On-Line Distributed Control System Tools for Statistical Process Control (SPC)

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ABSTRACT

Recent increases in resource costs and global competition have fostered the spread of a management philosophy called Statistical Process Control (SPC) from discrete manufacturing to continuous and batch industrial processing. Recent advances in microprocessor technology have substantially increased the computing capabilities available within process control systems. Today, computerized Statistical Quality Control (SQC) techniques which were once considered off-line, retrospective support for SPC activities can be used within the context of process control systems as on-line tools to improve the profitability of process operations.

The computing power of a modern microcomputer process controller provides cost-effective SPC tools for critical process parameters. This paper discusses on-line tools for SPC which can be implemented entirely within a distributed digital control system (DCS).

INTRODUCTION

Statistical Process Control (SPC) is based on the fundamental principle that there is a normal, quantifiable level of variation in every process parameter. This normal variation includes both random variation and variation which can be attributed to specific causes. Once the normal process variation is quantified, it can be managed to its most economically favorable level by improving process operations or by modifying the process itself.

Any significant change in process variation from this normal level can be detected and investigated. When a cause for abnormal variation is identified, operations managers can work to eliminate the cause if the abnormal variation is bad, or they can work to perpetuate the cause if the abnormal variation is good.

If the normal variation of a critical product quality parameter is greater than the tolerance of its manufacturing specification, substantial excess costs will be incurred to test, segregate, and dispose of or recycle off-specification product. On the other hand, excess operating costs may also be incurred by operating the process in a manner that reduces the normal variation of this parameter substantially below the required manufacturing tolerance.

SPC is a management philosophy which seeks to quantify and optimize process variation. Many of the tools for SPC were provided by the pioneering efforts of Walter Shewhart and W. Edwards Deming, which resulted in a group of techniques collectively called Statistical Quality Control (SQC). These techniques are solidly grounded in statistical theory and have been widely applied (**REFERENCE 1**).

Many of these techniques are best suited to off-line, retrospective analysis of historical process data and cannot be effectively applied as on-line operations tools. However, some SPC tools can be effectively utilized with live process data to provide on-line support for SPC activities:

- On-Line SPC Control Charts,
- SPC Alarms,
- On-line Pareto Analysis,
- Closed-Loop SPC.

These on-line SPC tools collectively alert process operators to abnormal process variation and help identify the cause(s) of this abnormal variation, prioritize corrective actions and manage process variation to its most economical level. Further, they can be implemented easily within a modern DCS.

Many of the off-line, retrospective techniques necessary to fully support SPC activities can also be implemented in modern distributed digital process control systems. The most widely used techniques include cause/effect correlation studies and process capability studies.

THE ECONOMICS OF SPC

Continuous and batch processing operations in a variety of industries provide striking examples of the economic benefits which can result from an effective SPC program. Increased annual profits ranging from $50,000 to $1.4 million are achievable by managing the variation of just one critical process parameter to its optimum.

A reduction in the variation of the Kappa Number for a continuous pulping operation in the Paper Industry can allow the average Kappa Number to be confidently shifted toward the most economical limit of the manufacturing specification. The Kappa Number is the primary quality/yield parameter for this process. Improvements in process operations which reduce the standard deviation in Kappa Number from 2.18 to 1.50, and shift the average Kappa Number from 17.40 to 18.45, will produce a net pulp yield increase of 0.475% (**REFERENCE 2**). This will result in an additional $410,000/year of profits for a 1000 ton/day pulp mill.

A reduction in the Kappa Number variation for a batch pulping operation in the Paper Industry can also allow the average Kappa Number to be shifted toward the most economical limit of the manufacturing specification. Improvements in process operations which reduce the standard deviation in Kappa Number from 0.88 to 0.67 and shift its average upward slightly can produce an increase of 0.15% in pulp yield. This will result in additional profits totaling $150,000/year for a 640 ton/day pulp mill (**REFERENCE 3**).

A reduction in the variation of cracking severity for an ethylene cracking furnace operation in the Petrochemical Industry can allow furnace control setpoints to be adjusted to increase selectivity for ethylene. Depending on the circumstances, this can produce additional profits totaling $1.4 million/year for a 500,000 metric ton/year ethylene plant (**REFERENCE 4**).

The reduction in cutpoint variation for a crude unit operation in the Petroleum Industry can substantially reduce giveaway of more valuable hydrocarbons with less valuable products. This can result in as much a $441,000/year increased profits for a 70,000 barrel/day crude unit (**REFERENCE 5**).

The reduction in electrical power demand variation for an industrial plant can save more than $50,000/year in power demand penalties (**REFERENCE 6**). This additional profit would result from avoiding one 0.5 megawatt demand peak over the established billing demand with a $10.00/kilowatt demand charge and a 0.9 forgiving factor.

ON-LINE SPC CONTROL CHARTS

The control chart from SQC has become the basic tool for SPC. There are many different types of control charts (X-BAR/R, X-BAR/S, Cumulative Sum, Exponentially Weighted Moving Average, etc.). However, each provides a visual comparison of the current variation in a critical process parameter (e.g. the key quality variable for a product) with its short-term and long-term historical variation. SPC relies on the control chart to identify when the current variation in the process parameter is significantly different than it has been historically.

In the context of a continuous or batch processing operation, an SPC control chart is a specific type of time trend for a critical process parameter (X). X may be the result of a periodic laboratory test, a measurement signal from an on-line sensor, the error (difference between setpoint and process variable) of a regulatory control loop, or any other quantifiable characteristic which represents the state of the process at a point in time.

Shewhart Chart

One type of SPC control chart, the Shewhart Chart, trends the average (X-BAR) for a subgroup of individual X values and the range (R) of the individual X values within the subgroup (maximum minus minimum). In addition to these SPC variables, the control chart also shows upper control limits (UCL's) for the X BAR and R trends, a lower control limit (LCL) for the X-BAR trend (the lower control limit for the R trend can be considered zero), the grand average (X-BAR-BAR) of all X values in the database, and the average range (R-BAR) for all subgroups in the database. A typical Shewhart Chart is shown in **FIGURE 1**.

The variation of X-BAR with time is a quantified indication of the long-term variation of the process parameter X. The variation of R with time is a quantified indication of the short-term variation of X. Observing both long-term and short-term variation of a critical process parameter on the same time axis provides useful information about the state of process operations.

For example, if the shift average for an hourly laboratory test (X-BAR) stays relatively constant, but the range of test values throughout the shift (R) is much larger during the third shift, a sampling/testing procedure problem might exist on the third shift. On the other hand, a relatively constant range for the shift test values (R), with a significant change in the shift average (X-BAR) for the third shift might suggest a substantial environmental influence on the process during the third shift which could be automatically compensated for. If X-BAR-BAR slowly increases or decreases over a period of several months, process equipment might be wearing or fouling, or a reagent used for the laboratory test in small amounts may be degrading.

The control limits utilize a statistical treatment of historical X-BAR and R data to establish the boundaries of "normal" variation in the process parameter. If the value of X-BAR or R falls above a UCL or below an LCL, there is a 99.7% probability that something abnormal has occurred in the process, and the situation should be investigated. In the example of the hourly laboratory test result, if the X-BAR started falling outside the upper control limit on the third shift at about the same time that a new technician rotated into the laboratory for the third shift, the cause of the situation would be clear.

Abnormal Variation

When the process is operating normally, the values of X-BAR and R will randomly vary between the UCL and LCL. If the region between the UCL and the X-BAR-BAR is divided into three imaginary zones of equal width (zones A, B and C, with zone C closest to X-BAR-BAR), and similarly for the region between the LCL and X-BAR-BAR, statistical theory suggests the following:

- 68% of the normal values will fall within the two C zones,
- 28% of the normal values will fall within the two B zones,
- 2.7% of the normal values will fall within the two A zones.
- 0.3% of the normal values will fall above or below the control limits.

An erratic trend on the SPC control chart indicates normal process operation, whereas this same pattern on a typical process control trend display should be cause for alarm. Conversely, if the variation of X-BAR or R becomes nonrandom (e.g. falls outside of the control limits, flattens out, cycles, ramps up or down, consistently stays outside of the C regions, or exhibits some other definite pattern), something within the process has changed significantly and the situation should be investigated immediately.

In addition to simple high/low tests to identify when X-BAR or R is outside of the control limits, a number of pattern tests have evolved to detect nonrandom variation of the process. Identifiable patterns of X-BAR or R within the ABC zones indicate that something is repeatably influencing process operations. Seven of the most common pattern tests are summarized in **FIGURE 2**.

On-Line vs. Off-Line

Historically, the magnitude of the computing task required that SPC control charts be prepared off-line, using data collected during the prior week or month. The cost-effective computing and communication capabilities provided with modern distributed digital control systems permit SPC control charts to be updated for presentation to the process operator as the data becomes available.

The SPC control chart shown in **FIGURE 1** is an on line SPC control chart. An on-line SPC control chart can be differentiated from an off-line control chart by the presence of time steps. An off-line control chart generally shows sharp spikes because individual data points are connected with straight lines. An on-line SPC control chart generally shows time steps because the value of X-BAR and R are held constant during sample intervals.

Although an SPC control chart does not specifically identify the cause(s) of a significant change in process operation, it does permit personnel to be alerted to start looking for the cause(s). Diagnosis of the cause(s) for abnormal variation is generally much more efficient while the variation is occurring. Off-line SPC control charts often identify abnormal process variation after it has passed, making diagnosis much more difficult, if not impossible.

The on-line control chart permits process operators to quickly recognize an abnormal operating condition, search for the cause(s) while the condition still exists, and eliminate or perpetuate the condition to increase the profitability of process operations. The net effect of on-line SPC may be as simple as avoiding a long production run of off-specification material which is costly to reprocess, or it may be as complex as shifting the grand average closer to the most economical limit of the manufacturing specification with the confidence that the normal variation of the process will not produce off-specification material.

Adaptive Control Limits

The normal variation of the process may change as a result of long-term operational improvement or degradation. If the control limits for an on-line SPC control chart represent the normal variation observed in the too distant past, they may be either too wide or too narrow for the process as it is currently operating. This condition will result in the operators either not reacting to situations where the current variation is well beyond the actual normal variation of the process, or reacting to situations where there is no identifiable cause for a change in variation.

To avoid both complacency and false alarms, the computing capabilities of modern DCS controllers can be used to accommodate these gradual process changes by automatically adjusting the control limits for on line SPC control charts. This adjustment can be accomplished by limiting the historical values used in the calculation of the control limits to a specific time horizon (e.g. 84, 28, 14 or 7 days). As process operations improve from an SPC perspective, a reduction in normal variation will narrow the control limits and the grand average will move towards the most economic limit of the manufacturing specification.

SPC ALARMS

The automatic alarming capabilities of modern distributed digital process control systems can also be used to immediately alert the operator to any abnormal process variation. This is especially critical for processes with more than a few SPC control charts to be monitored -- abnormal process variation could go unnoticed for days or weeks without on-line SPC alarms. An SPC alarm can be generated by the DCS just as any other process alarm.

When X-BAR or R falls outside of its control limits, an alarm can be sounded until acknowledged by an operator, and the alarm event can be automatically logged. This type of alarm is called an SPC limit alarm.

When a specific pattern or trend is identified in the X-BAR or R data, this situation can also be automatically alarmed to the operator and logged, with the specific pattern or trend identified. This type of alarm is called an SPC pattern alarm.

Once the cause for either type of SPC alarm has been identified, it can be entered into the operator console database, logged and archived with the rest of the process operating history. This information will be critical to any off-line SPC analysis.

ON-LINE PARETO ANALYSIS

Vilfredo Pareto, a nineteenth century Italian economist, is credited with the well-known 80/20 rule. In an SPC context, this rule predicts that 80% of the abnormal variation in a specific process parameter will be produced by only 20% of the potential causes. If this were true in a specific case, elimination or control of the correct 20% of the potential causes would eliminate 80% of the abnormal variation in a critical process parameter.

However, the correct 20 may change over time. As more information is collected on the process, different potential causes could emerge as having the most cost impact on process operations. The potential causes in the top 20% category may change with the seasons or with elapsed time since the last maintenance shutdown. As process operations are improved through application of SPC, potential causes of abnormal variation will be eliminated and different potential causes will move into the top 20% category.

The Pareto analysis could be based on the total number of incidents for which a specific cause has been identified. However, to help manage process variation toward its most economical level, the number of incidents assigned to each specific cause is weighted by a relative cost factor for that cause.

The computing capabilities of modern distributed digital control systems permit Pareto analysis to be accomplished on-line each time the cause for an incident of abnormal variation is identified. This Pareto analysis becomes an operations tool when it is used to prioritize investigation of potential causes for current abnormal process variation. In searching for the specific cause of an abnormal variation incident, the operator would first investigate the potential cause(s) with the highest economic impact. This approach will minimize the cost impact of the abnormal variation incident.

A typical on-line Pareto analysis is shown in **FIGURE 3**. This operator display represents a prioritized listing of the most costly causes for abnormal variation in a specific process parameter. Each potential cause is shown with its relative cost contribution to incidents for which causes have been assigned, and the cumulative percentage of assigned variation which has been accounted for by preceding causes (e.g. 80% for the second cause in a list of 10).

CLOSED-LOOP SPC

The on-line SPC control chart and its associated SPC alarms provide an open-loop operations tool to identify when some action is required due to abnormal variation in a critical process parameter. Long-term use of these tools may indicate that specific and predictable actions are repeatedly required to eliminate specific incidents of abnormal process variation. When this repeatability becomes apparent, corrective actions can be automated using various techniques.

The types of action that can be taken include starting/stopping a motor, opening/closing a routing valve, initiating an automatic sequence or biasing the setpoint for a regulatory controller. These actions may be triggered if an SPC parameter remains outside of a control limit for more than a preset number of subgroups or has exhibited a specific pattern in the recent past.

OFF-LINE SPC TOOLS

Off-line SQC techniques can be used to enhance the effectiveness of the on-line SPC tools. These techniques provide retrospective analysis of long-term process operating history. cause/effect correlation studies of historical process data identify when easy-to-measure process variables can be used to manage difficult-to-measure process parameters. Process capability studies with historical process data determine if the process can perform economically inside of manufacturing specification limits without major modification.

Cause/Effect Correlation Study

Several process parameters may significantly affect the variation observed in a critical process parameter, either singularly or by synergistic combination. A cause/effect correlation study attempts to identify a significant historical cause/effect relationship between an X-Y variable pair. In the context of SPC, Y is the critical process parameter (dependent variable) which may vary as a function of an an independent process parameter, X.

An X-Y graph can be made for a suspected cause/effect variable pair using data from one or several years to form a "scatter diagram". If there is a noticeable pattern of data points in this diagram, the relationship can be quantified using any of several regression techniques to define an equation which relates Y to X, and which permits the value of the dependent variable to be predicted from the value of the independent variable(s) with a certain confidence level.

A cause/effect correlation study might indicate that a critical process parameter was influenced considerably by three specific temperatures, two specific pressures and a particular flowrate. With this information, the process control strategy could then be modified to reduce the normal variation of these six process variables, thereby reducing the normal variation of the critical process parameter.

Alternately, a multivariable regression analysis could establish an equation for the critical process parameter based on the value of the six easy-to-obtain process measurements. An inferential control algorithm could then be applied to hold the critical parameter at its most economic value based on the six process measurements.

Process Capability Study

In Statistical Process Control, the "capability" of a process refers to the natural variation of a process parameter when there are no specific causes which can be attributed to the variation. This natural variation is considered totally random and results from unmeasurable and uncontrollable variations in sampling or testing techniques, raw material composition, ambient conditions, etc.

The natural variation of a critical process parameter is quantified by the following procedure:

- The historical control charts for the process parameter are reviewed to identify SPC variables which fall outside of the established control limits.
- All data is eliminated for subgroups which have a specific cause documented for the abnormal variation.
- Process capability limits (alias control limits) are calculated using the edited subgroup data.

If the natural variation of the process is not within the tolerances of the manufacturing specification, it will be very expensive to produce quality product. In this case, the operating practices or the process itself must be re-designed to reduce the natural variation so that it is within the tolerance of the manufacturing specification.

If the natural variation of the process is much less than the manufacturing specification limits, the process can be maneuvered toward the most economical limit of the manufacturing specification without producing significant amounts of off specification product. However, if the natural process variation is just inside the limits of the manufacturing specification, there is no room for maneuvering to improve the economics of the process -- in this case, serious consideration should be given to modifications which will decrease the natural process variation and pay for themselves through increased process profitability.

ON-LINE SPC WITH A DCS

The data processing, communications and graphic display capabilities necessary for on-line SPC tools exist within modern microcomputer distributed control systems. DCS controller modules can effectively perform the computations for X-BAR, R (or S), X-BAR-BAR, the control limits, SPC alarms and Pareto analyses. These controller modules can transmit this reduced data and alarm messages across the DCS communications network to one or several CRT-based operations consoles for display and historical data storage.

When an SPC parameter falls beyond a control limit or exhibits a specific pattern, the operator will be automatically alerted and the alarm automatically logged, just as with any other process alarm. As specific causes of abnormal variation incidents are identified, they can be entered into an on-line Pareto analysis through a convenient display on the operations console -- this cause information will also be time-tagged and accumulated in the console database for future analysis.

To support future off-line SPC analyses, the data historian capabilities of the operations console can be used to automatically archive the on-line SPC data. The resulting historical database can be manipulated and analyzed with tools resident in the console for long-term cause/effect correlation and process capability studies.

With a DCS implementation, the calculations and alarm processing are distributed throughout the control system. These functions are located in the controller modules which minimize the burden on the DCS communications network. Distribution of the SPC tools brings the same advantages to SPC that distribution of the control functions brings a process control system. In comparison with a centralized computer implementation, these advantages combine to reduce the life-cycle cost of the SPC tools -- the total cost for design, implementation, operation, maintenance, and modification (**REFERENCE 7**).

As these tools become critical to the profitable operation of the process, the enhanced reliability provided by the DCS implementation maximizes the availability of SPC information. The operation of one part of the process will not be affected by the nonoperation of another part of the process or control system. The fault tolerance of a modern DCS permits SPC data to be accumulated within a controller module for extended periods of time when an operations console is not available to display and archive this information, and permits historical SPC information to be maintained within the controller memory without electrical power.

AN APPROACH TO SPC USING ON-LINE TOOLS

The low-cost, incremental expansion capability of the DCS permits low-cost incremental implementation of on-line SPC tools. These on-line tools can provide the basis for either beginning an effective SPC program or enhancing the effectiveness of an existing SPC program.

On-line SPC tools can be implemented using the spare capacity of an existing DCS or they can be designed into a DCS replacement for an existing process unit control system. As SPC experience and effectiveness grows, on-line SPC tools can be easily implemented for additional process parameters, and additional features can be added to the DCS to further improve SPC effectiveness (e.g. data archiving and off-line analysis functions).

Incremental development of an SPC program using on-line SPC tools might follow this sequence:

1) Several DCS controllers are modified to provide an on-line control chart, SPC alarms and on-line Pareto analysis for the most critical process parameter of each major process unit.

2) After a sufficient process history has been accumulated for on-line calculation of reliable control limits (e.g. one time horizon), the cause for each incident of abnormal process variation is aggressively determined and entered into the on-line Pareto analysis. The relative cost impact for the on-line Pareto analysis is estimated for each cause as it is identified, and adjusted as necessary when new causes are identified.

3) After several incidents have been identified for several causes, the most costly 20% of the identified causes for abnormal process variation are aggressively eliminated or minimized.

4) Steps 2 and 3 are repeated until the normal process variation is roughly 2/3 of the manufacturing specification tolerance, or until no specific causes can be identified or quickly eliminated.

5) Process control setpoints are adjusted to shift the grand average closer to the most economical limit of the manufacturing specification without an on-line control limit crossing the specification limit.

6) The process economics are closely monitored to quantify the profitability impact of these process improvements.

7) Off-line cause/effect correlation is used to establish reliable relationships between easily obtained process measurements and difficult-to-measure process parameters.

8) Process control strategies are modified or developed to utilize easily obtained process measurements and the identified cause/effect relationships for indirect closed-loop control of the difficult to-measure process parameters.

9) Steps 2 through 8 are repeated, justifying additional effort by anticipated profitability improvements.

10) An off-line process capability study is accomplished with data from several time horizons (e.g. a year) to quantify natural process variation.

11) On-line control limits are managed toward the limits of natural process variation until the economic optimum is achieved (i.e. the costs of further improvements are balanced by the resulting increased profitability of operations).

Applying the Pareto Principle to an SPC program itself, it may be possible to achieve almost 80% of the benefit with only 20% of the effort. For many processes, this could mean that effective use of only the on-line SPC tools will be required to achieve substantial improvements in process profitability.

A DCS IMPLEMENTATION

This section discusses implementation of the on-line SPC tools in a Bailey NETWORK 90 microcomputer-based distributed control system. On-line SPC control charts are configured as dynamic trend displays in any of the Bailey CRT-based operations consoles -- the procedure used is the same as that for configuration of any process variable trend display. SPC alarms are configured into console graphic displays, just as any other process alarm. The on-line Pareto display is configured as a dynamic tabular display which accesses data from the controller module, just as any other NETWORK 90 on-line CRT display.

The computations and alarm processing for on-line SPC functions can be implemented in NETWORK 90 controllers using any of several programming languages, depending on the controller module selected:

- standard Bailey function blocks,
- interpreted BASIC,
- compiled C,
- BATCH 90 compiled batch configuration language.

Each language provides a unique combination of functionality and data processing efficiency.

For the purpose of illustration, the BASIC data processing for an on-line Shewhart Chart and the corresponding SPC alarms and Pareto Display will be presented. In this discussion, the critical process parameter is a laboratory test result which is entered periodically into the control system database by an operator through a CRT-based operations console.

Only minor modifications to this implementation are required to provide these on-line SPC tools for other types of process parameters (e.g. a continuous on-line process measurement, a periodic analyzer measurement, the error from a regulatory controller, etc.). For these applications, a subgroup of values can be established by periodically sampling the measurement or controller error over a specific period of time (e.g. a minute or an hour, depending on the process measurement).

The BASIC program to be discussed is shown in the **APPENDIX**. This BASIC program is executed within a Bailey controller module and communicates with the rest of the control system (i.e. measurement sensors, operations consoles) through standard Bailey function blocks, as shown in ***FIGURE 4***, ***FIGURE 5*** and ***FIGURE 6***. This function block interface is presented schematically in the form of logic diagrams which were generated by a Bailey Engineering Work Station. A detailed discussion of these function codes is provided by **REFERENCE 8** and **REFERENCE 9**.

x-bar

X-BAR is the average value of X (arithmetic mean) for a subgroup containing a specified number of values ($X_1, X_2 \ldots X_n$). The calculation of X-BAR is shown in Section 500 of the BASIC program.

A Remote Manual Set Constant block (Function Code 68) in **FIGURE 4** permits the laboratory test value to be entered at the operations console from a process graphic display or tabular display. A transition of the Remote Control Memory block (Function Code 62) from 0 to 1 designates that a new test value is available for the calculations.

Each new value of X is passed through tunable limit checks and the arithmetic mean is calculated by the BASIC program once n values of X have been obtained. The subgroup size (n) may be selected between 2 and 10 to align data collection with process operations (e.g. n = 4 to provide two X-BAR values per shift for a laboratory test result which is entered every hour). The value of X-BAR is output from the program by a BASIC Real Output block (Function Code 93) and captured for trending by the operations console with a Trend block (Function Code 66).

x-bar-bar

X-BAR-BAR is the grand average of all X values within the population of samples. It is calculated as an exponentially weighted moving average of X-BAR for the past N subgroups in Section 600 of the BASIC program, according to the following equation:

$$\text{X-BAR-BAR}_{\text{present}} = [\text{X-BAR-BAR}_{\text{past}} * (1-K)] + [\text{X-BAR} * K],$$

$$\text{where } K = 2 / (N+1).$$

N is selected based on the desired time horizon to be used for calculating the control limits (e.g. N = 168 for a 4-week time horizon with 2 subgroups for each of 3 shifts per day).

r and r-bar

R is the range of X values within each subgroup. R is calculated in Section 700 of the BASIC program from the values of X collected for each subgroup, according to the following equation:

$$R = X_{max} - X_{min}.$$

R BAR is calculated as the exponentially weighted moving average of R for the past N subgroups. This calculation is similar to the calculation of X-BAR-BAR and is shown in Section 800 of the BASIC program.

ucl(x) and lcl(x)

UCL(X) is the upper control limit for the process parameter (X) and represents the upper boundary of normal variation observed for the process parameter. LCL(X) is the lower control limit for the process parameter and represents the lower boundary of normal variation. The calculation of UCL(X) and LCL(X) is shown in Section 1100 of the BASIC program.

The control limits for X are calculated from the grand average of X values for the entire population of samples within the selected time horizon (X-BAR-BAR), and the average range (R-BAR) of values in the subgroups within the time horizon:

UCL(X) - X BAR BAR + (A2 * R-BAR) and

LCL(X) - X-BAR-BAR - (A2 * R-BAR).

A2 is a statistical significance factor which is based on the number of data samples in each subgroup (n). As the number of data samples in each subgroup increases, the value of the statistical significance factor decreases and the control limit moves closer to X-BAR-BAR. This relationship reflects increased statistical confidence that abnormal variation will not fall within the calculated control limits. The value of A2 is taken from a data table stored within the BASIC program.

ucl(r)

UCL(R) is the upper control limit for R and represents the upper boundary for normal variation of the process parameter within a subgroup (short-term variation). UCL(R) is calculated

Section 1100 of the BASIC program, according to the following equation:

$$UCL(R) = D4 * R\text{-}BAR.$$

D4 is a statistical significance factor based on the number of data samples in each subgroup (n) and is taken from a data table stored within the BASIC program.

Control Limit Alarms

The alarm processing for SPC control limit alarms is shown in Section 1100 of the BASIC program. The SPC control limit alarm levels are automatically set for each SPC parameter by the calculated control limit. The control limit alarm state is output to the operations console using a BASIC Binary Output block (Function Code 94) and a Digital Output block (Function Code 45).

SPC Pattern Alarms

The implementation of SPC pattern alarms enhances the utility of the on-line SPC control chart and the on-line SPC limit alarms. A pattern alarm alerts the operator when the last several values of an SPC parameter fall into one of the patterns shown in **FIGURE 2**. The implementation of SPC pattern tests for X-BAR and R is shown in lines 1500 through 2799 of the BASIC program. The alarm state and alarm pattern identification are output to the console through a BASIC Real Output block (Function Code 94) and an Analog Output block (Function Code 30) on **FIGURE 4**.

An on-line SPC control chart could also be implemented for the process variable manipulated by a regulatory controller. In this case, the pattern tests would be modified to provide only the appropriate pattern alarms since X-BAR can be expected to oscillate tightly around the grand average and exhibit very narrow control limits due to the regulatory action of the process controller.

Pareto Analysis

The on-line Pareto analysis is accomplished by counting the number of abnormal variation incidents assigned to each of 10 potential causes by the operator . The function block logic shown in **FIGURE 5** counts the number of times that a cause identification number is entered using the Pareto Display (**FIGURE**

3) at an operations console. Each time the cause for an incident is entered, the analysis in Section 3000 of the BASIC program is repeated.

The total number of entries for each cause is multiplied by an adjustable cost factor which is entered through a Manual Set Constant block (Function Code 2). This cost factor may represent either the absolute cost of abnormal variation attributed to a cause or the relative factor which scales the cost impact of one cause to the other potential causes This cost factor can be adjusted at any time and the Pareto analysis will immediately reflect the adjustment.

The cost-weighted number of incidents for each potential cause is totaled and the contribution of each cause to this total is calculated as a percentage. Each potential cause is rank-ordered from highest to lowest based on its cost impact percentage. The cumulative percentage of abnormal variation accounted for by the list down through each potential cause (e.g. 80% for the second of ten potential causes) is then calculated.

The BASIC program also counts the total number of SPC alarms which have occurred. The percentage of these incidents of abnormal variation which has been assigned a cause by the operator is calculated from the total incident count.

The Pareto analysis information is output to the operations console through BASIC Real Output (Function Code 93) and Analog Output (Function Code 30) blocks. This information includes the percentage of all SPC alarms which has been assigned a cause, as well as the rank-ordered cause identification number and associated percentages for each potential cause.

Product/Grade Change Compensation

The logic required to accommodate different products and/or grades is shown in Section 300 of the BASIC program. The historical values for X-BAR-BAR, R, the incident count for each potential cause, and the total SPC alarms are stored as a function of a product/grade identification number. When the grade/product is changed by the operator from the operations console, the control limits, grand average and incident counts are changed immediately, but new values of X are excluded from the calculation of the grand average and control limits for a selected number of samples to allow time for the process to stabilize at the new production conditions. SPC alarms are also inhibited for the selected number of samples to prevent false alarms.

The grade is entered by the operator from the operations console through a Remote Manual Set Constant block (Function Code 68) on **FIGURE 4**. This entry causes the Real Recipe Table blocks (Function Code 118) for X-BAR-BAR and R-BAR in **FIGURE 4**, and each potential cause incident count and total SPC alarms from **FIGURE 6**, to input the historical values for the selected grade into the BASIC program.

Fault Tolerance

This implementation has been designed to prevent loss of long-term data required for on-line SPC control charts and Pareto analysis when electrical power is disconnected from the controller module. Each time a subgroup or cause assignment is processed, the critical values are saved to nonvolatile memory so that only the data missed when the controller is out-of-service will be excluded from the SPC calculations. A redundant controller can be used to minimize the risk of lost data due to controller failure.

The Real Recipe blocks (Function Code 118) which are used for product/grade change compensation on **FIGURE 4** and **FIGURE 6** are also used for nonvolatile storage of the previous values of X-BAR-BAR, R-BAR incident counts for each potential cause, and the total number of SPC alarms. When power is applied to the controller module, the BASIC program reads the previous values from these Real Recipe blocks.

Expansion to Multiple Process Parameters

This implementation has also been designed for simple integration into an existing controller module and/or expansion to multiple process variables. The entire BASIC program and function block configuration can be inserted into a controller module using the cut-and-paste edition features of the Bailey *Engineering Work Station.*

The BASIC program can provide SPC data processing for any number of critical process parameters, as long as the controller has available memory. To increase the number of process *parameters, ND must be changed from 1 to the desired number in* Section 10000 of the BASIC program -- a data array will be formed by the BASIC program and the process parameters will be processed at roughly 2/second (the compiled C and BATCH 90 versions of this program execute four times faster). Additionally, the entire function block configuration *shown in* **FIGURE 4, FIGURE 5** and **FIGURE 6** must be duplicated for each process parameter and connected to the Basic program -- this can also be accomplished with the cut-and-paste editing features of the Bailey Engineering Work Station.

Each process variable with full implementation of on-line Shewhart Control Chart, SPC alarms and on-line Pareto analysis requires 2.6 kBytes of nonvolatile memory. Implementation without the on-line Pareto analysis requires 0.8 kBytes of nonvolatile memory. These requirements are more related to the function block input/output processing, than the BASIC program memory requirements. A NETWORK 90 controller with 80 kBytes of nonvolatile memory could support a maximum 30 process parameters with on-line Pareto Analysis or 100 parameters without on-line Pareto analysis. The presented SPC configuration can be expanded to utilize any available memory in existing DCS controllers for on-line SPC control charts and/or Pareto analysis.

CONCLUSION

The capabilities of modern distributed digital process control systems enhance and extend the utility of classical SQC techniques. On-line SPC tools can be effective operations tools. Operators can be quickly and automatically alerted to abnormal process variation without time consuming preparation and interpretation of manual SPC control charts. Operators can be quickly directed to the most costly potential causes for abnormal variation to minimize its overall cost impact on process operation. Most importantly, operators can search for the cause of abnormal variation while it is actually occurring -- this substantially increases the probability that a specific cause will be identified and eliminated. In the hands of process operators, these on-line SPC tools can produce substantial improvements in the profitability of process operations.

Further, the on-line SPC tools discussed in this paper can be easily and cost-effectively implemented within a modern process control system. They can often occupy unused controller memory and console display capacity. Using appropriate engineering tools, they can be integrated with process control functions with very little effort.

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FIGURE 1 - On-Line Shewhart Control Cha

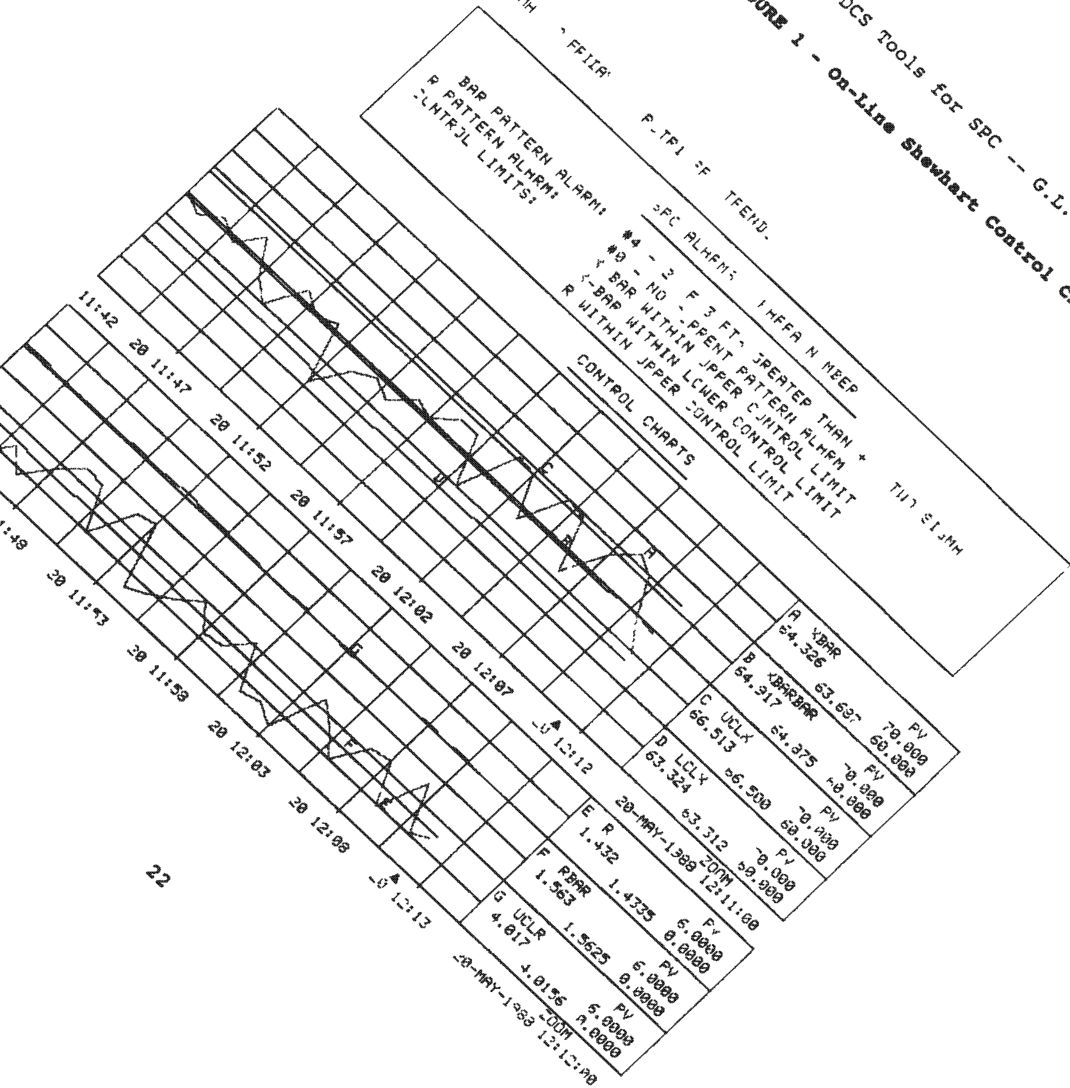


FIGURE 2 - Typical SPC Pattern Tests

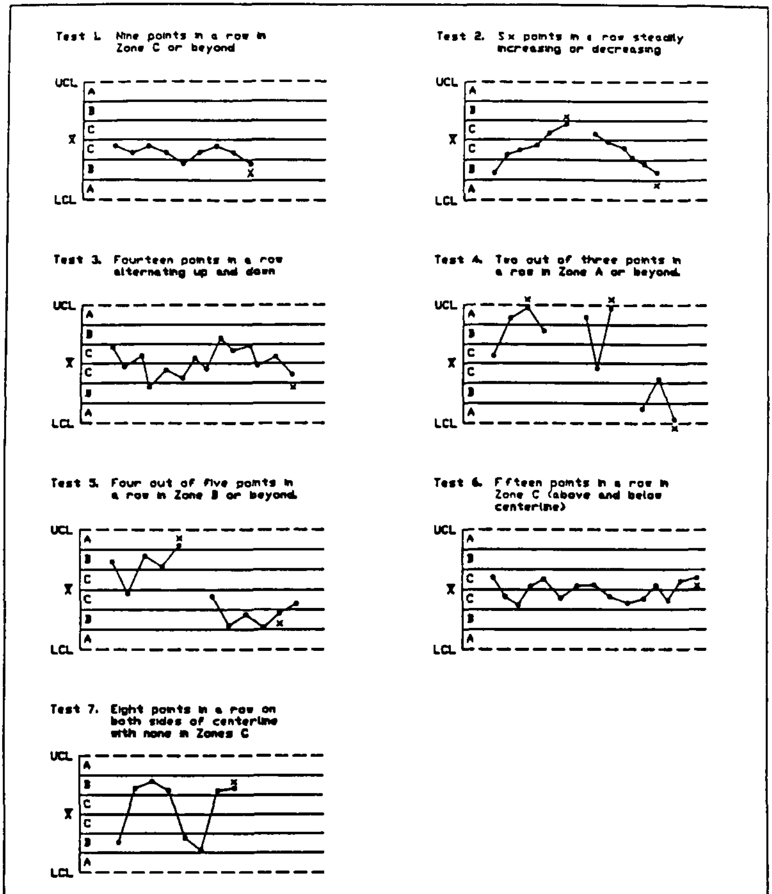


FIGURE 3 - On-Line Pareto Display

1_:00:45 20-MA _9 FRIDAY PARETO

ON-LINE PARETO ANALYSIS - H-FACTOR OVERSHOOT

ABNORMAL VARIATION CAUSE ASSIGNMENT	ASSIGNABLE CAUSE	1	#5	DIGESTER BLOW COLLISION
	CONFIRM CAUSE	2	NO	
	TOTAL SPC ALARMS		197	
	TOTAL ASSIGNED CAUSES		160	ASSIGNMENT RATE 81.12 %

COST RANK	CAUSE CODE	CAUSE DESCRIPTION	% OF TOTAL ASSIGNED COST	CUM % OF TOTAL ASSIGNED COST
1ST	#2	- HIGH BLOW TANK LEVEL	72.39	72.39
2ND	#4	- WASHER DOWN	11.91	84.30
3RD	#5	- DIGESTER BLOW COLLISION	7.98	92.29
4TH	#7	- HIGH ACCUMULATOR LEVEL	3.50	95.79
5TH	#6	- DIGESTER TRS COLLISION	1.49	97.29
6TH	#9	- OPERATOR ERROR	0.84	98.13
7TH	#3	- BLOW TANK INSTRUMENTATION MALFUNCTION	0.65	98.78
8TH	#8	- DIGESTER INSTRUMENTATION MALFUNCTION	0.60	99.39
9TH	#1	- PLUGGED BLOWLINE	0.46	99.85
10TH	#10	- OTHER OR UNKNOWN	0.14	100.0

TOTAL ASSIGNED COST _158.

FIGURE 4 - Bailey NETWORK 90 Function Block Configuration for On-Line SPC Control Chart and SPC Alarms

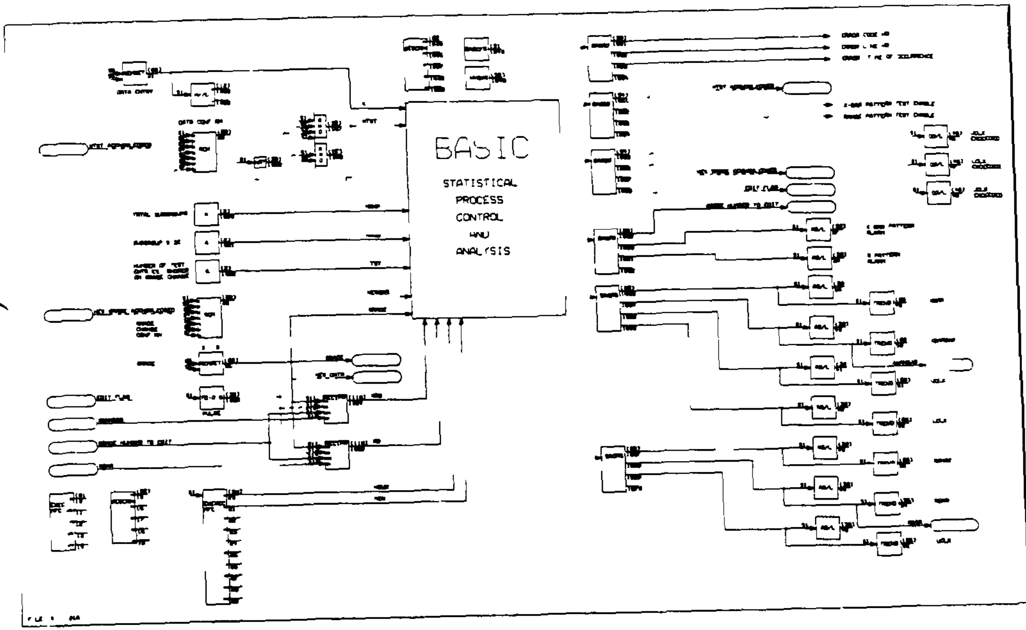


FIGURE 5 - Bailey NETWORK 90 Function Block Configuration for On-Line Pareto Analysis

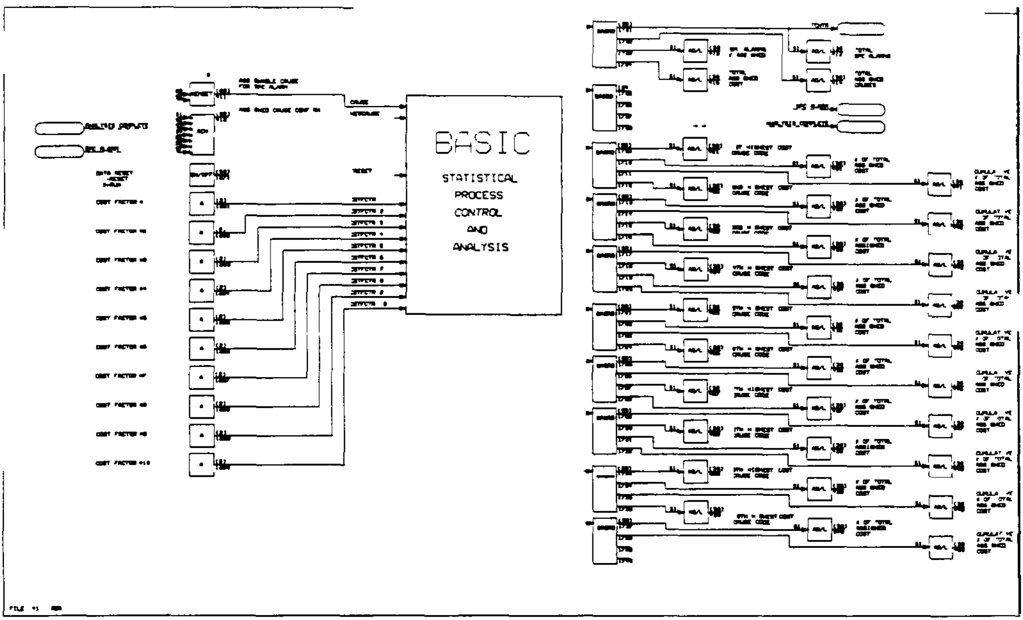
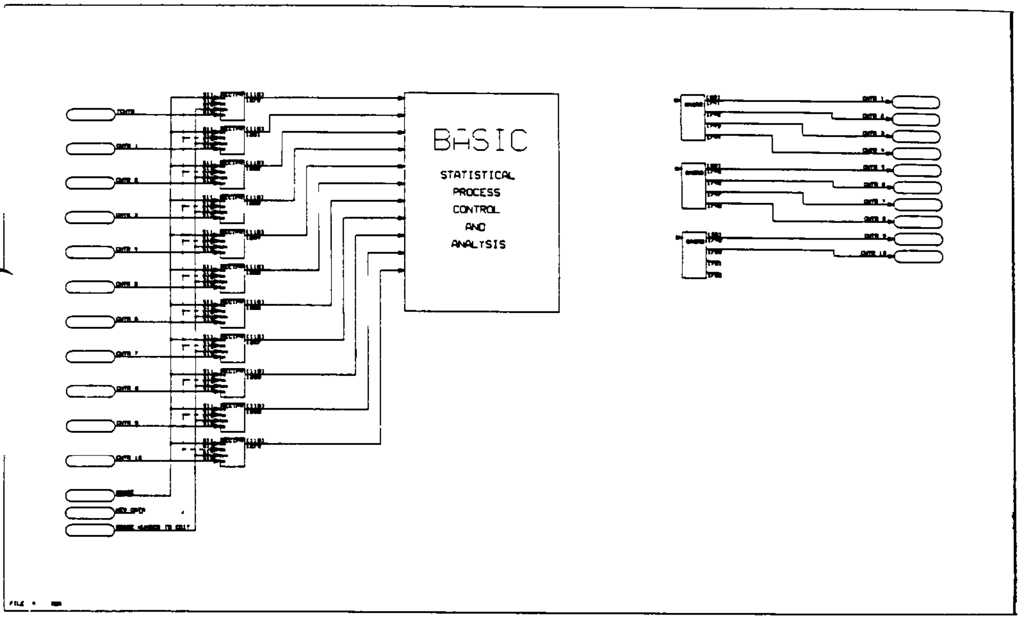


FIGURE 6 - Bailey NETWORK 90 Function Block Configuration for On-Line Pareto Analysis Product/Grade Change Compensation



APPENDIX - BASIC Program for On-Line SPC Tools

```
  0 REM - - ---    - -  - --      -------- -   -  -               -- -
  0 REM
  0 REM                      STATISTICAL PROCESS CONTROL
  0 REM                                with
  0 REM                          SPC PATTERN ALARMS
  0 REM                                and
  0 REM                           PARETO ANALYSIS
  0 REM
  0 REM -- - -     =-      --     -- -=-=-- -  _--  _------    -          -
  0 REM
  5  IF NOT INIT THEN GOSUB 10000                       INITIALIZE
 10  ON ERROR GOTO 20000
 15  FOR NV  1 TO ND
 20    GOSUB 200                                        N M INPUT
 30    GOSUB 300                                        GRADE CHANGE
 35      IF NOT NEWX(NV) THEN 130
 40    GOSUB 400                                        X-INPUT
 45      IF NOT IFLG(NV) THEN 130
 50    GOSUB 500                                        XBAR CALC
 60    GOSUB 600                                        XBARBAR CALC
 70    GOSUB 700                                        R CALC
 80    GOSUB 800                                        RBAR CALC
 90      REM  GOSUB 900                                 S CALC
100      REM  GOSUB 1000                                SBAR CALC
110    GOSUB 1100                                       CONTROL LIMIT CALC
120      IF IFLG(NV) THEN GOSUB 1400                    PATTERN ANALYSIS
130      IF IPARETO(NV) THEN GOSUB 3000                 PARETO ANALYSIS
140    GOSUB 4000                                       OUTPUT
150  NEXT NV
160  GOSUB 25000  END
  0 REM
  0 REM -===-  --=-=-  ---- -----  DATA INPUT =--  - -  ---   --  -.-  -==-  =- -
  0 REM
200  HOUR-BIN(20)  MIN=BIN(21)
205  NTST(NV)=-BIN(1027+(NV 1)*15)
210  NEWX(NV)=(NTST(NV) AND NOT OLDX(NV))  OLDX(NV)= NTST(NV)
215  NSUB(NV)=FNAMIN(10,FNAMAX(1,BIN(1031+(NV-1)*15)))          LIMIT CHECKED
220  MSMP(NV)=FNAMAX(1,BIN(1030+(NV-1)*15))
225  A2(NV)=CLA2(NSUB(NV))   REM  A1(NV)=CLA1(NSUB(NV))
230  D4(NV)=CLD4(NSUB(NV))   REM  B4(NV)=CLB4(NSUB(NV))
235  NEWGRD(NV)=-BIN(35+(NV 1)*25)
240    IF NEWGRD(NV) THEN GRADE(NV)=BIN(36+(NV 1)*25) JTST(NV)-BIN(1032+(NV-1)*15)
245    IF GRADE(NV)=OLDGRD(NV) THEN NEWGRD(NV)=0
250  OLDGRD(NV)=GRADE(NV)
255    IF NOT IPARETO(NV) THEN RETURN
260  IRESET(NV)= BIN (1271+(NV-1)*25)
```

APPENDIX (cont'd)

```
265   REM CAUSE(NV)=BIN(411+(NV-1)*40) REM NEWCAUSE(NV)=-BIN(412+(NV-1)*40)
270   FOR I=1 TO 10  CSTFCTR(I,NV)-BIN(1250+I+(NV 1)*25)  NEXT I
299   RETURN
  0 REM
  0 REM --=====--- ==--=--====-=== GRADE CHANGE ====-=-==--=--_--==----==----  ---
  0 REM
300   IF NEWGRD(NV) THEN IGRD(NV)= 1 GCNTR(NV)=0
305   IF NOT IGRD(NV) THEN RETURN
310   IF NEWX(NV) THEN GCNTR(NV)=GCNTR(NV)+1
315   IF GCNTR(NV)<=ITST(NV) THEN NEWX(NV)=0 ELSE IGRD(NV)=0
320   XBB(NV)=BIN(1034+(NV-1)*15)  RB(NV)=BIN(1035+(NV-1)*15)
322     REM  SB(NV)=BIN(1035+(NV-1)*15)
325   IF XBB(NV)=0 OR RB(NV)=0 THEN M(NV)=0  ELSE GOSUB 380
330   IF NOT IPARETO(NV) THEN 370
335   PCNTR(NV)=0  PT(NV)=0
340   FOR I 0 TO 2  ILIM(NV,I)=0  PATTERN(NV,I)=0  NEXT I
345   TCNTR(NV)=BIN(1272+(NV 1)*25)
350   FOR J=1 TO 10
355     CCNTR(J,NV)=BIN(1260+J+(NV-1)*25)
360     PCNTR(NV)=PCNTR(NV)+CCNTR(J,NV)
365   NEXT J
370   BOUT 1657+(NV-1)*20,-NEWGRD(NV)
379   RETURN
380     XBARBAR(NV)=XBB(NV)
385     RBAR(NV)=RB(NV)
390       REM SBAR(NV)=SB(NV)
395   M(NV)=MSMP(NV)
399   RETURN
  0 REM
  0 REM ========-================== X-INPUT ==========----===---=-----=-==--====
  0 REM
400   IFLG(NV)=C
410   INC1(NV)=INC1(NV)+1
420   X(INC1(NV),NV)=SAMPLE                       BIN(31+(NV-1)*25)
430     IF INC1(NV)<NSUB(NV) THEN RETURN
440   IFLG(NV)= 1 INC1(NV)=0
499   RETURN
  0 REM
  0 REM ============================ XBAR =======================================
  0 REM
500   M(NV)=M(NV)+1 MFLG(NV)=0
510     IF M(NV)>MSMP(NV) THEN M(NV)=MSMP(NV)
520   SUM = 0
530     FOR J=1 TO NSUB(NV)
540       SUM=SUM+X(J,NV)
550     NEXT J
560   XBAR(NV)=SUM/NSUB(NV)
599   RETURN
```

APPENDIX (cont'd)

```
  0 REM
  0 REM ----  -  ---        ----- XBARBAR ----- ----      - - -          -
  0 REM
600   AK(NV) 2/(M NV)+1)
610   XBARBAR(NV)-XBARBAR(NV)*(1-AK(NV))+XBAR(NV)*AK(NV)
699   RETURN
  0 REM
  0 REM -- -- -------------- ---------- R ---------- ----------------   -- -
  0 REM
700   XMAX-X(1,NV) XMIN-X(1,NV)
710     FOR I 1 TO NSUB(NV)
720       IF X(I,NV)>XMAX THEN XMAX-X(I,NV)
730       IF X(I,NV)<XMIN THEN XMIN-X(I,NV)
740     NEXT I
750     IF NSUB(NV)>1 THEN 790
760     IF XOLD(NV)>XMAX THEN XMAX=XOLD(NV)
770     IF XOLD(NV)<XMIN THEN XMIN=XOLD(NV)
780   XOLD(NV) X(1,NV)
785     IF NOT PASS(1,NV) THEN PASS(1,NV)= 1  RETURN
790   R(NV)-XMAX XMIN
799   RETURN
  0 REM
  0 REM =---- ------------=--------   RBAR -------=-====--    - -------   ---
  0 REM
800   RBAR(NV)-RBAR(NV)*(1 AK(NV))+R(NV)*AK(NV)
899   RETURN
  0 REM
  0 REM    -     ------- -  - ---     S    -    = -     -    -     -
  0 REM
900   SX2=0
910     FOR J=1 TO NSUB(NV)
920       SX2-SX2+X(J,NV)*X(J,NV)
930     NEXT J
940   IF NSUB(NV)>1 THEN 980
950     SX2=X(1,NV)*X(1,NV)+XOLD(NV)*XOLD(NV)
955     AVG=(X(1,NV)+XOLD(NV))/2
960     XOLD(NV)=X(1,NV)
965       IF NOT PASS(2,NV) THEN PASS(2,NV)=-1  RETURN
970   S(NV)=SQR(((SX2/2)-AVG*AVG)*2)  RETURN
980   S(NV)=SQR(((SX2/NSUB(NV))-XBAR(NV)*XBAR(NV))*(NSUB(NV)/(NSUB(NV)-1)))
999   RETURN
  0 REM
  0 REM ========-=-=======-=--====== SBAR ==========--=---==--===-===----- -- ---
  0 REM
1000  SBAR(NV)=SBAR(NV)*(1-AK(NV))+S(NV)*AK(NV)
1099  RETURN
  0 REM
```

APPENDIX (cont'd)

```
   0 REM -=-====-=-====-----==== CONTROL LIMITS ===-===-=----=========-=-==----==
   0 REM
1100  UCLX(NV)=XBARBAR(NV)+RBAR(NV)*A2(NV)
1105  LCLX(NV)=XBARBAR(NV)-RBAR(NV)*A2(NV)
1110    REM  UCLX(NV)=XBARBAR(NV)+SBAR(NV)*A1(NV)
1115    REM  LCLX(NV)=XBARBAR(NV) SBAR(NV)*A1(NV)
1120  UCLR(NV)=RBAR(NV)*D4(NV)
1125    REM  UCLS(NV)-SBAR(NV)*B4(NV)
1130  FOR I= 0 TO 2  ILIM(NV,I)=0  NEXT I
1135    IF XBAR(NV)>UCLX(NV) THEN ILIM(NV,0)= 1
1140    IF XBAR(NV)<LCLX(NV) THEN ILIM(NV,1)=-1
1145    IF R(NV)>UCLR(NV)    THEN ILIM(NV,2)=-1
1150      REM IF S(NV)>UCLS(NV) THEN ILIM(NV,2)=-1
1199  RETURN
   0 REM
   0 REM ===-===-============== UPDATE TREND FILE ======-=========--=========----=
   0 REM
1400  FULL=0  IF PT(NV)<EOTF  THEN PT(NV)=PT(NV)+1  ELSE FULL=-1
1405  FOR MM= 1 TO 2
1410  IF FULL  THEN 1415  ELSE 1420
1415  FOR I= 1 TO EOTF 1  TREND(I,MM,NV)= TREND(I+1,MM,NV)  NEXT I
1420  IF MM=1  THEN TREND(PT(NV),MM,NV)=XBAR(NV)  GOTO 1500
1425  TREND(PT(NV),MM,NV)=R(NV)
   0 REM
   0 REM ===========--======= TREND PATTERN ANALYSIS ====-====-=================
   0 REM
   0 REM **** SET UP CONTROL CHART PARAMETERS
   0 REM
1500  IF MM=1  THEN BAR=XBARBAR(NV)  UCL= UCLX(NV)  LCL= LCLX(NV)  GOTO 1510
1505  BAR= RBAR(NV)  UCL= UCLR(NV)  LCL= 0
1510  XOC= 0  PATTERN(NV,1)= 0· PATTERN(NV,2)=0  SIGMA= (UCL-BAR)/3
   0 REM
   0 REM **** CHECK TO ENABLE PATTERN ANALYSIS
   0 REM
1515  ENABLE= -1
1520  IF (LCL>=UCL) OR (SIGMA<=0) OR (PT(NV)<5)  THEN ENABLE=0
1525  BOUT 1651+MM+(NV-1)*20, -ENABLE· IF ENABLE  THEN 1530  ELSE 1555
   0 REM
   0 REM **** TEST PATTERN RULES
   0 REM
1530  FOR N= 1 TO 7
1535  PO= FNAMAX(PT(NV)-RULE(N,2)+1,1)
1540  ON N GOSUB 2100,2200,2300,2400,2500,2600,2700
1545  IF XOC  THEN PATTERN(NV,MM)= N: N= 7
1550  NEXT N
1555  BOUT 1659+MM+(NV-1)*20, PATTERN(NV,MM)
1560  NEXT MM
1565  BOUT 1651+(NV-1)*20, -NTST(NV)
```

```
1570  GOSUB 25000
1599  RETURN
   0 REM
   0 REM **** RULE 1 SHIFT   NINE POINTS IN A ROW ABOVE OR BELOW MEAN
   0 REM
2100  ABOVE- 0  BELOW- 0
2110  FOR J  PO TO PT(NV)
2120  IF TREND(J,MM,NV)>BAR  THEN ABOVE=ABOVE+1
2130  IF TREND(J,MM,NV)<BAR  THEN BELOW=BELOW+1
2140  NEXT J
2150  IF FNAMAX(ABOVE,BELOW)>=RULE(1,1)  THEN XOC= 1
2199  RETURN
   0 REM
   0 REM **** RULE 2 TREND   SIX POINTS IN A ROW INCREASING OR DECREASING
   0 REM
2200  INC= 0  DEC= 0
2210  FOR J  PO TO PT(NV)-1
2220  IF TREND(J+1,MM,NV)>TREND(J,MM,NV)  THEN INC-INC+1
2230  IF TREND(J+1,MM,NV)<TREND(J,MM,NV)  THEN DEC-DEC+1
2240  NEXT J
2250  IF FNAMAX(INC,DEC)>=(RULE(2,1) 1)  THEN XOC= 1
2299  RETURN
   0 REM
   0 REM **** RULE 3 ALTERNATION   14 PTS IN A ROW ALTERNATING UP AND DOWN
   0 REM
2300  ALT- 0
2310  FOR J= PO+1 TO PT(NV) 1
2320  IF TREND(J,MM,NV)>TREND(J 1,MM,NV) AND TREND(J,MM,NV)>TREND(J+1,MM,NV) THEN ALT ALT+1
2330  IF TREND(J,MM,NV)<TREND(J-1,MM,NV) AND TREND(J,MM,NV)<TREND(J+1,MM,NV) THEN ALT-ALT+1
2340  NEXT J
2350  IF ALT>=(RULE(3,1) 2)  THEN XOC= 1
2399  RETURN
   0 REM
   0 REM **** RULE 4 ZONE A   2 OF 3 POINTS GREATER THAN + OR   TWO SIGMA
   0 REM
2400  UZA= 0  LZA= 0: UPRZONEA= BAR+2*SIGMA  LWRZONEA= BAR-2*SIGMA
2410  FOR J= PO TO PT(NV)
2420  IF TREND(J,MM,NV)>UPRZONEA  THEN UZA-UZA+1
2430  IF TREND(J,MM,NV)<LWRZONEA  THEN LZA=LZA+1
2440  NEXT J
2450  IF FNAMAX(UZA,LZA)>=RULE(4,1)  THEN XOC=-1
2499  RETURN
   0 REM
   0 REM **** RULE 5 ZONE B   4 OF 5 POINTS GREATER THAN + OR   ONE SIGMA
   0 REM
2500  UZB= 0  LZB= 0. UPRZONEB= BAR+SIGMA: LWRZONEB= BAR-SIGMA
2510  FOR J= PO TO PT(NV)
2520  IF TREND(J,MM,NV)>UPRZONEB  THEN UZB=UZB+1
```

APPENDIX (cont'd)

```
2530   IF TREND(J,MM,NV)<LWRZONEB  THEN LZB-LZB+1
2540   NEXT J
2550   IF FNAMAX(UZB,LZB)>-RULE(5,1)  THEN XOC- 1
2599   RETURN
   0 REM
   0 REM **** RUL- 6 STRATIFICATION   15 PTS IN A ROW WITHIN +/  ONE SIGMA
   0 REM
2600   ZONEC- 0
2610   FOR J  PO TO PT(NV)
2620   IF TREND(J,MM,NV)>LWRZONEB AND TREND(J,MM,NV)<UPRZONEB  THEN ZONEC-ZONEC+1
2630   NEXT J
2640   IF ZONEC> RULE(6,1)  THEN XOC- 1
2699   RETURN
   0 REM
   0 REM **** RULE 7 MIXTURE   8 PTS IN A ROW OUTSIDE OF + OR   ONE SIGMA
   0 REM
2700   MIX- 0
2710   FOR J= PO TO PT(NV)
2720   IF TREND(J,MM,NV)<LWRZONEB OR TREND(J,MM,NV)>UPRZONEB  THEN MIX-MIX+1
2730   NEXT J
2740   IF MIX>=RULE(7,1)  THEN XOC- 1
2799   RETURN
   0 REM
   0 REM =------------ -    --==     PARETO ANALYSIS ---=   =---        ----
   0 REM
3000   IF IRESET(NV) THEN GOSUB 3100
3010   IF IFLG(NV) THEN GOSUB 3200
3020   GOSUB 3300  GOSUB 3400
3099   RETURN
   0 REM
   0 REM **** RESET PARETO PARAMETERS
   0 REM
3100   FOR I=1 TO 10
3110     CCNTR(I,NV)=0
3120     COST(I,NV)=0
3130     PCOST(I,NV)=0
3140   NEXT I
3150     PCNTR(NV)=0
3160     TCNTR(NV)=0
3199   RETURN
   0 REM
   0 REM **** UPDATE ALARM COUNTER
   0 REM
3200   ITCNTR(NV)=0
3210   IF (PATTERN(NV,1)>0 5) THEN ITCNTR(NV)=-1
3220   IF (PATTERN(NV,2)>0 5) THEN ITCNTR(NV)=-1
3230   IF (ILIM(NV,0) OR ILIM(NV,1) OR ILIM(NV,2)) THEN ITCNTR(NV)=-1
3240   IF ITCNTR(NV) THEN TCNTR(NV)=TCNTR(NV)+1
```

APPENDIX (cont'd)

```
3299  RETURN
   0 REM
   0 REM **** UPDATE PARETO PARAMETERS
   0 REM
3300  IF NOT NEWCAUSE(NV) THEN 3315
3305  CCNTR(CAUSE(NV),NV)=CCNTR(CAUSE(NV),NV)+1
3310  PCNTR(NV)=PCNTR(NV)+1
3315  FOR I=1 TO 10
3320    COST(I.NV)=CCNTR(I,NV)*CSTFCTR(I,NV)
3325  NEXT I
3330  TCOST(NV)-0
3335  FOR I-1 TO 10
3340    TCOST(NV)-TCOST(NV)+COST(I,NV)
3345  NEXT I
3350  FOR I=1 TO 10
3355    PCOST(I,NV)=COST(I,NV)/FNAMAX(1,TCOST(NV))
3360  NEXT I
3399  RETURN
   0 REM
   0 REM **** SORT PARETO PARAMETERS
   0 REM
3400  FOR I-1 TO 1C
3405    SRTCST(I,0)-I  SRTCST(I,1)-100*PCOST(I,NV)
3410  NEXT I
3415  FOR I 2 TO 1C
3420  JFLG=0
3425    FOR J-1 TO I-1
3430      IF JFLG THEN GOTO 3440
3435      IF SRTCST(I,1)>SRTCST(J,1) THEN JFLG- 1 GOSUB 3500
3440    NEXT J
3445  NEXT I
3450  SUM-0
3455  FOR I=1 TO 10
3460    SRTCST(I,2)-SRTCST(I,1)+SUM
3465    SUM=SRTCST(I,2)
3470  NEXT I
3499  RETURN
   0 REM
   0 REM **** SWAP ARRAYS
   0 REM
3500  TMP(0)=SRTCST(I,0)  TMP(1)=SRTCST(I,1)
3510  FOR K=I TO J STEP -1
3520    SRTCST(K,0)=SRTCST(K 1,0)
3530    SRTCST(K,1)=SRTCST(K-1,1)
3540  NEXT K
3550  SRTCST(J,0)=TMP(0)  SRTCST(J,1)=TMP(1)
3599  RETURN
   0 REM
```

```
    0 REM =====-=========== -======-= OUTPUT =====-=== =  ====  -==  ===========
    0 REM
4000   BOUT 1663+(NV-1)*20,XBAR(NV) BOUT 1664+(NV 1)*20,XBARBAR(NV)
4005   BOUT 1665+(NV-1)*20,UCLX(NV) BOUT 1666+(NV-1)*20,LCLX(NV)
4010   BOUT 1667+(NV 1)*20,R(NV) BOUT 1668+(NV-1)*20,RBAR(NV)
4015   BOUT 1669+(NV-1)*20,UCLR(NV)
4020     REM BOUT 1667+(NV-1)*20,S(NV) REM BOUT 1668+(NV 1)*20,SBAR(NV)
4025     REM BOUT 1669+(NV-1)*20,UCLS(NV)
4030   BOUT 1658+(NV-1)*20,-IFLG(NV) BOUT 1659+(NV-1)*20,GRADE(NV)
4035   FOR I=0 TO 2 BOUT 1654+I+(NV-1)*20,-ILIM(NV,I) NEXT I
4040   IFLG(NV)=0
4045     IF NOT IPARETO(NV) THEN RETURN
4050   BOUT 1701+(NV 1)*60,TCNTR(NV)
4055   BOUT 1702+(NV-1)*60,PCNTR(NV)
4060   BOUT 1703+(NV 1)*60,100*PCNTR(NV)/FNAMAX(1,TCNTR(NV))
4065   BOUT 1704+(NV-1)*60,TCOST(NV)
4070   FOR I=1 TO 10
4075     BOUT 1709+3*(I-1)+(NV-1)*60,SRTCST(I,0)
4080     BOUT 1710+3*(I-1)+(NV-1)*60,SRTCST(I,1)
4085     BOUT 1711+3*(I-1)+(NV-1)*60,SRTCST(I,2)
4090     BOUT 1741+(I-1)+(NV-1)*60,CCNTR(I,NV)
4095   NEXT I
4098   BOUT 1705+(NV 1)*60, NEWCAUSE(NV). BOUT 1706+(NV-1)*60,-ITCNTR(NV)
4099   RETURN
    0 REM
    0 REM ============-==-===  PROGRAM INITIALIZATION  ===========-== ===-=======
    0 REM
10000  OPEN #0,8,1,N,H,N  OPEN #1,8,1,N,H,N
10005  A$= ###-  B$= ### #-  C$= ## ###-
10100  DEFINT I-K,M,N  DEFSNG A-H,L,O-Z
10190  ND=1                                NUMBER OF PROCESS PARAMETERS
10200  DIM A1(ND),A2(ND),B4(ND),D4(ND)
10205  DIM CLA1(10),CLA2(10),CLB4(10),CLD4(10)
10210  DIM AK(ND),CAUSE(ND),CCNTR(10,ND),COST(10,ND),CSTFCR(10,ND)
10215  DIM GCNTR(ND),GRADE(ND),IFLG(ND),ILIM(ND,2),INC1(ND)
10220  DIM IPARETO(ND),IRESET(ND),ITCNTR(ND),ITST(ND),M(ND),MFLG(ND)
10225  DIM MSMP(ND),NFLG(ND),NEWCAUSE(ND),NEWGRD(ND),NSUB(ND)
10230  DIM NTST(ND),OLDGRD(ND),OLDX(ND),PATTERN(ND,2),PASS(2,ND)
10235  DIM PCNTR(ND),PT(ND),R(ND),RB(ND),RBAR(ND),RULE(7,2)
10240  DIM SRTCST(10,2),TCNTR(ND),TMP(1),TREND(20,2,ND)
10245  DIM X(9,ND),XBAR(ND),XBARBAR(ND),XBB(ND),XOLD(ND)
10250    REM DIM S(ND),SBAR(ND),SB(ND)
10300  DEF FNAMAX(A,B)= -(B>A)*B-(A>=B)*A
10310  DEF FNAMIN(A,B)= -(B<A)*B-(A<=B)*A
    0 REM
    0 REM **** SET UP TREND PATTERN ANALYSIS RULES
    0 REM
10500  DATA 9,6,14,2,4,15,8. REM NUMBER OF SUBGROUP INCIDENTS
```

APPENDIX (cont'd)

```
10510   DATA 9,6,14,3,5,15,8  REM NUMBER OF SUBGROUPS TO BE EXAMINED
10520   FOR N= 1 TO 2
10530   FOR I= 1 TO 7  READ RULE(I,N)  EOTF= FNAMAX(RULE(I,N),EOTF)  NEXT I
10540   NEXT N
    0 REM
    0 REM **** DEFINE STATISTICAL SIGNIFICANCE FACTORS
    0 REM
10600   DATA 3 76,3 76,2 39,1 88,1 60,1 41,1 28,1 17,1 09,1 03   REM A1
10610   DATA 2 66,1 88,1 02,0 73,0 58,0 48,0 42,0 37,0 34,0 31   REM A2
10620   DATA 3 27,3 27,2 57,2 27,2 09,1 97,1 88,1 81,1 76,1 72   REM B4
10630   DATA 3 27,3 27,2 57,2 28,2 11,2 00,1 92,1 86,1 82,1 78   REM D4
10640   FOR I=1 TO 10  READ CLA1(I)  NEXT I
10650   FOR I=1 TO 10  READ CLA2(I)  NEXT I
10660   FOR I-1 TO 10  READ CLB4(I)  NEXT I
10670   FOR I=1 TO 10  READ CLD4(I)  NEXT I
    0 REM
    0 REM **** READ AND CHECK HISTORICAL DATA
    0 REM
10700   FOR I=1 TO ND
10710     GRADE(I)=BIN(36+(I 1)*25)
10720     XBB(I)=BIN(1034+(I-1)*15)  RB(I)=BIN(1035+(I 1)*15)
10730       IF XBB(I)=0 OR RB(I)=0 THEN M(I)=0  GOTO 10750
10740     XBARBAR(I)=XBB(I)  RBAR(I)=RB(I)  M(I)=9999
10750   NEXT I
    0 REM
    0 REM **** PARETO ANALYSIS ENABLE/DISABLE
    0 REM
10800   DATA  1  REM  1 = ENABLE, 0 = DISABLE
10810   FOR I=1 TO ND  READ IPARETO(I)  NEXT I
10820   FOR I=1 TO ND
10830     IF NOT IPARETO(I) THEN 10890
10840     TCNTR(I)=BIN (1272+(I-1)*25)
10850     FOR J=1 TO 10
10860       CCNTR(J,I)=BIN (1260+J+(I-1)*25)
10870       PCNTR(I)=PCNTR(I)+CCNTR(J,I)
10880     NEXT J
10890   NEXT I
10900   INIT= -1
10999   RETURN
    0 REM
    0 REM ========================== ERROR TRAP ========================-==========
    0 REM
20000   ERNO= ERR  ERLN= ERL  ON ERROR GOTO 0
20500   BOUT 1631, ERNO  BOUT 1632, ERLN  BOUT 1633, HOUR*100+MIN
20999   ERROR 199
    0 REM
```

APPENDIX (cont'd)

```
    0 REM ==== ====:======- =    - -= USER BREAK ====== - =              -=    =----=
    0 REM
25000   IF INQUE=0  THEN RETURN  ELSE ON ERROR GOTO 0
25500   IN ZZZ  IF ZZZ-26  THEN OPEN #0,8,1,N,H,N  ERROR 255
25999   IF INQUE<>0  THEN 25500  ELSE RETURN
    0 REM
    0 REM ============--======--=== END OF PROGRAM -=--==-==-==---==--=---  ==----
```

00 04 00 04 11 07

00 04 01 04 11 07

00 04 01 04 11 07

00 04 03 04 11 07

Bailey Controls

Babcock & Wilcox, a McDermott company

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