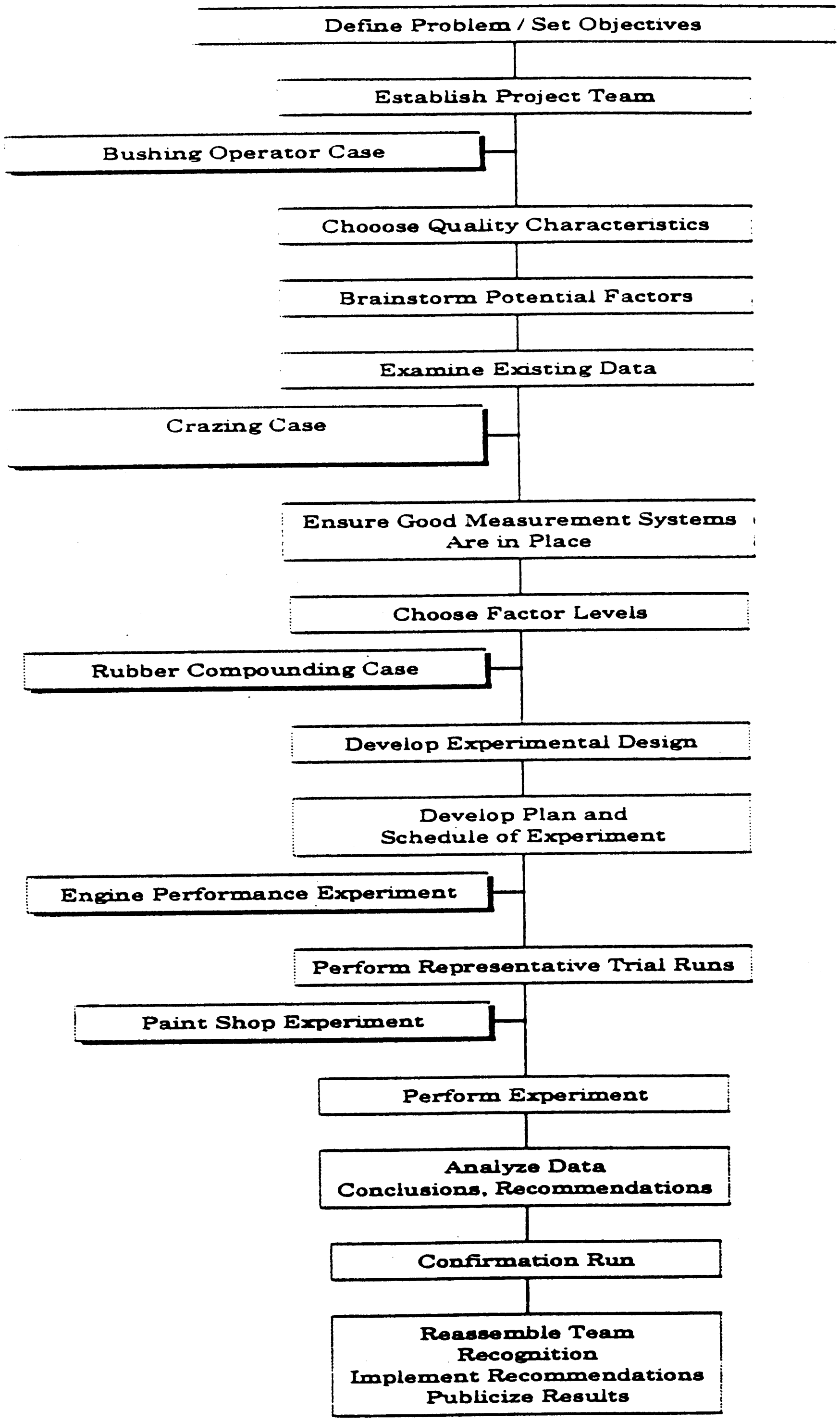
6. CONCLUSIONS

To summarize, it is important that a structured approach be applied to the process of experimental design. Organizations should also document experiments that did not work out as planned in order that the lessons learned from these situations may be added to the corporate technical memory.

There are several different flowcharts and models for the process of experimental design. Figure 5 is one example that has been found to be a useful model. The case studies previously discussed have been listed on this chart next to the relevant

Figure 5

EXPERIMENTAL DESIGN PROCESS



process step. Notice from the chart, that most of the activities are in the planning stages of the experiment. Budgeting time for these activities can often avoid costly, time consuming mistakes during the running of an experiment.

An in-house statistician who has been trained to understand, think, interact, and communicate with operators, engineers, and management has a vital role in implementing and nurturing experimental design activities. Operators appreciate a statistician who is willing to spend time on the plant floor to understand the nature of the problem and the limitations that production conditions often impose on an experiment. Similarly, engineers often require a statistician who can help formulate the statement of the problem in engineering terms, and expose engineers to statistical concepts, and who is willing to invest time in understanding the nature of the engineering function. The statistician must also be able to presetn the overall picture of the experimental design process to management and there by assist the management in proper planning for an experiment.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the managers, engineers, and operators of companies where the discussed experiments were conducted. Our work with these companies has been a mutually rewarding learning experience.

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Figure 1
Tail Light Manufacturing Process

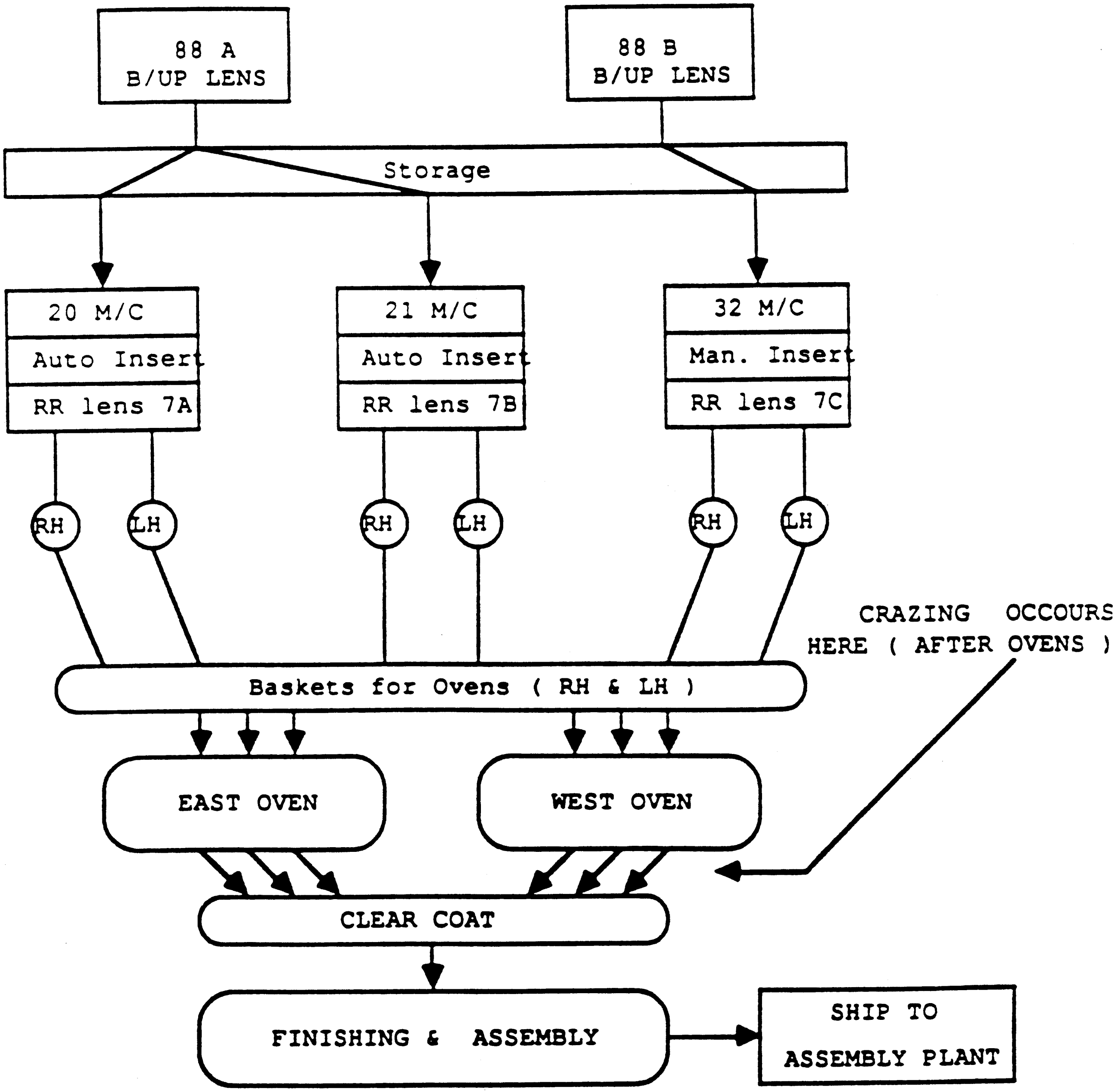
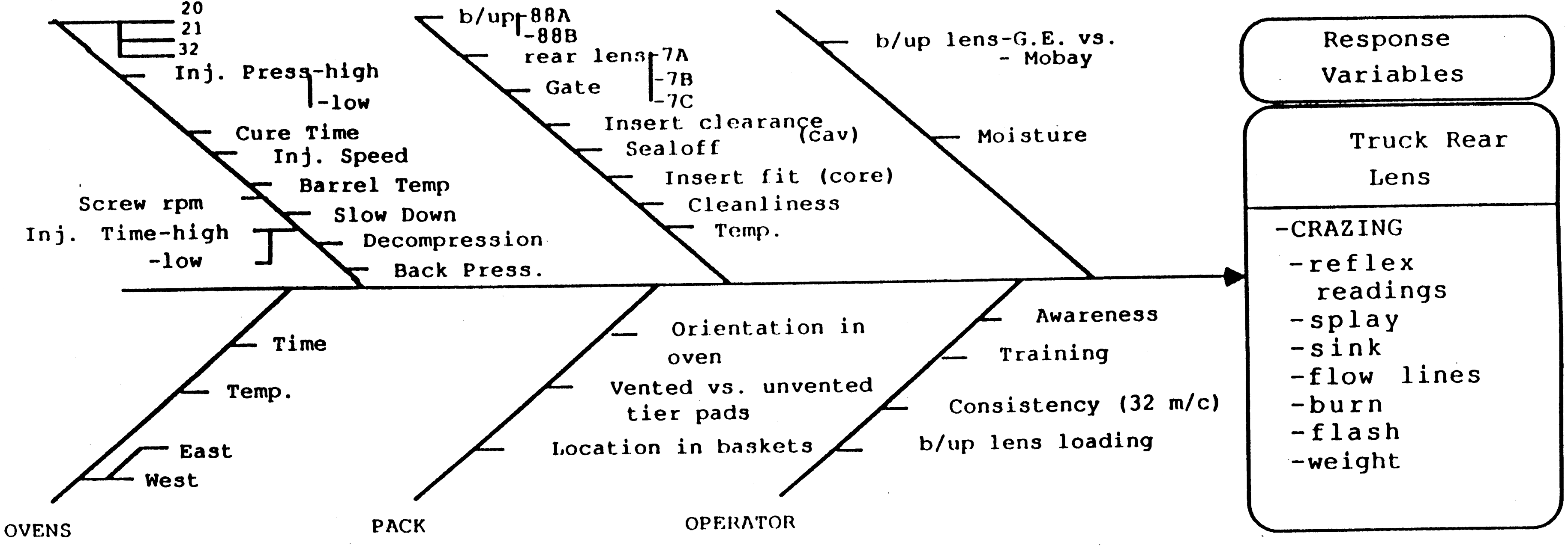


Figure 2

CAUSE and EFFECT DIAGRAM



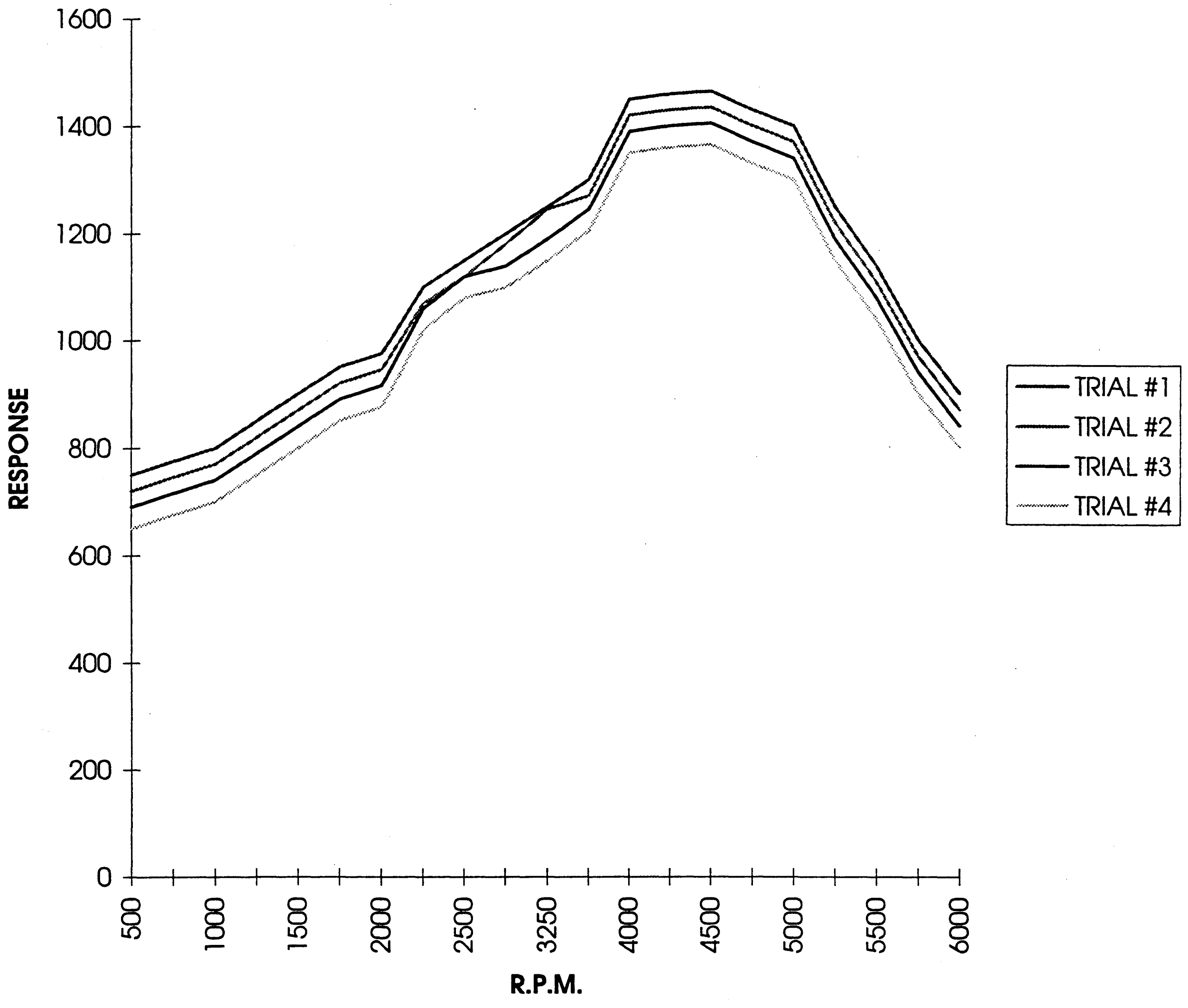


Figure 3

ENGINE PERFORMANCE

Figure 4
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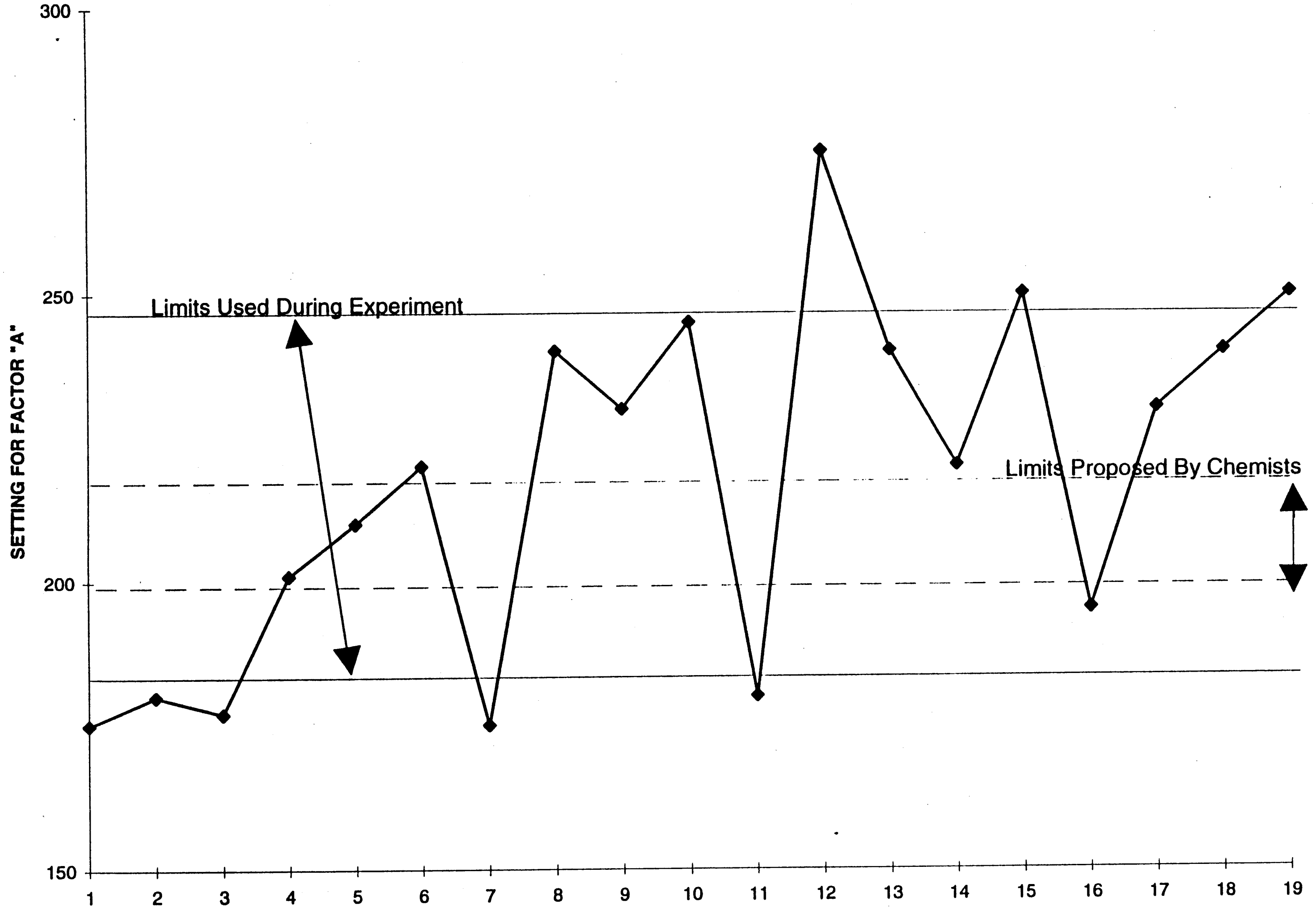

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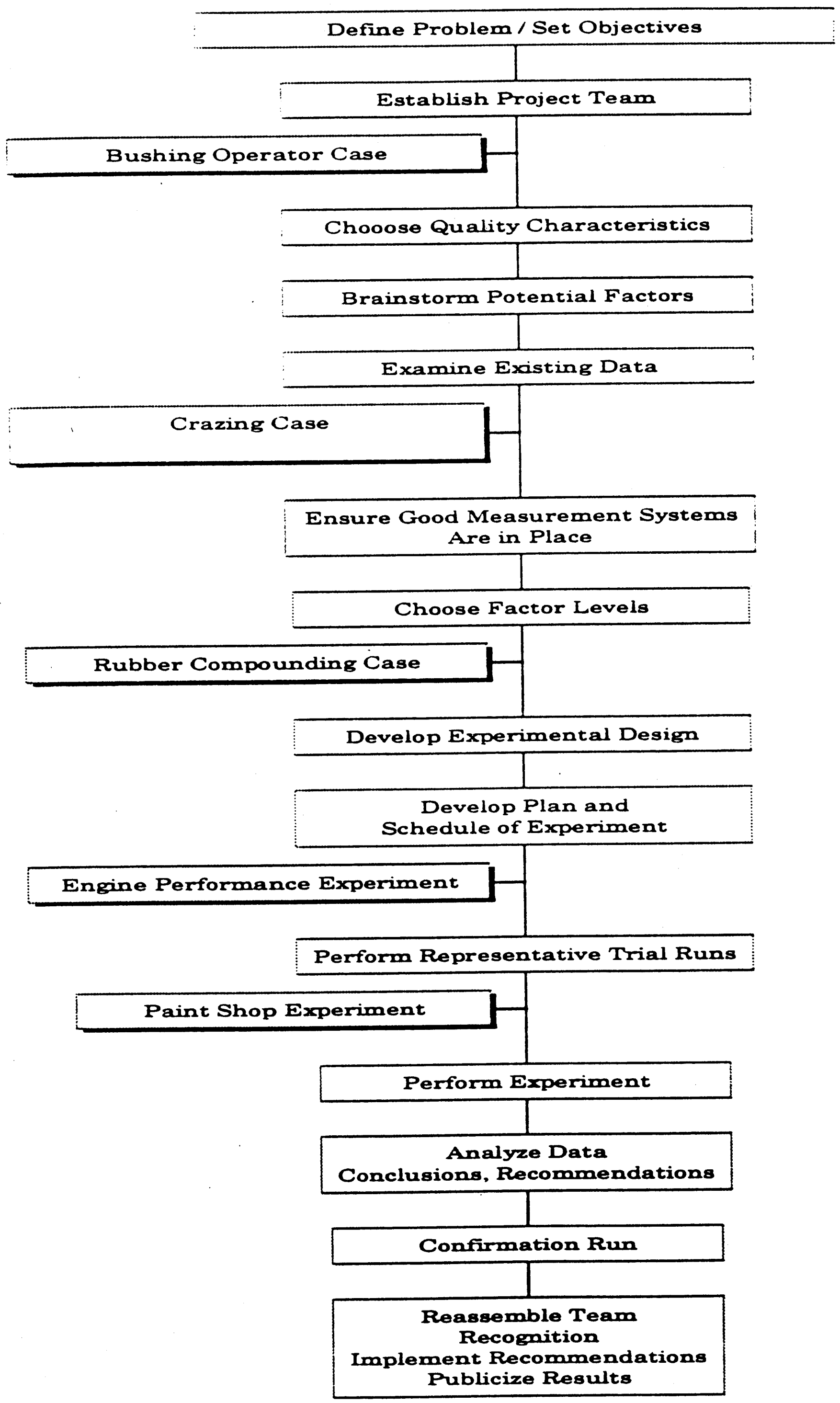

Real Experiments, Real Mistakes, Real Learning!

Bovas Abraham
Institute for Improvement in Quality and Productivity
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Mike Brajac
General Motors of Canada
Oshawa, Ontario

Abstract

Experimental design case studies typically document a successful application of the technique. Successful case studies are valuable in broadening the perspective of the industrial experimenter and are useful in teaching. In this paper we explore, through the use of case studies, the lessons that can be learned from cases which were not successful or where problems were encountered. All data have been disguised to protect proprietary interests without compromising the learning value of the case.

1. INTRODUCTION

Experimental design has demonstrated its value as an effective process learning and problem solving tool. Many case studies have been written publicizing the broad range of application and impressive results, Bisgaard (1992). Cases have proven themselves to be a valuable tool for teaching and broadening perspective

In general, published case studies can be categorized into two main groups. The first type is case studies that detail a specific application, for example injection moulding. These types of cases are of interest to others involved in injection moulding, particularly when common problems such as "sink", "short shots", or excessive shrinkage are involved.

It is very difficult to teach the application of experimental design to engineers in a foundry using such case studies. This has given rise to specialized courses sponsored by groups such as the American Foundrymen's Association. The second type of case study is concerned with documenting the approach used to solve a problem rather than the nature of the problem. Common examples of this approach are case studies which discuss techniques such as Taguchi methods or response surface methodology.

A third type of case study that is seldom published and rarely discussed, documents experiments which were not successful for a variety of reasons. This is a difficult area to gather any kind of information, since failure is stigmatized both in academia and in industry. Symposium organizers are generally more interested in projects which were successful and saved hundreds of thousands of dollars than a project that was a "failure", but in which valuable lessons were learned.

Learning from a Mistake

In an experiment that has gone well, it is difficult to communicate the importance of the planning that led to the success. These details, if they are documented, are often overlooked in favour of the impressive results that have been achieved.

For the student, learning from a mistake, changes the focus of learning. Some of the questions that arise in the mind of the student are: "What happened to cause the experiment to fail?", "Why did the event happen?", "Could I make the same mistake?" and "What are the implications of the mistake?" In the world of medicine, hospitals set up committees to review the way patients are treated. Mistakes are viewed as an educational opportunity not just for the person that made the mistake, but also for other professional staff. This same philosophy can and should be carried over to the practice of experimental design.

There is also an element of psychology present in learning from a mistake. This element is called a "psychological anchor". An "anchor", in psychology, is an event that triggers a whole set of related emotions, feelings, or memories. In teaching experimental design, it is difficult to get students to remember the steps of systematic experimentation. One model of systematic experimentation is shown in Figure 5. Montgomery and Coleman (1993) discuss the need for a systematic approach and suggest the use of questions on check sheets to guide the experimental process. In industry, where experimenters are also involved in short term "fire-fighting", some steps in the process of experimentation may be skipped due to time pressures. A case study that illustrates a mistake can create a "psychological anchor" in the mind of the experimenter. For example, in consulting with students after they have been exposed to case studies where errors have been made, the consultant only needs to state: "Remember the case of the crazing tail light." The main issues in the tail light case will immediately come to mind. This is much easier and considerably more effective than saying, "Remember the fourth step of the fourteen step problem solving model for experimental design".

The case studies that we have chosen to discuss effectively complement the teaching of a structured approach to design of experiments. They also reiterate the importance of the following:

(i) utilizing existing data before the design of an experiment,
(ii) paying attention to setting levels for a factor
(iii) conducting trial runs
(iv) having good communication among the team.

The cases have been integrated into teaching in both industrial and academic settings. We have found that students are interested and motivated to learn from these case studies.

2. THE CASE OF THE CRAZING TAIL-LIGHT

Background and Review of Process:

A tail-light consists of two portions, the clear back-up lens and the surrounding red lens. In the process under investigation, the back-up lens is moulded first, then inserted into another mould where the red lens polycarbonate is injected around the clear lens. The problem in this case was "crazing" of the back-up lens. Crazing consists of fine cracks that can affect the translucency of the part. The typical discrepancy rate for crazing was 2-3%, which was easily managed. The rate, for no apparent reason, increased dramatically to 20-30% and remained high.

Other relevant background information that influenced this case is detailed below:

(i) The plant was on a three shift operation thereby compounding communication difficulties.
(ii) Experimental design was new to the organization and was viewed as a panacea.

(iii) Engineers from the plant had just completed a ten day Design of Experiments course and were eager to put into practice what they had learned.

Figure 1 is a flow chart of the process to produce taillights. Two moulds 88A and 88B produce one right side and one left side clear polycarbonate lens. The clear lens is then inserted into another moulding machine. The red polycarbonate is then injected around the clear lens. The three moulds, 7A, 7B, and 7C produce one complete assembly per cycle. The parts are then put into a basket for baking in an oven. Baking is necessary to relieve the high internal stresses that occur during the process of moulding the red lens around the clear insert. After leaving the oven, the parts are sprayed with a protectant to avoid ultra violet degradation of the polycarbonate.

Crazing was not noticeable until after the parts left the oven. This was frustrating for the team since a great deal of value added time and material was lost when a part was scrapped.

Cause and Effect Diagram

An extensive cause and effect diagram was constructed (Figure 2). Input from a number of operators and engineers was obtained in constructing the diagram. The team also decided to list a number of response variables. The reason for this is that the team did not want to eliminate crazing only to have another problem occur. Listing multiple responses on the cause and effect diagram helped to keep this issue in mind.

Two experiments were conducted. The first experiment focused on injection moulding machine factors such as "screw speed", "clamp time", etc. The second experiment focused on factors involving the oven and moulds.

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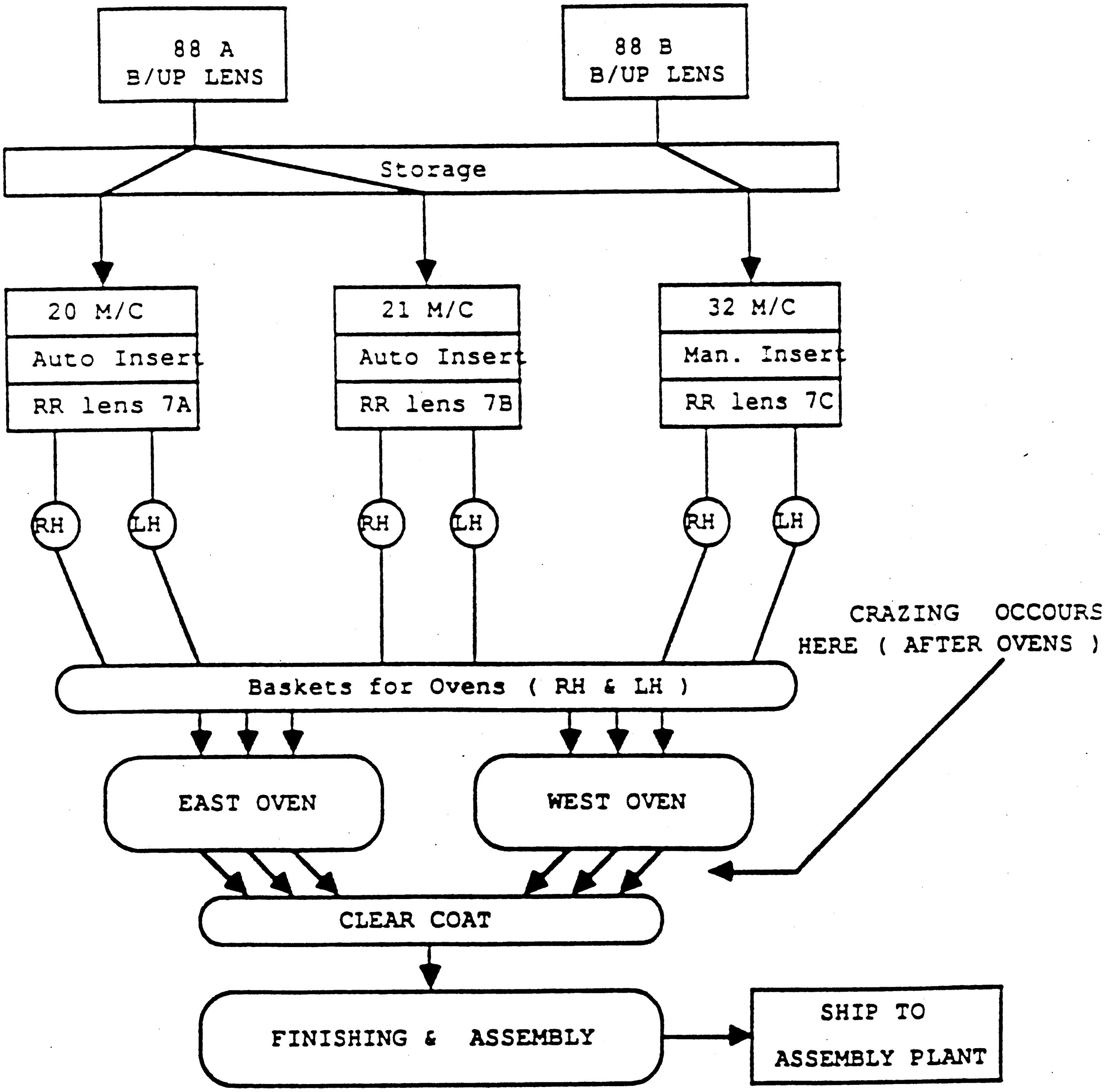
Tail Light Manufacturing Process



Experimental Design Layout and Results

The experiment consisted of 11 factors, 16 runs, "blocked " over two types of base material. In effect, a 32 run experiment--something that is not trivial in a manufacturing environment.

After the first experiment, very little was learned that could reduce the scrap rate of the lenses. A second experiment was planned to focus on differences in moulds. This second experiment clearly demonstrated that most of the scrap produced during the experiment came from one mould.

A search for a special cause was made and it was discovered that during routine preventive maintenance some minor changes were made to one of the moulds. Unfortunately, these changes were the source of the problem.

What Was Learned

In this case the second experiment was successful in finding the cause of the problem. Beginning industrial experimenters are often disappointed after a first experiment that does not find the answer. In some situations, management loses patience and concludes, "We tried experimental design here and it does not work". In this case, the experimental design team and management of the plant deserve credit for their persistence in sequential experimentation.

After the team completed the second experiment and discovered that one particular mould was causing the problem, a valuable lesson in experimental design practice was learned.

The mould and the point where the crazing was first observable were separated in time and space. Thus a cause and effect relationship was not readily observable. However, each taillight carries a "witness mark" that indicates which mould produced the part. Since the plant was having high rates of scrap, it would have been a relatively easy matter to stratify scrap by mould.

Figure 2

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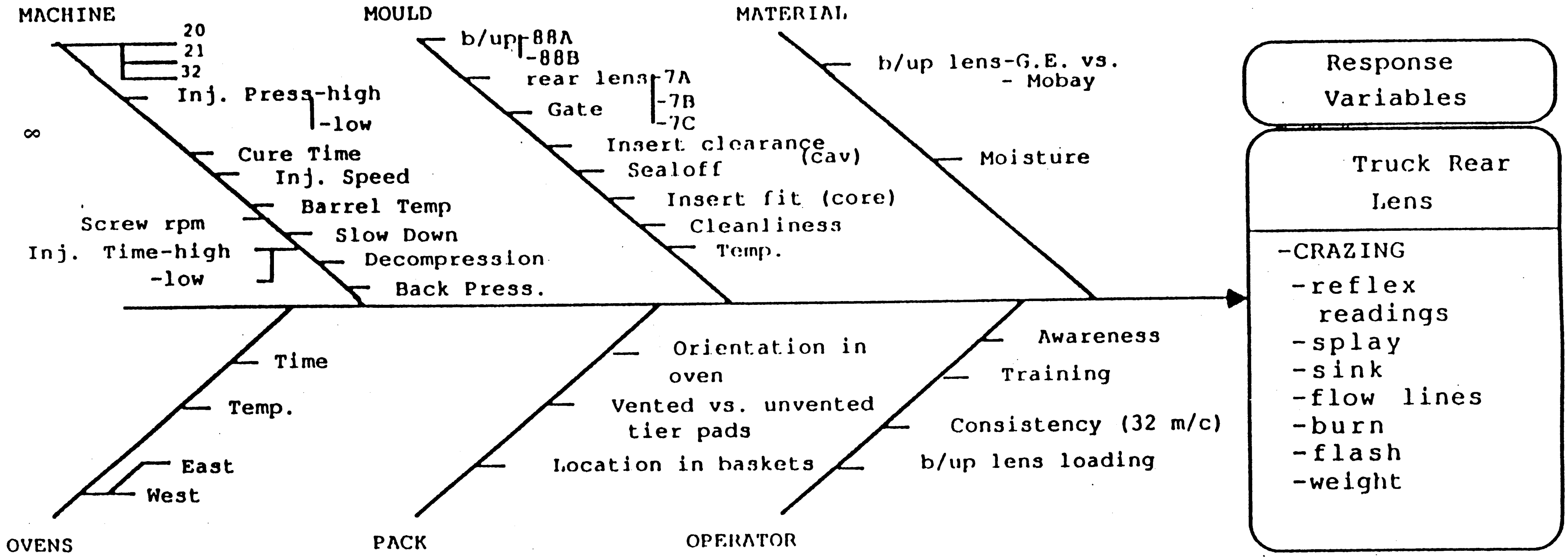

Histograms of scrap by mould would easily have isolated the source of the problem.

In the eagerness of the team and the consultants working with them to perform an experiment, the power of the "seven basic tools" was overlooked, Ishikawa (1976). The parallel streams in this process strongly suggested that stratification would be a meaningful analytical tool.

3. LEARNING FROM TRIAL RUNS

Background

Trial runs are recommended for a number of reasons. Some of which are:

(i) An opportunity to evaluate potential problem treatment combinations before proceeding with the experiment.

(ii) Trial runs provide a final chance to fine tune levels of a factor.

(iii) As the word "trial" suggests it is a test of the system that will be engaged during the course of an experiment. This is important in a production environment where the experimenter may only have one chance to obtain the needed data. Trial runs provide a chance to make any needed changes in the experimental plan before an experiment begins.

(iv) Trial runs can help considerably in estimating the time to complete a run, logistical support required for level changes, and total time needed to complete the experiment.

(v) Finally a trial run is also an excellent communications vehicle. Any breakdown in communications will likely be apparent during trial runs. Trial runs also provide an opportunity to remedy the situation before proceeding with the experiment.

We will review two cases to discuss trial runs. The first case deals with measuring engine performance in a research and development project. The second case deals with evaluating the size of a new dip tank in a paint shop.

Situation 1 -- Engine Performance Experiment

In this situation the experimenters were interested in evaluating the effect of a number of factors on engine performance. Due to the need for specialized test equipment, the experiment was contracted to an outside laboratory. The lab had an excellent reputation for research. However, lab engineers had very little exposure to experimental design. Facilities at the lab were in great demand and expensive, consequently the need by everyone involved to minimize the amount of test cell time.

The process of experimental design was reviewed with the team that would be conducting the experiment. Equipment and materials were ordered and the experiment was planned. The test cell was very complex, and four trial runs were suggested to evaluate the operation of the whole system as well as a potentially sensitive level setting.

Data collection in the test cell was automated. It was possible to collect numerous observations and have the data automatically logged in a computer. The engineers at the lab decided that they would "spot check" key values from the trial to make sure everything was running properly. The laboratory informed the engineers at the company that requested the experiment that the engine horsepower and some other responses were not performing as specified. They also indicated that the discrepancy must be due to the engine supplied. The laboratory was requested to supply the complete data set for the trial runs.

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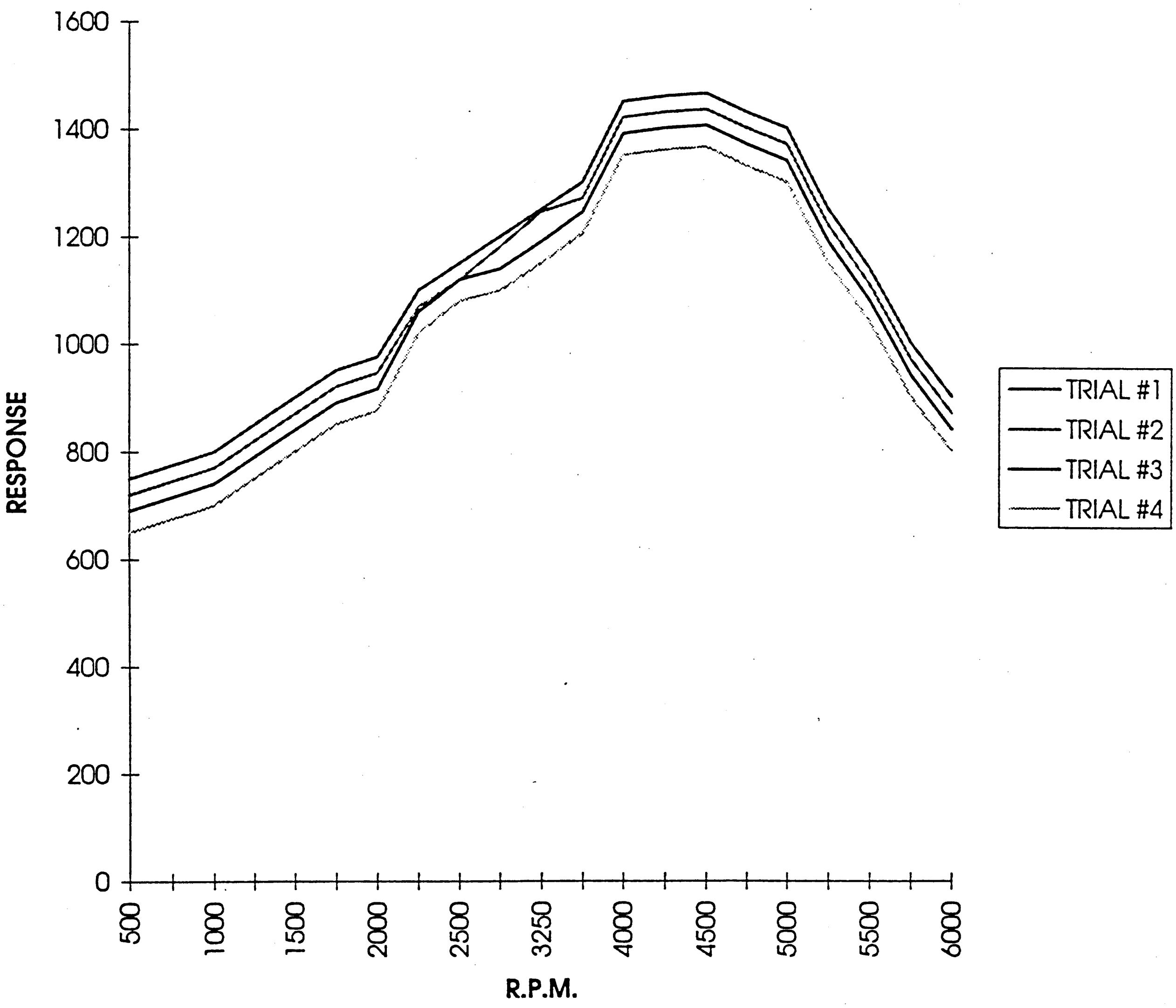

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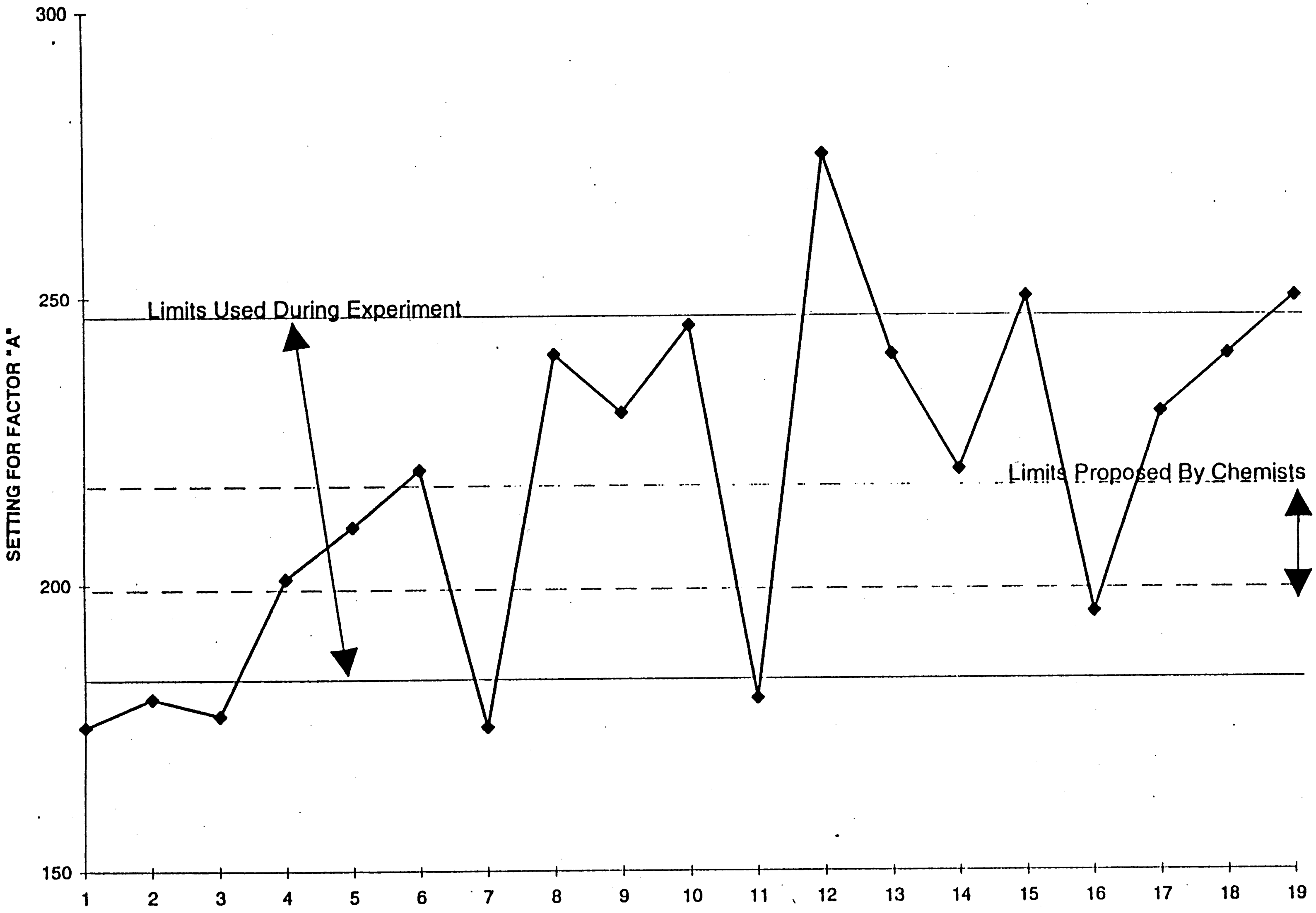
The chemists were not convinced of the experimental design approach and appeared to be somewhat threatened by the process. They insisted on what appeared to be a very narrow range for the levels. One of the chemists even suggested that the corresponding factor should be left out of the experiment.

The remainder of the team insisted that the factor was important and should be included in the experiment. Some members of the team felt the range for the level proposed by the chemists was too narrow. The team became deadlocked and turned to the consultants working with them for help. The consultants also felt that the range was too narrow, but lacked supporting data. Fortunately, the company was rich in data and poor in information. The consultants reviewed process history data and found that there was a great deal of variation in the level of the factor.

A chart was prepared of the setting of the factor over the past year and was presented to the team. (See Figure 4) This chart clearly demonstrated to the chemists that the range they were proposing was too narrow. After examining the chart, the chemists relented and more reasonable levels were chosen.

This case demonstrates the power of substituting facts for emotions. This has to be done in a non-threatening manner and is best handled by keeping issues within the team. Often political motivations will manifest themselves during the planning of an experimental design, particularly with respect to factors and levels. The consultant and team leader should be aware of the potential for this to happen and to be prepared to handle the situation in an objective (facts based) manner.

Figure 4
OPERATIONAL RANGE OF FACTOR "A" OVER TIME



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5. COMMUNICATION BEFORE THE EXPERIMENT

A manufacturer of rubber bushings was planning an experiment for improvement of cosmetic and functional problems encountered with inserting rubber into a metal sleeve. An experiment was planned to investigate the effect of a number of different process settings on the finished bushing.

Running the experiment involved interfering with regular production. Consequently, the management of the plant granted permission to run the plan on a Saturday solely for the purpose of the experiment. Further, the plant management pledged that the "best" operators would be made available to come in and assist with running the equipment.

The team gathered on a Saturday morning. A few trial runs were planned to ensure that no changes would be needed prior to running the actual experiment. During the first trial, some scrap started to be produced by one of the machines. The operator immediately noticed the problem and started to make adjustments to the settings. When questioned why he was doing this the natural reply was "Surely you do not want to make scrap during your experiment!". The situation was immediately noticed by the consultant who asked if the operators had been exposed to any experimental design concepts. The reply was, "I am just here to do my job and my job is not to make scrap". The conflict in this situation is that if the operator had changed settings during the middle of a treatment, the results for the treatment would be confounded. The purpose and essence of the experiment was to evaluate specific level settings that had been determined beforehand.

The experiment was halted for thirty minutes while the experimental design process was explained to the operator. Specifically, the operator was told that, "In order to understand how to make good product, we must learn how bad product is made." The remainder of the experiment was completed without incident. The experiment was successful in significantly reducing scrap.

In this case, the experiment was salvaged.

The team had held planning meetings but had neglected to make the operator a part of the team. The issue was compounded by the fact that the operator had specific tasks to do and was not aware of the conditions needed to run a successful experiment. The contribution that an operator can make to the experimental design process is often overlooked and crowded out by technical discussion.

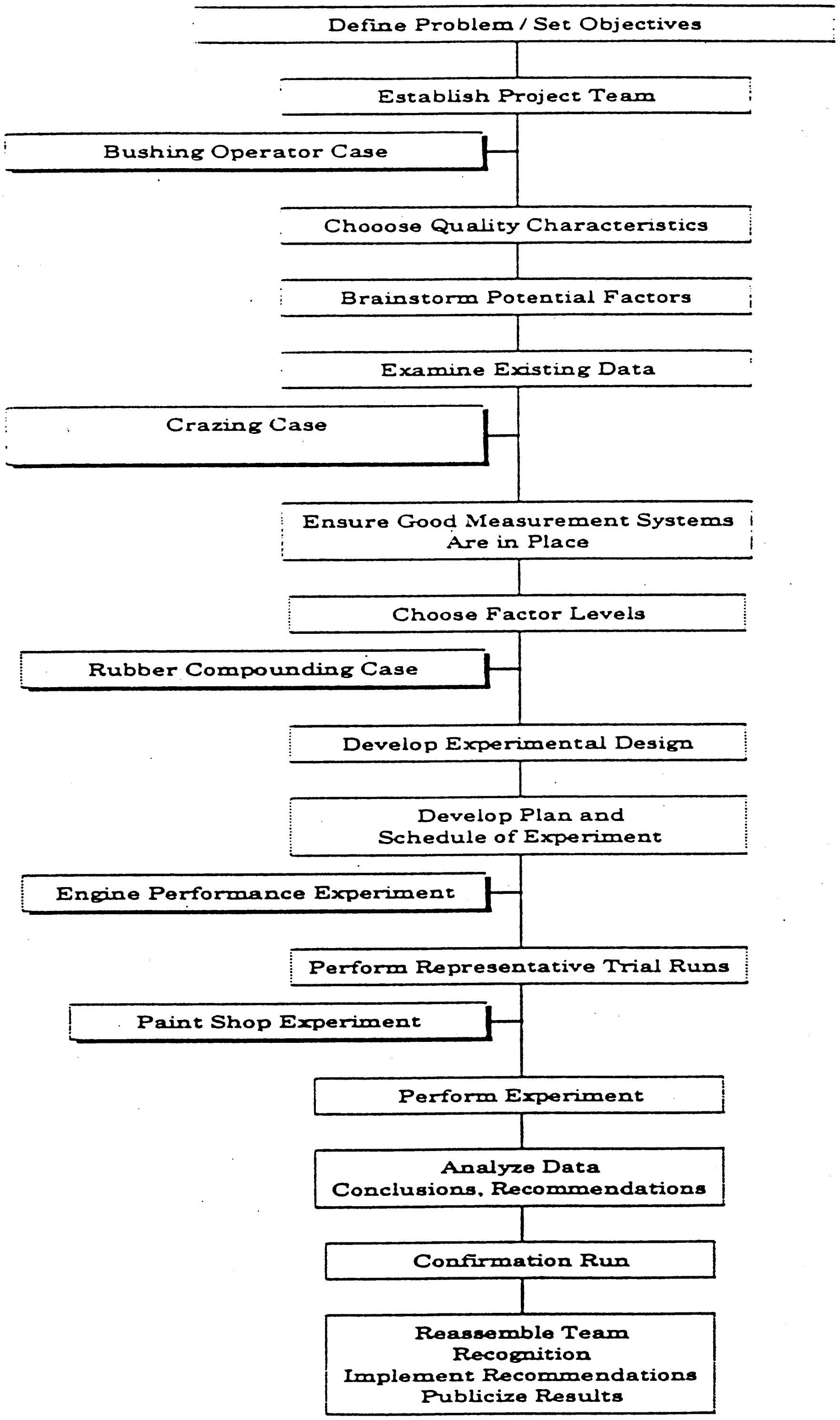
6. CONCLUSIONS

To summarize, it is important that a structured approach be applied to the process of experimental design. Organizations should also document experiments that did not work out as planned in order that the lessons learned from these situations may be added to the corporate technical memory.

There are several different flowcharts and models for the process of experimental design. Figure 5 is one example that has been found to be a useful model. The case studies previously discussed have been listed on this chart next to the relevant process step. Notice from the chart, that most of the activities are in the planning stages of the experiment. Budgeting time for these activities can often avoid costly, time consuming mistakes during the running of an experiment.

Figure 5

EXPERIMENTAL DESIGN PROCESS



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The authors gratefully acknowledge the managers, engineers, and operators of companies where the discussed experiments were conducted. Our work with these companies has been a mutually rewarding learning experience.

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