IEC TR 62010

Edition 2.0 2016-12

TECHNICAL REPORT

colour inside

Analyser systems – Maintenance management

IEC TR 62010:2016-12(en)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 71.040.01 ISBN 978-2-8322-3684-0

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ANALYSER SYSTEMS – MAINTENANCE MANAGEMENT

FOREWORD

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IEC TR 62010, which is a Technical Report, has been prepared by subcommittee 65B: Measurement and control devices, of IEC technical committee 65: Industrial-process measurement, control and automation.

This second edition cancels and replaces the first edition published in 2005, This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) addition of data, examples and clarifications.

EEMUA Publication 187: 2013 – *Analyser systems: A guide to maintenance management*, has served as a basis for the elaboration of this Technical Report, with the permission of the Engineering and Equipment Users Association.

The text of this Technical Report is based on the following documents:

Enquiry draft	Report on voting
65B/990/DTR	65B/1063/RVC

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

This document covers best practices for the maintenance of on-line analysers. Analysers are used in industry to measure variables which significantly contribute to safety, environmental, asset protection and profit maximisation.

Maintenance organisation, prioritising of maintenance effort, maintenance methods, correct resourcing, performance monitoring and reporting all play an important role in successful application of on-line analysers.

The ultimate effectiveness of the contribution of on-line analysers is measured by the ability to perform their functional requirements upon demand. This document gives guidance on performance target setting, strategies to improve reliability, methods to measure effective performance, and the organisations, resources and systems that need to be in place to allow this to occur.

The various subjects covered in this document are discrete items and can appear unrelated in the overall scheme of analyser maintenance procedures and strategies. The following flow path in Figure 1 ties the clauses together in a logical sequence of approach.

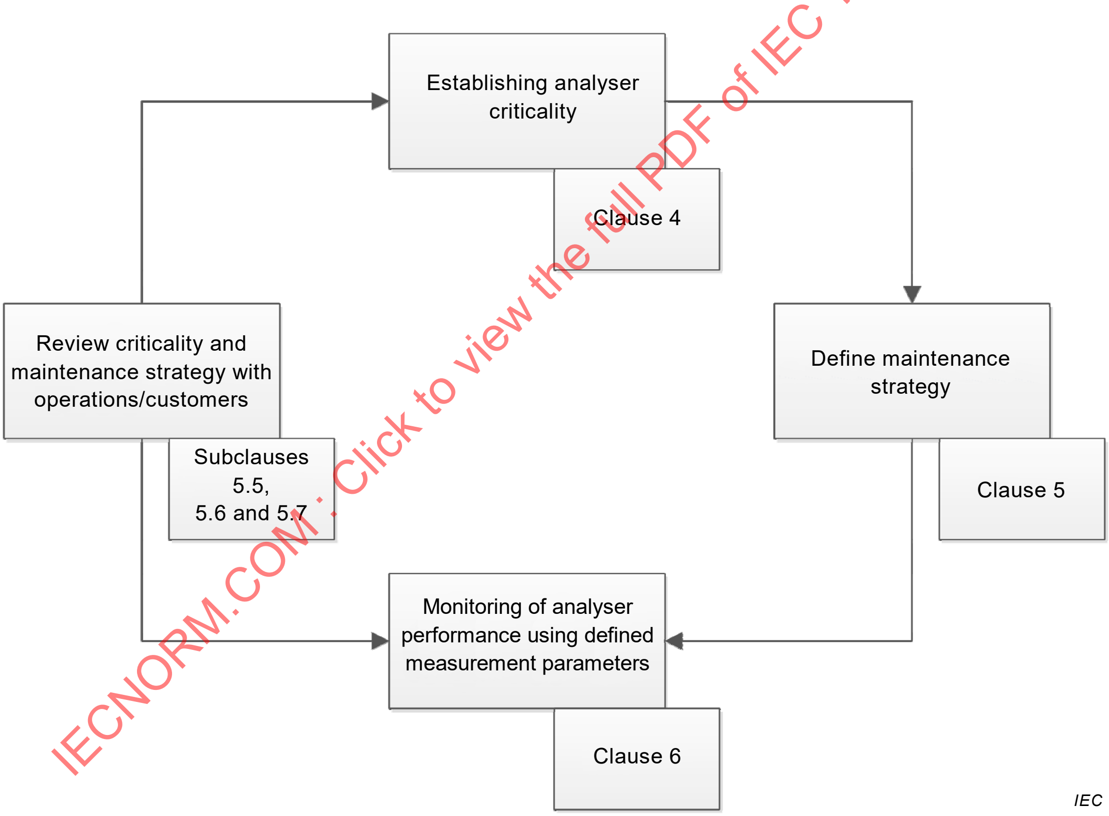


Figure 1 – Flow path detailing interrelationships of subject matter in IEC TR 62010

This document provides a mechanism by which the criticality of an analyser can be determined by means of a risk assessment. The risk assessment is based on consideration of the consequence of the loss of the analysis to the operation of a process unit, or group of process units, personnel/plant safety and the environment.

Determination of a criticality rating for the analyser allows target values for reliability to be set for each criticality classification and prioritisation for maintenance and support. Such approaches are covered in Clause 4.

A numbers strategy designed to allow the target reliabilities calculated by the risk assessments to be met are defined in Clause 5.

Finally, mechanisms for tracking analyser performance and quantifying the performance as meaningful measures are presented in Clause 6.

ANALYSER SYSTEMS – MAINTENANCE MANAGEMENT

1 Scope

1.1 Purpose

This document is written with the intention of providing an understanding of analyser maintenance principles and approaches. It is designed as a reference source for individuals closely involved with maintenance of analytical instrumentation, and provides guidance on performance target setting, strategies to improve reliability, methods to measure effective performance, and the organisations, resources and systems that need to be in place to allow this to occur.

Effective management of on-line analysers is only possible when key criteria have been identified and tools for measuring these criteria established.

On-line analysers are used in industry for the following reasons:

- **Safety and environmental**. One category of on-line analyser is those used to control and monitor safety and environmental systems. The key measured parameter for this category of analyser is on-line time. This is essentially simpler to measure than an analyser's contribution to profits but as with process analysers applied for profit maximisation, the contribution will be dependent upon ability to perform its functional requirements on demand.
- **Asset protection and profit maximisation**. On-line analysers falling into this category are normally those impacting directly on process control. They can impact directly on protection of assets (e.g. corrosion, catalyst contamination) or product quality, or can be used to optimise the operation of the process (e.g. energy efficiency). For this category of analysers, the key measured parameter is either the cost of damage to plant or the direct effect on overall profit of the process unit. Justification as to whether an analyser is installed on the process can be sought by quantifying the payback time of the analyser, the pass/fail target typically being 18 months. The contribution of the analyser to reduction in extent of damage to, or the profit of, the process unit, is difficult to measure. However, this contribution will be dependent upon the analyser's ability to perform its functional requirements upon demand.

This document focuses on the cost/benefits associated with traditional analyser maintenance organisations. Due to the complexity of modern analysers, support can be required from laboratory or product quality specialists, for example for chemometric models, who can work for other parts of the organisation. Inclusion of their costs in the overall maintenance cost is therefore important.

1.2 Questions to be addressed

When considering on-line analyser systems and their maintenance, the following key points list is useful in helping decide where gaps exist in the maintenance strategy.

- **What is the uptime of each critical analyser?** Do you measure uptime and maintain records? Do you know the value provided by each analyser and therefore which ones are critical? Do you meet regularly with operations ('the customer') to review priorities?
- **What is the value delivered by each analyser in terms of process performance improvement (i.e. improved yield values, improved quality, improved manufacturing cycle time and/or process cycle time, process safety (e.g. interlocks), environmental importance)?** Is this information readily available and agreed to in meetings with operations? Is the value updated periodically?

- **What is the utilisation of each critical analyser?** That is, if the analyser is used in a control loop, what percentage of the time is the loop on manual due to questions about the analyser data? Do you keep records on the amount of time that analyser loops are in automatic? Do you meet regularly with operations to review the operator's views about the plausibility of the analyser data?
- **Do you have a regular preventive maintenance programme set up for each analyser which includes regular calibrations?** Does the calibration/validation procedure include statistical process control (SPC) concepts – upper/lower limits and measurement of analyser variability (or noise)? Is the procedure well documented? Do you conduct it regularly, even when things are running well?
- **Do you have trained personnel (capable of performing all required procedures and troubleshooting the majority of analyser problems) who are assigned responsibility for the analysers?** Do the trained personnel understand the process? Do they understand any lab measurements which relate to the analyser results?
- **Do the trained maintenance personnel have access to higher level technical support as necessary for difficult analyser and/or process problems?** Do they have ready access to the individual who developed the application? Do they have ready access to the vendor? Can higher level support personnel connect remotely to the analyser to observe and troubleshoot?
- **Do you have a maintenance record keeping systems, which documents all activity involving the analysers, including all calibration/validation records, all repairs and/or adjustments?**
- **Do you use the record keeping system to identify repetitive failure modes and to determine the root cause of failures?** Do you track the average time-to-repair analyser problems? Do you track average time-between-failures for each analyser?
- **Do you periodically review the analysers with higher level technical resources to identify opportunities to significantly improve performance by upgrading the analyser system with improved technology or a simpler/more reliable approach?**
- **Do you meet regularly with operations personnel to review analyser performance, update priorities, and understand production goals?**
- **Do you have a management framework that understands the value of the analysers and are committed to and supportive of reliable analysers?**
- **Do you know how much the maintenance programme costs each year and is there a solid justification for it?**

Consideration of the above questions will help to identify opportunities for continuously improving the reliability of installed process analysers. Once the opportunities are identified the following clauses are intended to give guidance in achieving the solutions with the aim of:

- maximising performance and benefit of installed analysers;
- achieving full operator confidence in the use of on-line analysers;
- analyser output data becoming reliable enough to be used by operators, control systems, and other users, in order to improve plant operation versus world class manufacturing metrics to become the best process analysers possible.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
availability
ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided

3.2
catastrophic failure
failure of a component, equipment or system in which its particular performance characteristic moves completely to one or the other of the extreme limits outside the normal specification range

3.3
consequence
measure of the expected effects of an incident outcome case

3.4
control system
system which responds to input signals from the process and/or from an operator and generates signals causing the equipment under control (EUC) to operate in the desired manner

3.5
diversity
performance of the same overall function by a number of independent and different means

3.6
error
discrepancy between a computed, observed or measured value or condition and the true, specified or theoretically correct value or condition

[SOURCE: IEC 60050-192:2015, 192-03-02, modified — the notes have been deleted]

3.7
failure
termination of the ability of an item to perform a required function

[SOURCE: IEC 60050-603:1986, 603-05-06]

3.8
fault
state of an item characterized by the inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources

3.9
design fault
fault in the design caused by a mistake in the design phase of a system

Note 1 to entry: A design fault causes an error, remaining undetected in a part of the system until specific conditions affecting that part of the system are such that the produced result does not conform to the intended function. This results in a failure of that part of the system. If the conditions appear again, the same results will be produced.

3.10
undetected fault
fault which is not detected by a diagnostic check

3.11
mistake
human error
human action that produces an unintended result

3.12
failed state
condition of a component, equipment or system during the time it is subject to a failure

3.13
fault tree analysis
analysis to determine which fault modes of the sub-items or external events, or combinations thereof, may result in a stated fault mode of the item, presented in the form of a fault tree

3.14
functional safety
ability of a safety related system to carry out the actions necessary to achieve a safe state for the EUC or to maintain the safe state for the EUC

3.15
hazard
physical situation with a potential for human injury

3.16
maintainability
ability of an item under given conditions of use to be retained in or restored to a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources

[SOURCE: IEC 60050-192:2015, 192-01-27, modified]

3.17
mean time between failures
MTBF
expectation of the duration of the operating time between failures

[SOURCE: IEC 60050-192:2015, 192-05-13, modified — "operating" is omitted from the definition and the note has been deleted]

3.18
mean time to failure
MTTF
expectation of the operating time to failure

[SOURCE: IEC 60050-192:2015, 192-05-11, modified — "operating" is omitted from the definition and the notes have been deleted]

3.19
mean time to restoration
MTTR
expectation of the time to restoration

[SOURCE: IEC 60050-192:2015, 192-07-23, modified — the note has beend deleted]

3.20
proof testing
method of ensuring that a component, equipment or system possesses all the required performance characteristics and is capable of responding in the manner desired

3.21
random hardware failure
failure occurring at a random time, which results from one or more of the possible degradation mechanisms in the hardware

Note 1 to entry: There are many degradation mechanisms occurring at different rates in different components, and, since manufacturing tolerances cause components to fail due to these mechanisms after different times in operation, failures of equipment comprising many components occur at predictable rates but at unpredictable (i.e. random) times.

Note 2 to entry: A major distinguishing feature between random hardware failures and systematic failures, is that system failure rates (or other appropriate measures), arising from random hardware failures, can be predicted with reasonable accuracy but systematic failures, by their very nature cannot be predicted. That is, system failure arising from random hardware failure rates can be quantified with reasonable accuracy but those arising from systematic failure cannot be accurately quantified because events leading to them cannot easily be predicted.

3.22
redundancy
in an item, the existence of more than one means for performing a required function

[SOURCE: IEC 60050-351:2013, 351-42-28, modified — the notes have been deleted]

3.23
reliability
ability of an item to perform a required function under given conditions for a given time interval

[SOURCE: IEC 60050-395:2014, 395-07-131, modified — the notes have been deleted]

3.24
risk
probable rate of occurrence of a hazard causing harm and the degree of severity of harm

Note 1 to entry: The concept of risk always has two elements: the frequency or probability at which a hazard occurs and the consequences of the hazard event.

3.25
safety
freedom from unacceptable risk of harm

3.26
safety integrity
SI
probability of a safety related system satisfactorily performing the required safety functions under all the stated conditions within a stated period of time

3.27
safety integrity level
SIL
one of four possible discrete levels for specifying the safety integrity requirements of the safety functions to be allocated to the safety related systems

Note 1 to entry: SIL 4 has the highest level of safety integrity; SIL 1 has the lowest.

3.28
safety-related system
system that:

- implements the required safety functions to achieve a safe state for the EUC or to maintain a safe state for the EUC;
- is intended to achieve, on its own, or with other safety-related systems, the necessary level of integrity for the implementation of the required safety functions

3.29
safety-related control system
system which carries out active control of the EUC and which has the potential, if not in accordance with its design intent, to enter an unsafe state

3.30
safety-related protection system
SRPS
system designed to respond to conditions on the EUC, which may also be hazardous, or if no action was taken, could give rise to hazardous events, and to generate the correct outputs to mitigate the hazardous consequences or prevent the hazardous events

3.31
safety requirements specification
specification that contains all the requirements of the safety functions that have to be performed by the safety-related systems

Note 1 to entry: The specification is divided into:

- safety functions requirement specification;
- safety integrity requirement specification.

3.32
software
intellectual creation comprising the programmes, procedures, rules and any associated documentation pertaining to the operation of a data processing system

3.33
system
set of components which interact according to a design

Note 1 to entry: A component may be another system (a subsystem). Such components (subsystems) may be, depending on the level:

- a controlling or controller system,
- hardware, software, human interaction.

3.34
systematic failure
failure related in a deterministic way to a certain cause, which can only be eliminated by a modification of the design or of the manufacturing process, operational procedures, documentation or other relevant factors

[SOURCE: IEC 60050-395:2014, 395-07-133]

3.35
system life cycle
activities occurring during a period of time that starts when a system is conceived and ends when the system is no longer available

3.36
top event
unwanted event or incident at the 'top' of a fault tree that is traced downward to more basic failures using logic gates to determine its causes and likelihood

3.37
validation
confirmation by examination and provision of objective evidence that the particular requirements for a specific intended use are fulfilled

3.38
verification
confirmation by examination and provision of objective evidence that the specified requirements have been fulfilled

4 Classifying analysers using a risk based approach

4.1 General

Defining on-line analysers as being related to the functional categories of safety, environmental, asset protection or profit maximisation necessitates that the capability exists to determine the required priority for performance target setting and maintenance direction of each instrument by designed functional category. This can be achieved using a risk graph, whereby the target category rating of an analyser is calculated based upon the required risk factor. The hazard rate of the event the analyser is designed to protect against (the so called top event) and the consequence of the top event should be known.

The method takes the principle and general format of the risk graph approach for IEC 61508-5 [2][1]. However, as this document is aimed at analyser maintenance priorities, it should be noted that:

- where analysers are part of a safety system it is not an alternative approach to determining safety integrity levels (SILs) and where SILs demand certain proof checking periods, duplication of analysers etc., these will take precedence;
- the ranking system adopted is in line with accepted analyser maintenance practice, i.e. highest priority is '1' and lowest priority is '3'.

[1] Numbers in square brackets refer to the Bibliography.

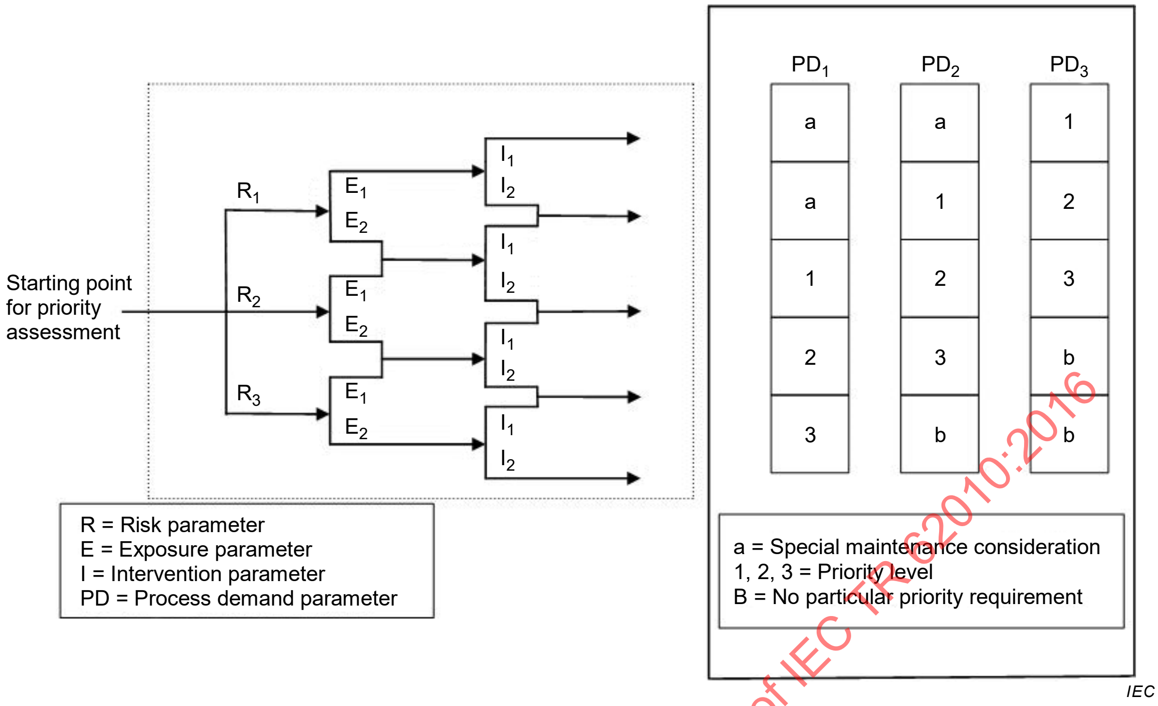


Figure 2 – Generalized risk graph

Using the generalized risk graph shown in Figure 2, each design functional category is considered in turn. The risk graph for each analyser function should be 'calibrated'. This is best achieved by defining the consequences for failures, then evaluating a number of scenarios. The exercise will establish if the outcome in terms of risk reduction is appropriate to the applications.

At the starting point of working through the risk graph towards priority setting it is necessary to establish the initial element which is the risk parameter (R), i.e. the main area of impact associated with analyser failure, for example plant damage, loss of profit, environmental damage, and serious injury/loss of life. The second element is applied on judgements of importance of the analyser in keeping the plant running and is termed the exposure parameter (E), for example high risk of immediate/short term damage, plant control scheme ability to function, environmental consent limitations, area sensitivity, or frequency of exposure of personnel to hazard. The third element is the intervention parameter (I), which is an assessment of whether operator intervention can mitigate the impact of the failure or not. The graph then leads to the prioritisation box which gives priority choice based on the process demand parameter (PD), i.e. the likelihood of the process requiring the measurement when a failure occurs. The following Table 1 summarises a typical application of elements in the risk graph and explanatory notes are given in 4.1, 4.2, 4.3 and 4.4.

Table 1 – Typical application of elements in the risk graph

	Safety	Environmental	Asset protection	Profit maximisation
R_1	Multiple fatalities on or off site	Release causing permanent damage or major clean-up costs	Damage with major replacement costs	Production profit margins high
R_2	Fatality on or off site, injury (resulting in hospitalisation to a member of the public or staff)	Release causing temporary damage requiring significant clean-up	Damage with moderate replacement costs	Production profit margins medium
R_3	Minor injury with lost time impact	Release with minor damage which should be recorded, or failure to record critical data	Damage with minor replacement costs or no damage	Production profit margins low
E_1	Frequency of exposure to the hazard is more frequent to permanent	Consent restrictions and / or sensitive area	High risk of immediate / short term damage	Control scheme cannot function
E_2	Frequency of exposure to hazard is rare to more often	No consent restrictions and / or non-sensitive area	Low risk of immediate / short term damage	Control scheme can function in short term
I_1	Unlikely that operator action will prevent or mitigate circumstances			
I_2	Possible for operator to take action to prevent incident or to significantly reduce consequences where there is sufficient time and suitable facilities available			
PD_1	Demand is frequent			
PD_2	Demand occurs on an average basis			
PD_3	Demand occurs very rarely			

4.2 Safety protection

IEC 61508 (all parts)[1] defines the requirements for devices in all safety related systems. Although this document is aimed at analyser maintenance priorities, any safety-related analysers should have their maintenance and testing requirements determined using IEC 61508 (all parts).

The following should be noted when considering the use of analytical instrumentation as measuring elements for safety-related systems.

The mean time between failures of analytical instrumentation is lower than standard instrumentation used in safety-related systems (pressure, temperature and flow measurements). This is especially true of complex analysers such as spectrometers and gas chromatographs.

Should analytical instrumentation be utilised in safety-related systems, duplex and triplex sensors, and frequent proof checking would routinely be required to achieve the necessary on-line times. These should be determined in accordance with procedures and rules laid down in IEC 61508 (all parts). The above risk graph usage in this document is intended as a guide only to setting maintenance priority and is not intended as an alternative route to defining safety integrity levels (SILs).

4.3 Environmental protection

The measurement of variables that impact directly on the environment are an increasingly important function of on-line analytical instrumentation. Data produced by environmental analysers may require submission to governmental bodies concerned with legal and procedural aspects of environmental monitoring.

There is significant diversity in the nature of the techniques. Traditional applications and methods are continuous air monitoring (CAM) and vent emission monitoring by gas chromatography or electrochemical sensors, organics in aqueous effluent by total carbon (TC) and total oxygen demand (TOD), and acidity/basicity of aqueous effluent by electrochemical pH sensor. These are supplemented by more modern techniques such as air quality monitoring by open path spectrometry and elemental analysis by X-ray fluorescence.

Failure of the analyser to perform its specified function may lead to consequences R_1, R_2, or R_3 depicted in Table 1. It should be noted that environmental analysers are often used to record data but examples whereby analyser failure directly leads to consequential damage are far fewer.

An R_1 consequence would be illustrated by the failure of a CAM system interlocked to process valves, the overall function of which would be to detect emission of chemicals and actuate the valves in order to contain the bulk of the process inventory.

An instance of an R_2 consequence would typically be the result of a failure of an organics in aqueous effluent monitor to detect a high level, thus neglecting to divert the out of specification effluent for further treatment before release to the surrounding environment.

Typically, an R_3 consequence would be an oxygen analyser failure on a burner, leading to emission of partly combusted fuel; or the failure of a vent gas composition analyser, with failure to record environmentally critical data.

The second element of Table 1 requires a determination to be made on the environmental status of the affected area.

Classification of an area as E_2 would require the probability of causing harm to populations in the affected area to be low. The potential to cause political as well as physical damage should be assessed. Should it be considered that the consequence of analyser failure has the potential to significantly affect populations in the affected area, that area should be classed as E_1. Alternatively, if environmental consent limits are imposed by the authorities, this will determine whether route E_1 or E_2 should prevail.

The third element requests a determination as to the likelihood of an operator mitigating the consequences of analyser failure. The probability of operator intervention depends on the nature of the operator's intervention with the process. Where the operator is required to directly carry out actions as a consequence of the analyser's results, there will be a high probability of positive intervention. Automated systems, whereby the operator has no direct involvement in implementing process adjustment due to the measured variable, are more prone to unrevealed failure. Analyser failure diagnostics and the facility given to the operator to mitigate the consequences of the failure by manual intervention, for example grab sampling and laboratory analysis, should be considered when selecting I_1 or I_2.

The final element of the risk graph is a determination of how often a demand is placed by the process upon the analyser.

Process demands on the analyser are broadly classed as infrequent, average and frequent. Categorisation of process demand is primarily the responsibility of the process engineer, and not the analyser/instrument engineer.

Some examples of process demand and frequency categorisation are detailed as follows:

- **PD_1**, a frequent demand can typically be considered to be one significantly exceeding the single annual demand defined in PD_2. The demand on either of the examples cited in R_3 are almost perpetual (the need to record environmentally critical data is considered to place a continuous demand on the process).

- **PD$_2$**, an average demand, can typically be considered to be a single demand placed upon a system on an annual basis. An example would be a high organic content in aqueous effluent occurring on an annual basis (see consequence R_2, failure of an organics in aqueous effluent monitor to detect a high level, thus neglecting to divert the out of specification effluent for further treatment before release to the surrounding environment).
- **PD$_3$**, an infrequent event, can typically be illustrated by the demand rate placed upon a CAM system such as the one described in R_1 (a CAM system interlocked to process valves, the overall function of which would be to detect emission of chemicals and actuate the valves in order to contain the bulk of the process inventory). Such systems are designed to detect emission of a large mass of airborne process material; an event which good process design should ensure is infrequent.

4.4 Asset protection

Protection of assets is a need which can be provided in many instances by use of on-line analysers. Examples include oxygen analysers for the monitoring of inerting systems, conductivity analysers for monitoring the mineral content of condensed steam for turbine safety and moisture analysers for monitoring water level in feed stocks or pH measurement for corrosion reduction.

The initial element of the risk graph requires an estimate of the impact of the failure of the analyser. The consequences of the loss of integrity of the asset protection analyser are generally of a more catastrophic nature and may have safety and environmental implications as well. For example, failure of an oxygen analyser on an inerting system may cause an explosion leading to widespread damage to a process plant (as well as causing injury to personnel and the public, and loss of containment).

The second element of the graph requires a judgement on the likelihood of tolerance of the plant to the onset of the damage mechanism if analyser failure occurs. Determination of damage risk should be determined by process dynamics or plant design (e.g. corrosion allowances). In the example of an oxygen analyser monitoring an inerting system, any oxygen ingress may be potentially rapid risking an immediate danger (high risk route on the graph) whilst on the other hand the space monitored may be under pressure and unlikely to allow oxygen ingress unless this pressure falls at the same time as the analyser failure. This case would allow other short term monitoring to be put in place (low risk route on the graph).

The third element requests a determination as to the likelihood of an operator mitigating the consequences of analyser failure. The possibility of this happening is strongly dependent on whether the operator normally represents a human element in a system. In the example of a failure of an oxygen analyser monitoring an inerting system sending its signal to an emergency shutdown system (assuming that the failure of the analyser is unrevealed), the operator is unlikely to detect the analyser failure, and thus action any corrective measures.

The final element of the risk graph is a determination of how often a demand is placed by the process upon the analyser. Again referring to the example of the oxygen analyser, assuming that the analyser is monitoring an inerting system, (and is not directly used in controlling the level of inert gas), the demand on the analyser (as a sub-component of an emergency shutdown system) would be expected to be low. This assumption can be justified by the fact that under normal conditions, the control of the flow of inert gas into the process is controlled by simple devices with low failure rates.

4.5 Profit maximisation

Utilisation of analysers for maximisation of profits is extremely common, applications being numerous and varied, for example measurement of the concentration of the product of a reactor using infra-red spectrometry, with subsequent feedback control of reactor feeds to maintain a constant concentration in the product; or control of the take-off at the top of a distillation column with the aim of maintaining a constant concentration at a point within the column.

The initial element of the graph requires an estimate as to the likely impact of analyser failure. The consequences of the loss of integrity of an analyser associated with profit maximisation will depend on the size of margins being derived by the extra quality control given over the simple process control of temperatures, pressures, levels and flows. The importance of production losses should be determined by company policy, i.e. the graph should be calibrated on a process by process basis.

The second element of the graph requires a judgement on the ability of a control scheme to tolerate analyser failure. Analysers normally trim control set points or optimisation models. More complex dynamic matrix control schemes may be unable to function at all without all inputs. Analyser failure can lead to loss of the whole automatic control scheme.

The third element requests a determination as to the likelihood of an operator mitigating the consequences of analyser failure. The possibility of this happening is strongly dependent on whether the operator normally represents a human element in a system.

Consider an analyser on a distillation column, the results of which are used for automatic control of the take-off at the top of a distillation column. By controlling the take-off rate, a constant concentration of the analyser of interest can be maintained at the sample point on the column. Should the operator be alerted to the failure of the analyser, for example by a grab sample analysed in the QA laboratory, a regime of grab samples can be instigated, the results of which can be used for process control. The scenario is especially true of systems where equilibria change very slowly.

The final element of the risk graph is a determination of how often a demand is placed by the process upon the analyser.

The distillation analyser example can be considered as a case where the process places a constant (i.e. frequent) demand upon the analyser. An oxygen analyser used only during a process regeneration cycle carried out only a few times a year could be placed in the 'demand occurs on an average basis' bracket.

4.6 Performance target

The risk graph analysis provides a method to classify analysers into category levels based on their application and importance to the application. Category levels enable the setting of realistic targets for process on-line analysers (availability and utilisation) and it also provides a basis upon which to prioritise support effort for routine maintenance and breakdown repair. This effectively helps to maximise analyser added value against support effort available. It may be necessary to use multiple analysers to reach the required performance target.

Depending on requirements within each functional category of the analysers, availability targets can be set against the categorisation numbers derived by the method outlined in 4.3, 4.4 and 4.5. This is typical, based on industry wide experience; and examples follow in Table 2.

Table 2 – Best practice availability targets

Availability target %				
Category rating	Safety	Environmental	Asset	Profit
1	98	97	96	97
2	96	95	92	92
3	92	92	90	85
NOTE The availability targets are not calculated directly from the risk analysis, but are quoted on what is considered to be best industry practice.				

4.7 Maintenance priority

For maintenance purposes, it is necessary to set proof check frequencies which allow the performance targets in 4.6 to be met. This is achieved by considering the mean time to failure and mean time between failures of the analyser. For an analytical instrument with known MTTF and MTBF, the proof check frequencies will need to be more frequent to achieve the higher reliabilities quoted for Category 1 analysers. When considering proof check frequencies, the fault diagnostic tools available on the analyser should also be taken into account. These can be used to warn the user of analyser failure, or ideally to alert the owner of impending failure. This can be taken into account when calculating the analyser's downtime.

4.8 Support priority

For support purposes, it is necessary to differentiate between the analyser categories to avoid conflict of priority, for example which should be given priority; asset protection, profit maximisation, environmental or safety and if breakdowns occur in the same category, which takes precedence? Calculation of a category rating via a risk-based approach allows maintenance priorities to be set in a straight forward manner using the following rules:

- Highest maintenance priority is given to the highest category analysers, for example Category 1 will have priority over Category 2.
- Where two Category 1 analysers require maintenance support, the order of importance shall be determined in the functional category order

  1. Safety, 2. Environmental, 3. Asset protection, 4. Profit maximisation.

If a priority rating greater than 1, i.e. an 'a' on the risk graph in 4.1, is found then the risk is too high for a solution with a single analyser and redundancy techniques are required. However these analysers would for maintenance purposes be Category 1 priority.

5 Maintenance strategies

5.1 General

A key aim for any analyser maintenance function is to improve analyser system reliability and try to avert failure and if failure does occur, to minimise the impact of any failure. The mechanism involved to meet these aims is a combination of many facets and functions within an analyser support organisation.

Important parameters in achieving the above aims include: management systems and organisation; maintenance programmes; technician training and competency; optimisation of resources through matching technician numbers to analyser work load and/or use of in-house against contracted out maintenance; analyser monitoring using statistical control tools; optimising maintenance strategy; and key performance indicator setting and review.

Knowing where a maintenance organisation stands in comparison to other sites is also a useful incentive for improvement. Benchmarking of best practices is another useful tool that can be applied.

5.2 Reliability centred maintenance (RCM)

5.2.1 General

RCM is an on-going process, which determines the optimum mix of reactive, preventive, condition based and proactive maintenance practices in order to provide the required reliability at the minimum cost, as shown below. The principal features of each strategy are shown in their block. These maintenance strategies, rather than being applied independently, are integrated to take advantage of their respective strengths in order to optimise analyser efficiency within given constraints.

5.2.2 Reactive maintenance

Reactive maintenance is also referred to as breakdown maintenance, repair, fix when fail or run to failure and has the following characteristics:

- Maintenance, equipment repair, or replacement occurs only when the deterioration in an analyser's condition causes a functional failure.
- Assumes that failure is equally likely to occur in any part, component, or system.
- The assumption precludes identifying a specific group of repair parts as being more necessary or desirable than others.
- If an item fails and repair parts are not available, delays ensue while parts are obtained.
- If certain parts are urgently needed to restore a critical analyser to operation, a premium for expedited delivery should be paid.
- There is no ability to influence when the failures occur because no action is taken to control or prevent them.
- When this is the sole type of maintenance practice, there are a high percentage of unplanned maintenance activities, high replacement part inventories, and inefficient use of maintenance effort.
- A purely reactive maintenance programme ignores the many opportunities to influence analyser reliability.

5.2.3 Preventative or planned maintenance (PM)

Preventative or planned maintenance (PM) consists of regularly scheduled inspection, adjustments, cleaning, lubrication, parts replacement, calibration, and repair of components and equipment and has the following characteristics:

- Referred to as time-driven or interval-based maintenance.
- It is performed without regard to equipment condition.
- Schedules periodic inspection and maintenance at pre-determined intervals (time, operating hours, or cycles) in an attempt to reduce analyser failures.
- Depending on the intervals set, PM can result in a significant increase in inspections and routine maintenance.
- It should also reduce the frequency and seriousness of unplanned analyser failures for components with defined, age related wear out patterns. However replacement components can introduce an additional risk of failure during initial life of the component (bath tub curve effect on failure rates).
- Traditional PM is keyed to failure rates and times between failures.
- It assumes that these variables can be determined statistically, and therefore one can replace a part due for failure before it fails.
- Statistical failure information leads to fixed schedules for the overhaul of analysers or the replacements of parts subject to wear.
- Failure rate or its reciprocal, mean time between failures (MTBF), is often used as a guide to establishing the interval at which the maintenance task should be performed.
- Weakness in using these measurements to establish task frequency is that failure rate data determines only the average failure rate.
- The reality is that failures are equally likely to occur at random times and with a frequency unrelated to the average failure rate.
- Thus, selecting a specific time to conduct periodic maintenance for a component with a random failure is difficult at best.
- PM is not for random failure analyser components.

5.2.4 Condition based strategy

Also known as predictive maintenance, condition based strategy uses primarily statistical process control (SPC) calibration/validation techniques, visual inspection, data comparison and trend data to assess analyser condition and has the following characteristics:

- Replaces arbitrarily timed maintenance tasks with maintenance that is scheduled only when warranted by the analyser's condition.
- Continuing analysis of analyser condition – monitoring data allows planning and scheduling of maintenance or repairs in advance of breakdown.
- Condition based data collected is used in one of the following ways to determine the condition of the analyser and identify the precursors of failure. The methods include:
  - tests against limits and ranges (SQC);
  - data comparison;
  - trend analysis;
  - correlation of multiple technologies (expert system).

5.2.5 Proactive maintenance

Proactive maintenance employs the following basic techniques to extend analyser life:

- failed part analysis;
- root cause failure analysis;
- reliability engineering (design changes);
- obsolescence management;
- failure mode and effects (FMEA).

Proactive maintenance has the following characteristics:

- using feedback and communications to ensure that changes in design or procedures are rapidly made available to analyser technicians;
- employing a life cycle view of maintenance and supporting functions;
- employing a continuous process of improvement;
- optimising and tailoring maintenance techniques and technologies to each analyser application;
- using root cause analysis and predictive analysis to maximise maintenance effectiveness;
- find the cause of the problem quickly, efficiently and economically;
- correct the root cause of the problem, not just working on its symptoms;
- provide a system that will prevent the problem recurring;
- a proactive maintenance programme is the keystone of the RCM philosophy.

5.2.6 Optimising maintenance strategy

With reference to the concepts of RCM introduced in 5.2.1, an optimum maintenance strategy can be adopted commensurate with the failure mode pattern shown in Figure 3.

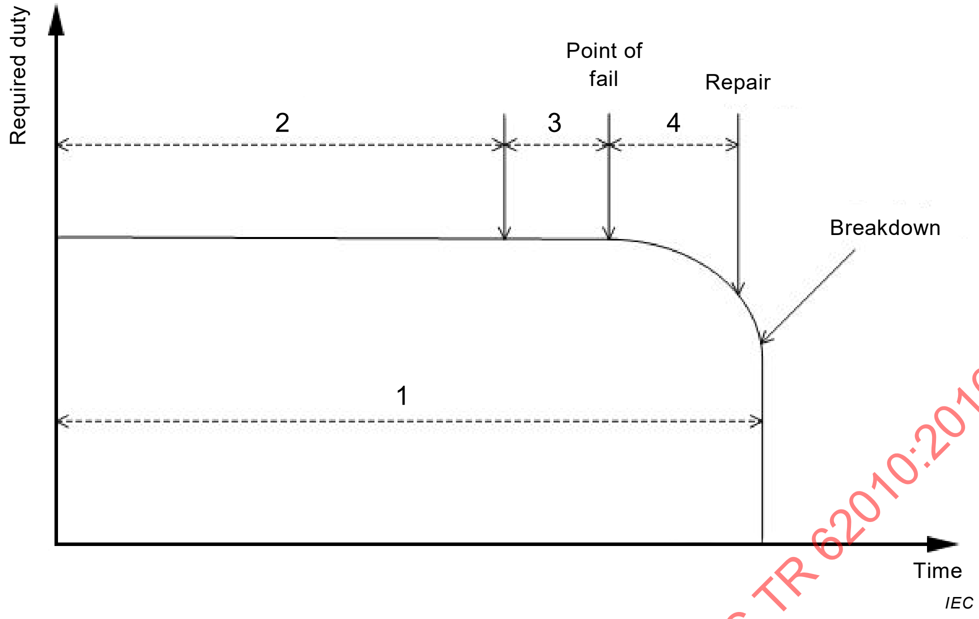


Figure 3 – Failure mode pattern

The following points correspond to the four distinct time phases indicated in Figure 3:

1) A thorough daily inspection should be made to identify minor problems and prevent them from growing into major ones. These daily inspections shall be more than an operator recording instrument readings alone. A trained, dedicated crew that performs a thorough visual inspection will minimise the likelihood of minor problems developing into major reliability issues.

   Additionally, minor problems can usually be corrected with basic tools allowing maintenance activities to be performed as part of the inspection activities. When minor problems are allowed to become reliability issues, the result is often unacceptably high in the form of reduced uptime, productivity, yield and quality and higher cost for maintenance including the possibility of increased capital cost for replacements.

   The daily checking is maintained for the life of the analyser, practical experience will allow the frequency to change, but should be reverted to if there is a personnel change.

2) During this period, statistical process control (SPC) with verification checks is used to maintain the accuracy of the analyser. The frequency of checks is dictated by the control chart and operator confidence (if the analyser is on sentinel duty for example).

3) Time-based PM activates condition-based maintenance (period determined by expected life, experience, etc.). This may mean increased verification/calibration checks to determine the point of fail which is expected in the near future with all data still under SPC.

4) This is where the calibration parameters are monitored (if available) to determine and plan the optimum time for repair.

The ultimate goal is for the majority of maintenance to be in the condition-based and proactive-based modes.

Appendix 4 gives an example of a flow chart to assist in decisions on which maintenance strategy is most suited to which analyser system.

5.3 Management systems/organisation

A good analyser maintenance organisation is necessary to achieve effective analyser performance. The ideal approach needs to include dedicated technicians with good training controlled by an analyser engineer with a full understanding of analysers, their duty and the process which they are monitoring. The analyser engineer controls the overall maintenance organisation and is a focal point for liaison between other refinery groups.

An important additional factor needed in the equation is the level of authority/influence given to the analyser engineer. Analysers should occupy a separate department within the maintenance organisation reporting directly to the management and not be a sub set of, for example, the instrument/electrical maintenance group. Also, regardless of whether technicians are in-house or contracted out, it is considered essential that the analyser engineer role is an in-house function to ensure company interests and requirements are upheld.

However, it can be claimed that analyser maintenance can be successful without well-defined and formalised group structures. There are many instances of groups at apparently low levels in the hierarchy, and even spread across separate departments/cost centres, operating with reasonable success. However such approaches rely heavily on personalities and are vulnerable to changes in personnel creating individual and changing perceptions of priority.

Due to the diversity of organisational approaches which can claim success, it is difficult to define a rigid organisational structure so a more conceptual approach needs to be taken. Figure 4 summarises how the analyser functions should be organised.

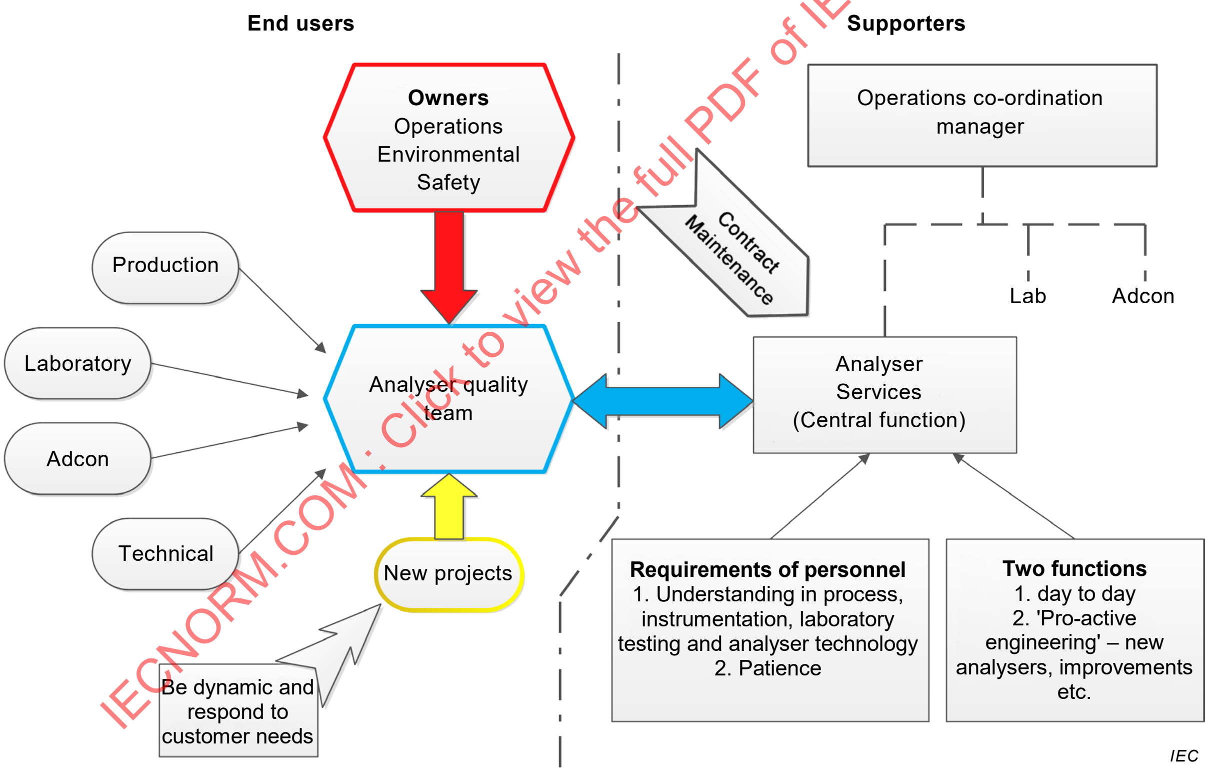


Figure 4 – Organisation of analyser functions

Such a conceptual approach should be able to be applied to operating sites of all sizes and with any number of analysers. The basic concept is for a central function in a supporting role ideally reporting to an operations co-ordination manager who has within his control the laboratory, advanced control, special skills and production groups. Priorities should be set through the owners and end users of the analysers via an analyser quality team, which comprises representatives from all interested departments.

In essence the importance is in where the analyser engineer/supervisor fits in the overall organisation and that the analyser function is recognised as an independent service from general instrument/electrical maintenance.

The importance of dedicated analyser maintenance technicians cannot be over emphasised.

5.4 Training/competency

5.4.1 General

Technician training and motivation is an important factor in a good analyser organisation. Motivation is achieved by giving a sense of valued contribution, continued interest through training and trust to work with minimal supervision.

5.4.2 Training needs

Training of personnel involved with analysers can be divided into two general categories: application and maintenance. Professionally trained personnel (engineers, chemists and others) are generally responsible for the application of analysers to the processes. Highly skilled specialists (technicians, inspectors or instrument mechanics) are usually, but not exclusively, responsible for maintenance. Therefore, the training needs for effective analyser applications are directed toward professionals and the training for analyser maintenance toward specialists.

Professionals should keep their general background skills updated in mathematics, chemistry, physics, electronics, hydraulics, computer science, refinery processes and other areas, which may be required for a thorough understanding of the operating principles of analysers and their sampling systems. This generalised training can be achieved by a combination of job experience, self-study, night school, short courses, seminars and other means that are beyond the scope of this document. In addition, specialised training on particular types of analyser systems is necessary.

This application-oriented training should focus on the capabilities and limitations of specific analysers and on the experiences of others using analysers in particular process applications.

Training personnel for analyser maintenance is quite different from application training. Maintenance training shall include general background updating of the personnel as well as specific training on analysers. It is not effective to teach troubleshooting of chromatographs if the maintenance person has no knowledge of electronics and physical chemistry. Thus the background knowledge listed above, which professional personnel possess, often shall be taught to specialists assigned to analyser maintenance.

5.4.3 Selecting trainees

It is important to choose the right people to train for the application and maintenance of analysers. The need for training is usually apparent but training the right people at the right time is also important. One general rule to follow is to choose those people to train who will be assigned responsibility in that area following the training. Training is expensive and can be wasteful. Nearly all knowledge gained will be forgotten if it is not used promptly. This is particularly important in maintenance training for specific equipment.

When choosing people for assignment to analyser maintenance, care should be taken to select those with the most interest and best background and characteristics to be effective in this work. Usually this means selecting some of the more advanced people who already possess, or can be trained to develop, the special skills required for analyser maintenance.

5.4.4 Types of training

Training can be categorised into individual efforts such as self-study, night school and correspondence schools, and formal group training. Although independent training is very important to the individual, particularly in keeping current with advancing technology, it will not be discussed further in this document. Group training sessions are available from vendors, schools, speciality contractors, technical societies, and there is on-the-job in-house training in many user companies.

5.4.5 Vendor training

Most analyser vendors offer training sessions for their own equipment. The cost of these sessions varies from nil to a modest fee and the sessions are held in the vendor's plants or in locations more convenient to the students. Vendor training may also be conducted in the user's plant in conjunction with new analyser commissioning and start up.

Vendor training is generally of high quality. Most companies use a format that combines classroom sessions, demonstrations and hands-on familiarisation. The classroom portion covers the principles and theory involved in the design of the analysers and the proper application of the analysers to processes.

The hands-on training is designed to teach proper functioning and maintenance, including calibration, testing, diagnostic procedures, adjustments and tuning, and assembly and disassembly.

5.4.6 Classroom training

Training provided by schools can be quite varied. It may be in the form of an evening class held in a local college or high school. The instructor for such a class is often recruited from local industry and is usually someone involved in the application or maintenance of analysers. In many respects this type of training session can be quite similar to vendor training except that the scope is broader, covering analysers from many vendor companies.

Some colleges and universities offer a series of short courses or seminars pertaining to analysers. These are designed for persons interested in analysers who can take the time away from their normal work to attend the sessions. Most of these short courses are of one week or less in duration. The teaching staff may be a combination of university and industry personnel. Course content is usually more theoretical and application oriented than maintenance oriented and therefore more directed toward professionals rather than specialists. Due to the wide variety of courses, the course content, the qualifications and experience of instructors and recommended prerequisites shall be reviewed carefully in order to select the most suitable training.

5.4.7 Technical societies

Technical societies also offer a wide variety of training opportunities. Written standards and practices pertaining to analysers, technical talks at society meetings, seminars, symposia and short courses may be available. Exhibits of analyser equipment are frequently included at technical society functions. This enhances the overall training aspect. In many instances, the authors of technical papers, standards and practices, the speakers at society meetings, and the classroom instructors at seminars and symposia are recruited from the membership of technical societies. Once again the reader is cautioned to be selective in choosing the specific training events.

5.4.8 User training

Many user organisations have established in-house training for individuals involved with analysers. In its simplest form this consists of a one-on-one training in which the trainee is paired with a more experienced maintenance person during normal working hours. In this system, the trainee receives individual instruction and hands-on experience. This can be a very effective training technique, particularly where only one or a small number of people are to be trained, or where group classroom work is to be supplemented with field work. However, it is an inefficient method in that it requires one instructor for each student. A potential problem may exist in that the experienced maintenance person may be effective in analyser work but not in teaching.

In-house training is frequently held in conjunction with the commissioning of one or more new analysers. Ideally this training should be held prior to start-up of the equipment but with the analysers actually operating with calibration samples. The analysers can be located in the workplace, in a training area or in the plant. The instructor may be a local employee or a vendor representative. This type of training can be very effective for maintenance personnel and for familiarising operating personnel with new equipment. Operators should be encouraged to ask questions about the application of the equipment and to learn how the information obtained is used. This type of familiarisation in advance of start-up can help bridge the credibility gap between operations and maintenance on analyser performance.

Many users have established analyser training sessions designed to train a group of people to maintain a variety of different analysers in use in their plants. These sessions consist of two to three hours of training held one or more times each week, usually during working hours. Training can continue for many weeks until all subjects are covered. Instructors often include vendor personnel for specific analysers and in-house experts for more general subjects. The personnel chosen for training should be those who will be assigned responsibility in that area following the training. The classroom should not be filled with people who will not use the training. Small classes are more effective than large ones.

Some users have set up corporate training centres at a central location drawing students from several plants. This is a highly formalised technique and can be effective because it is a full-time effort with the students relieved from all other responsibilities during the training. One company holds this type of training every year or two with sessions lasting from six to nine months. The goal is to convert the best available candidates into highly skilled analyser specialists through intensive training.

A full-time instructor plans the training and is supplemented by the vendor's personnel and corporate experts in various subjects. The class visits vendor locations for some of its sessions and usually conducts a major part of its training at an analyser systems house. This permits hands-on training on various analysers and sampling systems, which have been purchased by this company.

The timing is arranged so that the class performs the necessary checkout, calibration and inspection of analysers before they are shipped to the plants. Such a training course may include: basic subjects (mathematics, physics, chemistry and electronics), 25 %; analyser subjects (laboratory methods, sample systems and analysers), 10 %; miscellaneous subjects (purchasing, safety and documentation), 3 %; vendor instruction, 30 %; hands-on testing, 12 %; and classroom study, 20 %.

5.4.9 Retraining

A great need exists to continuously update and retrain persons already working with analysers. The technology is advancing so rapidly that continual retraining is required to ensure all information is current. Analysers today contain digital logic circuitry, microprocessors and measurement techniques previously not available. Personnel shall be provided with retraining opportunities to improve their skills and retrain their effectiveness.

The types of training discussed so far can be used for retraining as well. However, it is probably even more important in retraining to choose the right student for each type of analyser to ensure they are trainable. As analysers become more complex, analyser personnel will become more specialised. All personnel will not be equally proficient with all types of analysers. A plant will be doing very well indeed through its recruitment, training and retraining to provide analyser personnel with sufficient skills to effectively apply and maintain today's analytical instrumentation.

5.5 Optimal resourcing

5.5.1 General

Optimal resourcing ensures the right numbers of technicians to achieve the required performance of the analysers at the most economical cost. To achieve the correct technician workload can be difficult as each analyser can require varying degrees of attention depending on its complexity and application. To aid the estimation of workload the concept of the equivalent analyser is introduced. Equivalent analyser numbers are determined by normalising each analyser type and application to a typical analyser, which has a defined maintenance workload. From this can be derived a measure of the staff productivity, which can be used as a key performance indicator (KPI) as follows.

5.5.2 Equivalent analyser per technician (EQAT) calculation method

5.5.2.1 Approach

A site's EQAT number is essentially the total number of equivalent analysers maintained at that site divided by the total calculated technician number at that site needed to keep the analysers operational. The site EQAT number is only one of several analyser KPIs which need to be monitored and analysed collectively to make judgements on site maintenance effectiveness. Since site EQATs are not considered to be dynamic data they need to be updated at a frequency of no more than once per year.

5.5.2.2 Part 1 – Calculate total technician number

The worksheet in Clause A.1 is used to calculate the total number of technicians utilised to maintain all assigned analysers. It should include: permanent maintenance staff dedicated to analysers; permanent maintenance staff who have instrument and analyser responsibilities; long term contractors; on-going contracted maintenance services and any analyser work done by multi-craft personnel (i.e. operations staff doing analyser validation). The worksheet should not include any staff who do not have direct assigned responsibility to maintain/verify analyser systems, such as first line supervisors or staff assigned to special duty such as project work or work on non-permanent analysers not included in the equivalent analyser calculations.

5.5.2.3 Part 2 – Calculate equivalent analysers

The equivalent analyser calculation instructions and worksheets in Clause A.2 and Clause A.3 are used to equate all maintained equipment including analyser shelters to a common equivalent analyser reference. All equipment normally maintained by the technician number generated above should be included.

5.5.2.4 Part 3 – Equivalent analysers per technician index (EQAT)

The site wide equivalent analyser per technician index (EQAT) for each site is calculated by dividing the total number of equivalent analysers calculated in Part 2 with the total effective technician number calculated in Part 1:

$$\text{EQAT} = \frac{\text{total number of equivalent analysers}}{\text{total calculated number of technicians}}$$

To enable site-to-site comparisons, a site wide EQAT number should be calculated. An EQAT per business unit may also be of use for comparisons of similarly structured sites.

5.5.3 Ideal number of technicians

The ideal number of technicians to provide optimal maintenance cover depends on what is defined as the standard analyser and the average maintenance requirement for that standard analyser. This will provide a mechanism for justification of analyser technician numbers (hence optimal resourcing) and provide a target EQAT number as a KPI (see 6.4).

For example, if all comparisons are to be based on a flue gas extractive oxygen analyser system on a relatively clean application (gas firing), if the average technician maintenance load for this analyser works out at say 60 h per year to achieve a minimum of 95 % availability, the equivalency of 1,0 is then 60 h work.

NOTE These are hours of work inclusive of visual inspection time, administration time, etc., but not hours of downtime of an analyser, which can be vastly different due to availability of spares, priority requirements for maintenance, etc. A more complex analyser system requiring 120 h work per year will have an equivalency number of 2,0 and so on.

The number of hours a technician works per year then has to be looked at, excluding overtime and allowing for leave, national holidays, etc. In the UK, this works out at around 1 800 h per year. On this basis, the number of equivalent analysers that a single technician can comfortably maintain is therefore 1 800 / 60 which equals 30.

It is suggested that all sites in a company (or ideally an industry) get together and compare maintenance times of all analysers and come to an average number, which would then reflect the company (or ideally industry) operation and provide a level playing field for KPI comparisons.

An example of a typical target EQAT number for process control analysers is between 40 and 60 with present day (2013) technology with target availabilities of 95 %.

The target EQAT number will need to be reviewed say on a yearly basis as new analyser technologies, improved system designs, improved analyser reliability, etc., will tend to require less maintenance effort. SHE (including CEMs) or other analysers with special requirements may require lower EQAT numbers.

5.5.4 In-house or contracted out maintenance

Due to the complexities of analyser systems, the multiplicity of analyser technologies and suppliers, and in most cases the requirement for a full time presence on site to fulfil maintenance functions, it is preferable for a company to employ its own staff trained to understand equipment and its application. There are many relatively simple analysers requiring rudimentary maintenance and in relatively large numbers (e.g. gas detectors, oxygen analysers) that can justify being contracted out. Depending on the analyser requirements there will be a point where contracted-out costs start to exceed in-house costs. In deciding on the use of contracted out maintenance, the relative costs have to be considered as indicated below in Figure 5.

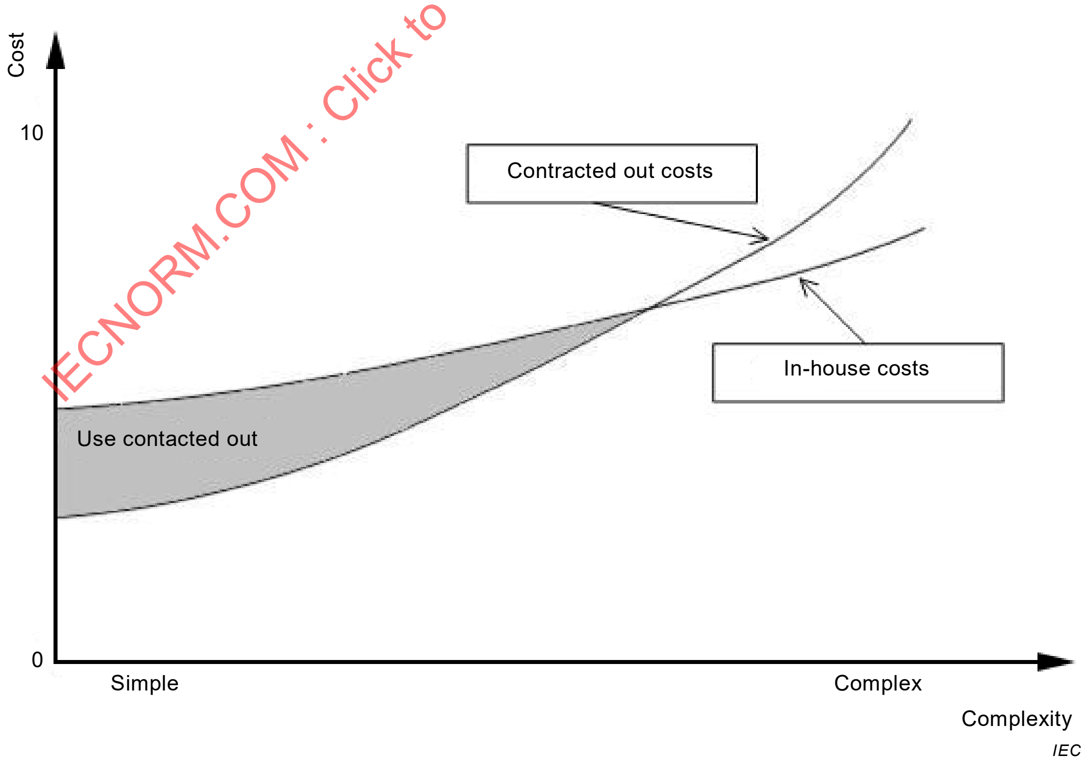


Figure 5 – Relative maintenance costs

In considering the above, all costs need to be taken into account including use of site stores facilities, use of site workshop facilities and site support overheads. These tend to be inclusive for in-house technician rates and maintenance costs but not with contractor rates. Simple savings on man-hour rates or simplifying budgets by fixed price contracts may not be what they seem especially if the contracted out work involves the need for a site-based contract technician(s).

5.5.5 Off-site technical support requirement

The modern industrial analyser group finds its instrumentation responsibilities becoming more complex as technology and economics results in on-line and at-line analysers becoming hybrids of what were essentially laboratory based instruments only a few years ago. This and the introduction of robotics and chemometrics may present little option but to use off-site expertise, though a prudent grounding of at least one member of staff should be considered. The result from a management standpoint is a firm understanding of minimum downtime/plant cost ratios, which can be used to negotiate the external contracts required to keep these analysers running, callout times, internet link troubleshooting, etc.

5.6 Best practice benchmarking

The promotion of good management of analysers and subsequent performance improvements is best served by identifying best practices and assessing organisations against these practices. Benchmarking against best practices is a good tool to engender competition between organisations and raise awareness of analysers within management circles creating an environment of continuous improvement towards optimum and most efficient use of analysers.

The elements of ‘best practice’ are:

- management systems;
- formal analyser group structure;
- central supervised group;
- supervisor authority level;
- dedicated analyser technicians;
- adequate manning levels;
- recognised ownership;
- performance monitoring;
- analyser value recognition;
- analyser quality team;

The implementation of best practice should be stewarded by the organisation.

5.7 Annual analyser key performance indicator (KPI) review

To ensure analyser performance requirements keep pace with process operational requirements, KPIs should be regularly reviewed via a formal procedure. Generally they should be performed for individual areas of the plant, depending on analyser population and operational units, etc. This would normally be one function of the analyser quality team discussed in 5.3. Attendees (positions and titles will vary with each organisation) should comprise:

- operational management;
- operators and panel personnel;
- process engineer;
- maintenance/analyser engineer;

- maintenance/analyser technicians;
- specialists/supervision.

The KPI review agenda suggested is given in Table 3.

Table 3 – Example agenda for a KPI review meeting

	Item	Actioned by
1.	**Review the previous meeting's next steps** Only appropriate after initial meeting.	Operational management
2.	**Review the individual analysers' criticality** This is where the business owner or users review the criticality along with the attendees to see if the criticality suits the current business need. The attendees are such that this can be adjusted instantly.	All
3.	**Presentation of monitoring data** This is where the maintenance technician presents the data collated to the meeting, explaining the highs and lows of the previous year's work. This imparts ownership on behalf of the technician and allows effort, or problems, to be highlighted. As each analyser has been reviewed the meeting leader will allocate the next steps to attendees as required.	Technician
4.	**Next steps** After the data presentation, the next steps and actions are clarified along with completed-by dates.	Operational management
5.	**Benchmarking** The data collated can be generally compared with other areas of the same site or other companies. Questions may be raised and differences discussed.	All

6 Analyser performance monitoring

6.1 General

In order to assess the true value of on-line analysers and to ensure that analyser performance on one site can be easily compared to performance on another site, it is necessary to have a common approach to performance measures which can be identified as key performance indicators (KPIs).

The accepted criterion for performance measurement is the availability of the analyser. This value can then be used to assess benefits put at risk by analyser downtime and to justify additional overheads necessary to maintain the target availability to maximise the benefits.

Availability and potential benefit/risk are inextricably interwoven but there is a flaw in direct use of the availability value traditionally based on actual analyser uptime for this purpose. A third component in the equation is needed and that is the utilisation factor. It is no use having an analyser fully operational and returning measurements within accepted uncertainty limits if it is not actually used, i.e. if ignored by the operator who then relies on manual sampling and analysis or if the control scheme analyser input is put on manual.

Analyser reliability data such as mean time between failures (MTBF) and mean time to repair (MTTR) are not themselves a direct measure of availability. These are different functions to availability as they are independent of plant running times or routine maintenance functions. However, analyser reliability does contribute towards overall availability measurement.

A consistent approach to measurement of availability, utilisation and benefit that can be achieved from analysers is essential in 'benchmarking' analyser performance. These and other performance indicators are given in 6.4.1. The mechanisms to measure major performance indicators such as availability, utilisation and benefit are also discussed.

6.2 Recording failures – reason/history codes

6.2.1 General

To enable improved traceability on analyser breakdown causes and to provide meaningful data for reliability statistics for MTBFs, etc., reason/history codes are a useful tool to employ.

Reason/history codes can be classified into four main groups: w, x, y and z as follows:

w_0 repair of unforeseen breakdown – analyser not taken offline;

w_1 repair of unforeseen breakdown – analyser taken offline;

x_0 time-based jobs (schedules, inspections, etc.) – analyser not taken offline;

x_1 time-based jobs (schedules, inspections, etc.) – analyser taken offline;

y_0 repair of foreseen breakdown – analyser not taken offline;

y_1 repair of foreseen breakdown – analyser taken offline;

z_0 improvement/development jobs – analyser not taken offline;

z_1 improvement/development jobs – analyser taken offline.

These four main reason/history code categories cover the reliability centred maintenance conceptual approaches (see 5.2) of reactive, preventative, predictive, and proactive maintenance. These codes can then be sub-divided into cause and component codes.

Cause history codes aid in identifying failure trends, which can then be addressed under category ‘z’ where improvements and/or development work can be undertaken to improve analyser reliability.

Component history codes aid in identifying poor reliability items and such data can be used in optimising spares holdings, decisions on looking at alternative suppliers and areas where the analyser performance can benefit from redundancy considerations.

6.2.2 Typical failure pattern

A basic understanding of the failure curve is required to be able to adopt a maintenance strategy for the equipment. A traditional failure curve is shown below. The equipment will run at its required duty for a scheduled period (this may be shorter if the equipment is operating above design). It will then begin to lose performance at the point of fail and then decline at a rate to the point of breakdown. For further details, refer to Weibull analysis (IEC 61649) [3] and Power law (IEC 61710) [4].

The times will vary immensely, i.e. the point of failure to actual breakdown (period of fail) could be a matter of seconds in a light source but could be a considerable number of weeks for a gas detector. This length of fail is an important guide to the strategy required. In other words, if the period of fail is short, a run to fail (reactive maintenance) strategy may be practical if the consequences of failure are not significant or there is redundancy in the system.

It may be pointless checking extensively early during the scheduled life or lengthen a time-based strategy to a point where it is longer than the period of fail, as it is possible that the equipment could fail in between the time-based checks, effectively wasting time and effort.

Ideally, the checks are best set to look for the point of fail, which could be based on the scheduled life (planned or preventative maintenance – a time-based strategy), and around that point, begin to monitor more regularly for the point of fail and, once found, monitor (predictive or condition based maintenance – a condition-based strategy). The results of the monitoring will dictate the time to repair to prevent a breakdown and allow for planned work to occur.

Another maintenance tool is proactive maintenance where sources of potential breakdown are identified and circumvented by re-design, replacement with improved hardware, awareness of and adoption of better technology, etc.

The ideal is essentially a mix of all the available strategies, which shall be selected, and blended to form the right overall approach to meet business needs.

The following diagram, see Figure 6, indicates the life cycle to the point where unacceptable performance begins to be important. This can be mitigated by an in-depth knowledge of the failure patterns for a particular type of apparatus. This allows predictive maintenance to be applied.

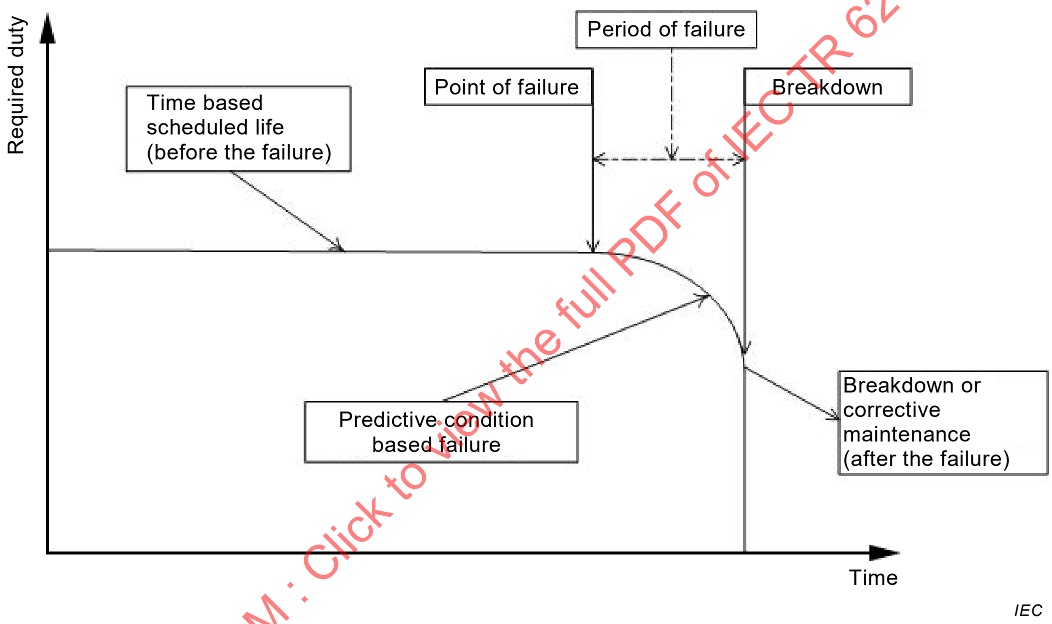


Figure 6 – Life cycle diagram

Typical reliability centred maintenance (RCM) failure patterns for electro-mechanical equipment are as follows:

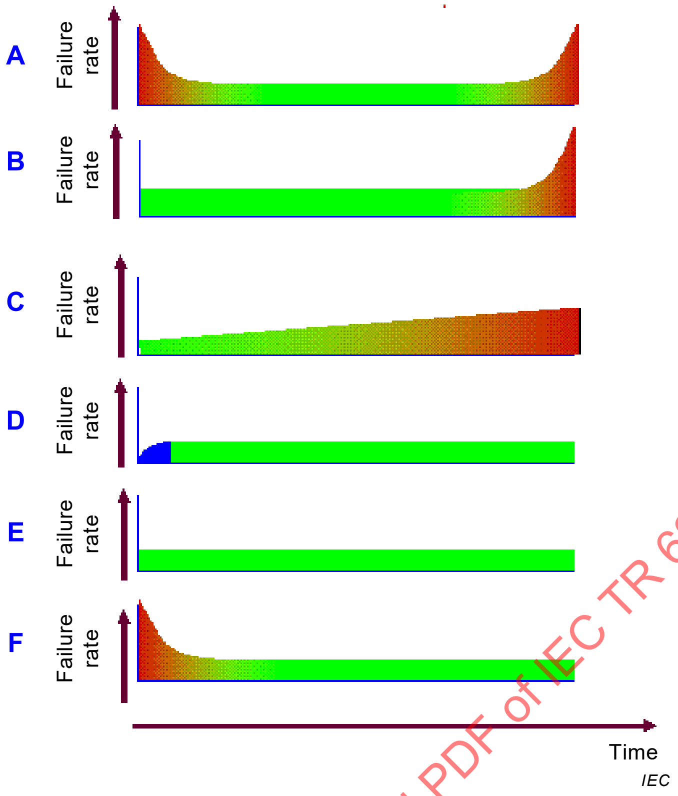


Figure 7 – Reliability centred maintenance failure patterns

Figure 7 shows failure rate (y-axis) plotted against time (x-axis). A is the widely known 'bathtub curve'. It starts with a high frequency of failure. This is followed by gradually increasing conditional probability of failure, then by a wear out zone. B shows increasing conditional probability of failure, which also ends in a wear out zone. C shows slowly increasing conditional probability of failure and no identifiable wear out age. D has a low conditional probability of failure when new. This is followed by a constant level. E shows constant conditional probability of failure at all ages, which is random. F is initially likely to fail, with a decreasing likelihood of failure dropping to a constant conditional probability of failure.

6.3 SPC/proof checking

6.3.1 Analyser control charting

Analyser calibration can be verified through either paired sampling methods using laboratory analysis of samples or use of pre-analysed and/or certified samples. Regular monitoring (verification checks) of the analyser against a reference provides a powerful tool for predictive maintenance and performance enhancement of on-line analysers.

The main problem with on-line analysis is that the uncertainty associated with the reference measurement or sample is usually at best of the same order of magnitude or worse than the analyser/system repeatability. The only true way to monitor analyser performance is through statistical analysis, i.e. employing control charting procedures.

The control chart is an application of statistical process control (SPC) to process analysis and employs a graphical display of the deviation value in relation to the aim line (the known standard) and the warning and control limits. The aim of SPC is to allow for minor deviations around the aim line to occur without changing the calibration, i.e. span and zero settings of the analyser. Without these adjustments any deviation causes, i.e. reference variation, sample handling variations, temperature, pressure, etc., are not amplified and no unnecessary work is undertaken.

It is usual to set two control chart limits against which actions can be taken. Guidance in setting these limits is covered in 6.3.2.

The lower limit is the 'warning limit' and in general when a deviation is outside this limit it is a prompt to the technician that the analyser may need to be re-calibrated in subsequent checks. Also, an increase in verification check frequency may be required.

The upper limit is the 'control limit' and when the deviation exceeds this value it is an indication of possible system malfunction. A re-calibration may be required subject to investigation to establish if a system fault exists and where it resides.

Only over a number of weeks can a pattern of results be obtained which will indicate any biases or drift from within the normal scatter of results that will be inevitable due to the test/analyser uncertainties as shown in Figure 8:

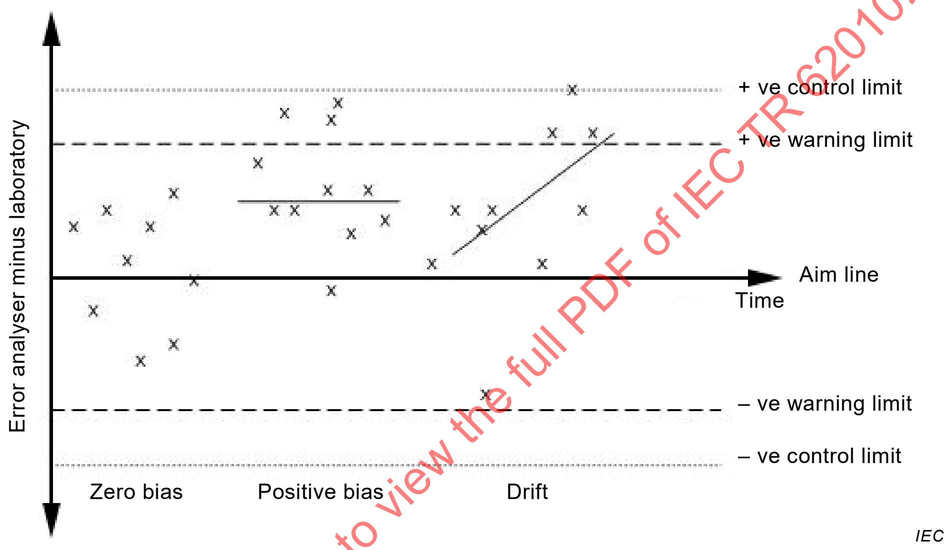


Figure 8 – Control charting diagram

Where bias is encountered this should remain the same unless drift is indicated. The control chart zero error axes can then be re-defined or analyser output given an appropriate offset to account for the bias and no further actions need be taken as long as the results agree within the control chart limits.

Examples of interpretation of control chart readings are shown in Annex B.

A variant of simple control charting is a statistical method based on cumulative calculations of errors. The technique is known as CUSUM and requires two independent measurements of the same sample repeated over a period of time but not necessarily on a regular basis. This is satisfied in the case of on-line analysers since routine samples are collected with analyser readings recorded at time of collection for later comparison to the laboratory analysis of those samples.

CUSUM is defined as the cumulative sum of the differences between the laboratory and the analyser results. The difference is then added to a running total, i.e.

$$CUSUM\ (\mathrm{n}) = CUSUM\ (\mathrm{n}-1) + [L\ (\mathrm{n}) - A\ (\mathrm{n})]$$

where

n is the current time paired value;

L is the laboratory result;

A is the analyser result;

CUSUM is the cumulative sum.

Results are plotted as shown on the following diagram (Figure 9):

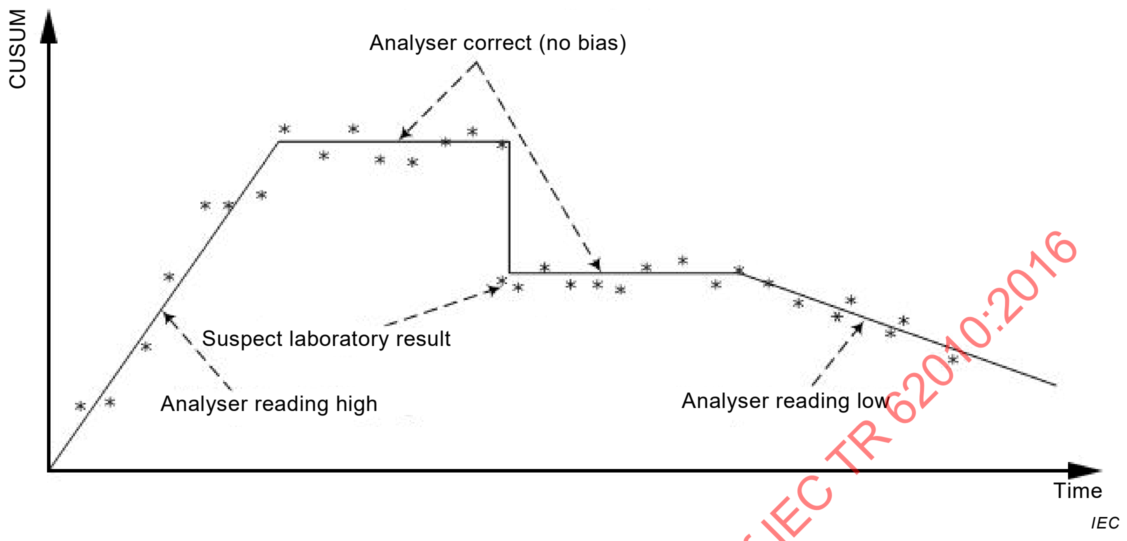


Figure 9 – Examples of analyser results

The horizontal axis is related to time in that the results are plotted in chronological order. However, the interval between the samples is plotted as a constant irrespective of what the actual time interval is. The slope of the plot is the average bias between the analyser and the laboratory.

Interpretation of the plot is based on the following:

- The slope is the bias (+ve or -ve).
- A horizontal plot indicates zero bias.
- A vertical discontinuity, but same slope either side, indicates a suspect laboratory result.
- Scatter of points about the mean lines indicates the uncertainty of analyser/laboratory comparisons.

Controls using CUSUM would include the maximum change in slope (bias) permissible and what to do if the limits are exceeded.

Control charting can be implemented based on data contained in a suitable information system, for example a lost data historian system, which can have access to laboratory information and process control systems.

6.3.2 Control chart uncertainty limits

Any warning and control limits with control charting techniques should be based on a realistic assessment of the relative performance criteria of both the analyser and the corresponding laboratory test. Realistic uncertainties (+ve and -ve limits on the simple control chart and acceptable scatter on the CUSUM chart) can be calculated from the reference uncertainty and analyser plus indication system repeatability combined using the root sum square method.

The warning limits are normally set, in statistical terms, equal to two standard deviations which are equivalent to uncertainties quoted at 95 % confidence limits i.e. only one deviation in 20 is expected to fall outside the warning limit under normal circumstances:

- For paired sample methods the reference test uncertainty (95 % confidence) can be taken as the reproducibility of the test.
- For pre-analysed samples the reference uncertainty can be taken as the laboratory repeatability.
- For certified samples the reference uncertainty should be defined on the certificate.

The relevant reference uncertainty added by the root sum squares method to the analyser repeatability (sensor plus signal handling to final measurement used by the operator/control system) gives a control chart warning limit inside of which the regular analyser verification should agree with the reference.

The control limits are normally set, in statistical terms, equal to three standard deviations which are equivalent to uncertainties with 99 % confidence limits, i.e. only one deviation in 100 is expected to fall outside the control limit under normal circumstances. These limits can be set from the 'warning limit' values multiplied by 1,5.

Once the initial settings of the control limits have been determined, verification checks will be required to establish whether the analyser is within limits (or in control). The frequency of ongoing planned maintenance checks should then be decided by interpretation of the results.

In the absence of reliable uncertainty data for the analyser and reference method, the warning and control limits can be set as a good starting point at 6 % and 8 % of analyser full scale deflection respectively allowing immediate monitoring of analyser performance. Alternatively the standard deviation and hence chart limits can be determined in operations by initially calibrating the analyser and then performing a minimum of eight verification checks without further calibration adjustments, noting the data each time on the control chart. When eight or more checks have been completed, the calculation of standard deviation can be performed and hence the warning and control limits can be derived. An example calculation is shown in Annex B. It shall be noted, however, that these techniques for initial limit setting are very approximate and will need to be revised as experience of the analyser performance is gained. Limit settings should be reviewed after 20 or more data points are obtained (i.e. the minimum for the standard deviation calculations to be statistically significant).

6.4 Analyser performance indicators

6.4.1 Key performance indicators (KPI)

Analyser availability (service factor). The analyser is deemed available when it is on process sample, delivering a process measurement within defined uncertainty limits and there is demand for that measurement. This is a measure of maintenance effectiveness.

$$\text{analyser availability (\%)} = \frac{\text{analyser uptime during process run time}}{\text{process run time}} \times 100$$

Analyser utilisation. The analyser is deemed utilised when available under the definition of analyser availability and being used by the operator in the control/management of the process.

$$\text{analyser availability (\%)} = \frac{\text{time used by the operator during analyser uptime}}{\text{analyser uptime during process run time}} \times 100$$

Analyser benefit. The analyser only adds value when it is being used as intended. This value can be measured by defining an analyser benefit factor. This is the product of analyser availability and analyser utilisation.

$$\text{analyser benefit (\%)} = \frac{\text{time used by the operator during analyser uptime}}{\text{process run time}} \times 100$$

Equivalent analyser per technician index (EQAT) is a measure of maintenance staff productivity.

$$\text{EQAT} = \frac{\text{total number of equivalent analysers}}{\text{total calculated number of analyser technicians}}$$

Cost per equivalent analyser (CEQA) is a measure of the overall normalised cost of maintaining analysers.

$$\text{CEQA} = \frac{\text{total analyser repair costs in last 12 months}}{\text{average number of equivalent analysers in last 12 months}}$$

Repair costs include all direct costs associated with performing analyser repairs. This includes total labour and material costs. Cost should be reported in both local currency and converted to US dollars.

Manual validations per equivalent analyser (MV/EQA) is a measure of expended effort for key analyser activity.

$$\frac{\text{MV}}{\text{EQA}} = \frac{\text{total number of manual validations in last 12 months}}{\text{average number of equivalent analysers in last 12 months}}$$

Total number of validations includes scheduled as well as unplanned validations carried out.

% Scheduled manual validations compared to total number of manual validations performed is a measure of key analyser activity planning effectiveness.

$$\frac{\text{sch. V}}{\text{tot. V}} = \frac{\text{total number of scheduled manual validations}}{\text{total number of manual validations performed}} \times 100$$

6.4.2 Additional analyser performance indicators

Mean time between repairs (MTBR) is a measure of reliability, preventative maintenance (PM) effectiveness and work activity level.

$$\text{MTBR (months)} = \frac{\text{total number of equivalent analysers} \times 12}{\text{total number of repairs in last 12 months}}$$

Mean time between failures (MTBF) is a measure of effectiveness of the preventative maintenance (PM) programme.

$$\text{MTBF (months)} = \frac{\text{total number of equivalent analysers} \times 12}{\text{total number of failure repairs in last 12 months}}$$

A 'failure repair' is defined as any work requiring a disassembly of an analyser system to clean, repair or replace components to make the analyser 'fit for use'. This excludes validations where only a calibration adjustment is required.

Mean time to repair (MTTR) is a measure of maintenance responsiveness and efficiency.

$$\text{MTTR (months} = \frac{\text{total hours spent on failure repairs in last 12 months}}{\text{total number of failure repairs in last 12 months}}$$

% Scheduled work compared to total work is a measure of PM effectiveness.

$$\%\ \text{scheduled work} = \frac{\text{total hours of scheduled interventions in last 12 months}}{\text{total number of all interventions in last 12 months}} \times 100$$

An 'intervention' is a repair, a successful or unsuccessful validation or PM action where no repair was made.

% Validations in control compared to total number of validations is a measure of effectiveness of the frequency of validations.

$$\%\ \text{validations within control limits} = \frac{\text{total number of successful validations in the last 12 months}}{\text{total number of all validations within the last 12 months}} \times 100$$

% Scheduled work completed on-time. Compared to total scheduled work, this is a measure of effectiveness of completing the PM program

$$\%\ \text{scheduled work completed on time} = \frac{\text{total number of planned preventative maintenance actions completed on time in the last 12 months}}{\text{total number of planned preventative maintenance actions in the last 12 months}}$$

% Root cause indicator is a measure of 'bad actors' and identifies areas for improvement.

$$\%\ \text{root cause indicators for each category} = \frac{\text{total number of repairs attributed to specific root cause category in the last 12 months}}{\text{total number of repairs in the last 12 months}} \times 100$$

The specific root cause categories are defined as follows:

- process utilities;
- lack of or incorrect maintenance;
- design fault;
- manufacturing fault;
- acceptable/expected wear;
- unknown.

6.4.3 Points to consider in measurement of analyser availability

6.4.3.1 General

The analyser availability value is derived from the following:

- analyser uptime;
- plant uptime.

6.4.3.2 Analyser uptime

Analyser uptime is measured as the period of time the analyser is operating on a plant sample within the accepted limits of uncertainty of measurement. This time needs to be measured only during the periods the plant is running.

Routine calibration checks of the analyser (planned maintenance) or automatic validations which take the analyser off line all contribute to reduction in analyser uptime as this is in effect putting benefit at risk, i.e. the control system may drift away from the optimum during the period the analyser is not giving real time information to the control system.

In the case where the analyser fails a routine calibration check, the problem of knowing exactly when the failure (i.e. accuracy going out of limits) occurred is difficult. In the absence of methods to back track via other process parameters, which could be used to indicate the onset of the analyser result going outside acceptable limits, then the reduction of uptime should be taken from the beginning of the last successful calibration check.

The issue of calibration failure and delegation of downtime associated with this failure is not unique. Obviously taking the full calibration interval as downtime is likely to overestimate downtime and reflect badly and unfairly on performance. The calibration interval approach can be improved slightly by taking half the period which will reflect statistically the average effect (assuming a normal distribution of calibration drift). These methods are very sensitive to calibration interval and when deciding on calibration frequency the risk of a large reduction in measured availability needs to be balanced against loss in availability due to the calibrations themselves. The best solution, however, is to try to pin-point the actual time the analyser goes out of calibration as near as possible. This can be achieved via control charting techniques, which require regular laboratory sample checking and also operator proactive participation in observing process trends vis-a-vis analyser readings to assess whether analysers become suspect.

Catastrophic failures can easily be identified by operator observation but the more subtle failure mode of slow drift is not so easily detectable. Control charting techniques combined with a simple linear interpretation between the last good calibration result and the confirmed out of calibration result provides a workable solution. An example is shown in Figure 10:

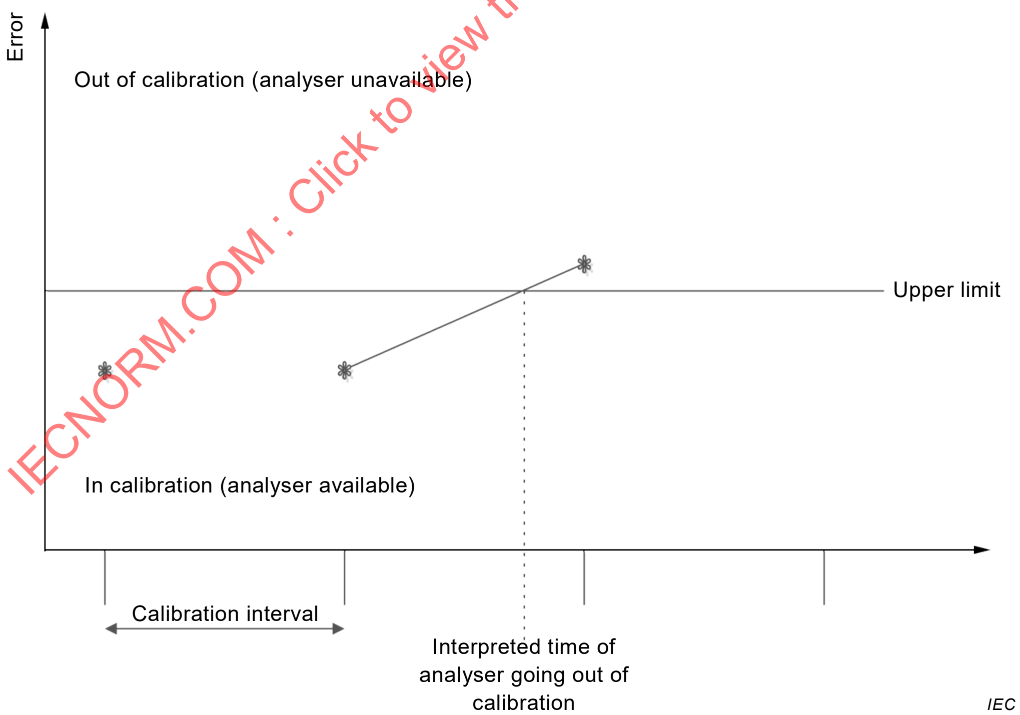


Figure 10 – Example of control charting with linear interpretation

In the case where the analyser fails a validation test, the analyser downtime can be taken as starting from the time of initiation of the validation, i.e. when the operator notices that the analyser performance is suspect and attempts to confirm performance. However, if the analyser passes the validation test then the time the analyser was off line will not count against availability but it will count against utilisation and analyser benefit value.

When the analyser is down for corrective maintenance, the uptime will only start once the analyser has passed the calibration tests and plant sample is restored.

Routine/planned maintenance work (excluding calibration checking) on the analyser for cleaning, component inspection/replacement that requires the analyser is taken off line will affect uptime and the analyser will be deemed down at the start of this work. Uptime will not re-start until the analyser has passed a calibration check and/or plant sample is restored, i.e. the downtime will include calibration checks that verify the analyser is available for plant use if the work may have affected calibration (examples are detector replacement and column changes).

NOTE Not all routine maintenance will necessitate a calibration check. This will depend on the nature of the work, for example filter changes, replacement of system components such as flow meters, pressure gauges.

6.4.3.3 Plant run time

Plant run time (also known as plant up time) is important to record for the calculation of analyser availability as it is only during the running of the plant that benefits are put at risk from the analyser failing. The plant run time can be measured by monitoring plant operating indicators such as product flow or stream flow associated with the particular analyser. Plant downtime can and should be used as an opportunity to carry out analyser maintenance as this will improve availability.

If the analyser is tied into a process information system, which is configured to monitor for operator flags and self-diagnostic flags from the analyser/sample system/validation systems, the above time can be automatically derived with the automatic generation of availability data.

6.4.4 Points to consider in measurement of operator utilisation

Utilisation depends on:

- use made of the analyser measurements to control the plant – open loop schemes;
- the analyser control loop being closed – closed loop schemes;
- manual sampling and analysis requests at normal levels.

The utilisation factor will not reflect analyser maintenance or routine checking times and will be a measure of whether analyser results are actually being used when the analyser is available.

Closed loop schemes should be relatively easy to monitor with indication of control loop status. Open loop schemes are more difficult. These can be monitored by either gaining operator confidence in the on-line analysis and getting prompt initiation of fault flags when the analyser result is suspect (preferred method) or by attempting to correlate plant control adjustments to analyser output or to laboratory sample result reporting and detecting an increase in manual sampling requests.

Other assessments can be made by daily routine contact with plant operators by the analyser groups to discuss problems/status of analysers.

With availability data collection and reporting, there needs to be a method of determining the difference between utilisation and availability data. If an analyser is taken off control or the operator raises a flag that the analyser result is suspect, the time between the suspect fault initiation and verification by the analyser group that there was indeed a problem should be recorded separately and either a) assigned to the availability calculation if a fault is confirmed or b) assigned to the utilisation calculation if the analyser check shows nothing wrong.

If a problem is confirmed then as far as availability is concerned, the analyser downtime will start at the operator initiated flag (or when taken off control) up to restoration of valid measurements. If a problem is not found then the utilisation calculation should use the time from initiation of the flag (or disconnection from control) till accepted by operations by restoration of automatic control and/or cancelling of the operator initiated flag.

6.4.5 Points to consider in measurement of analyser benefit value

The benefit the analyser gives to the process is proportional to the percentage of the demand time (process uptime) the analyser is giving correct process signals and being used for process control. This is simply the product of availability and utilisation measures.

Benefit measures are affected whenever the analyser is offline during process demand. Thus calibrations, validations, routine maintenance, etc., all reduce the benefit value regardless of whether the analyser is proved correct or not.

6.4.6 Deriving availability, utilisation and benefit measurement

Figure 11 below depicts the way that all three measurements of availability, utilisation and benefit can be achieved. The logic applied can be implemented through manual systems but ideally it should be automated via the use of plant DCS systems and plant information systems (e.g. PI).

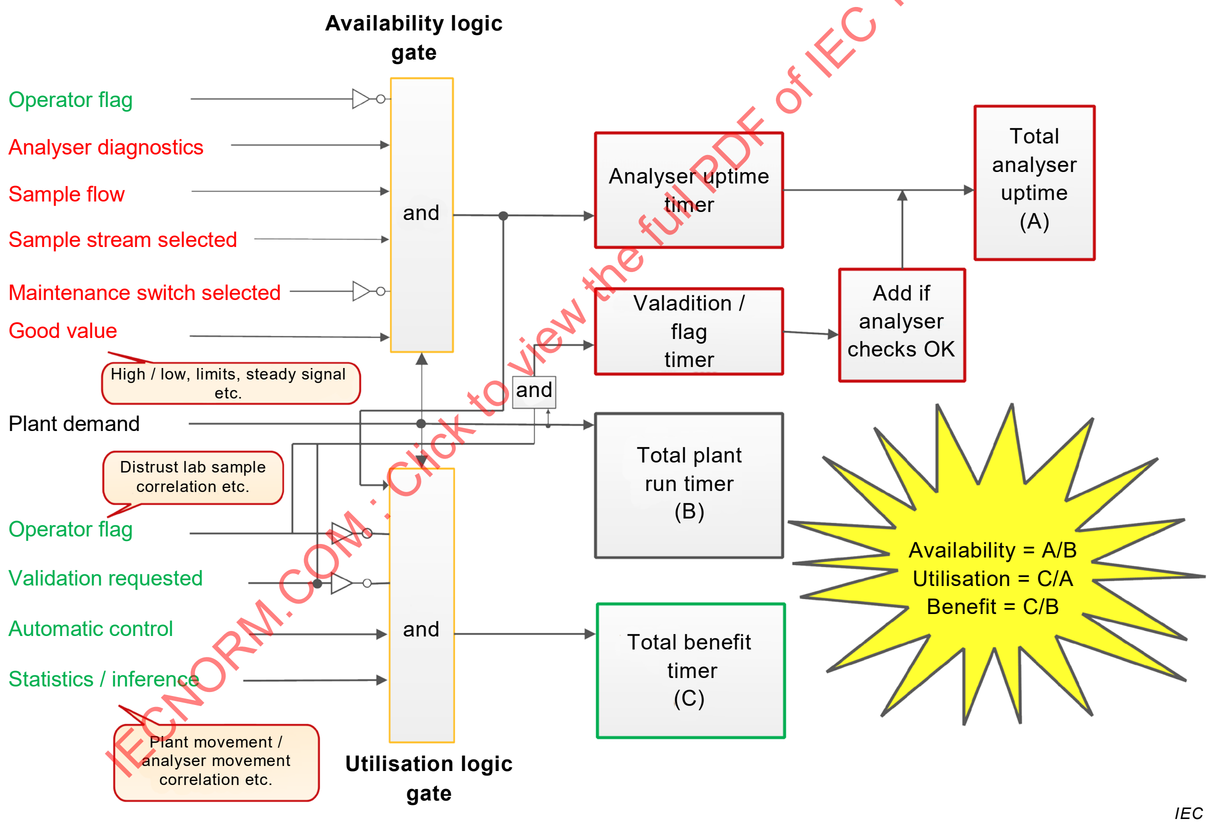


Figure 11 – Deriving availability, utilisation and benefit measurement

The approach is to allocate inputs associated with analyser availability and those which directly affect utilisation. From these, analyser uptime can be measured and by feeding back uptime measurement status output into the utilisation logic the analyser benefit time can be measured.

NOTE The 'operator flag' is fed into both the availability and utilisation gates. 'Validation' is also fed back into the availability gate by way of the sample stream selection status (i.e. it is implicit that a validation will take the analyser stream off line).

This approach simplifies the way in which utilisation/availability issues associated with validation/operator queries on analyser performance are measured.

Measurement of the process uptime (plant demand time) is used with analyser uptime and benefit time values to calculate the three required measurements.

Analyser validations or operator queries on analyser performance are addressed by a separate time function, which depending on the final outcome of the analyser performance query, affects the final availability measure. In the case of an automatic validation, simple logic can be used to detect pass/fail status and update the analyser availability time as appropriate. In the case of the operator flag, provision may be needed to manually update the availability timer as appropriate when resetting the operator initiated flag status. This function should only be effective during process uptime (plant demand time).

6.4.7 Optimising analyser performance targets

6.4.7.1 General

The above measurements serve to indicate the performance being achieved by the analysers but does not address the problem of what is the best target value to aim for. Too high an availability target could result in excessive maintenance effort to achieve the desired result whilst too low a target could result in benefit value being lower than necessary. Analyser benefit indicator target value would demand 100 % in isolation but this is impractical for the following reasons:

- By their very nature of operation and complexity, analysers require regular calibration checks (the best method being by injection of reference samples which take the analyser off line) and they will inevitably break-down from time to time, making process results unavailable till repaired (both these effects can be removed if duplication is considered). Therefore, for non-duplicated analysers, these factors preclude any possibility of 100 % availability and in effect define the maximum possible availability.
- The increase in availability follows the law of diminishing returns. There shall be a point where the incremental cost of increased maintenance effort starts to exceed the incremental benefits to the process that can be achieved.

To optimise analyser performance targets there needs to be a balance between analyser maintenance costs and benefit to the process. Utilisation targets can be 100 % as this is a matter of confidence in the analysers and in theory any downtime of the analyser should be due to genuine faults – this is dependent on good education of operators and demonstration to the operators of analyser reliability. Thus, the two main factors are essentially the analyser availability and the perceived benefit of the analyser measurement to the process control scheme.

Analyser availability relies on good maintenance and in turn this maintenance costs money. In order to try to set realistic targets on performance, it is necessary to have a good method of relating availability to maintenance effort. Such a model is proposed below, which encompasses the basic idea that availability is sensitive to three main factors:

- **Maximum possible availability**. All analysers require a minimum downtime to cover calibrations and inevitable downtime due to breakdown.
- **Overtime cover**. Normal working days only cover a limited time and breakdowns can occur any time with a time penalty if immediate cover is not available.
- **An exponential relationship with maintenance effort**. No maintenance means availability will approach zero. Also, no matter how much effort is applied, availability can only approach a maximum depicted by a minimum off line time (calibrations and breakdowns which all take a finite time irrespective of how many people are available to do the work).

Assessment of maintenance effort needs to define the ideal manning level which, if achieved, would reduce the exponential relationship mentioned above to unity. An equivalent analyser concept can be used as a tool to help in assessing the ideal technician manning level requirements for maintenance. In assessing the ideal manning levels, it shall also be appreciated that not all hours worked reflect the analyser downtime with estimates of around 50 % of technician time accounted for by training, paperwork, etc.

The suggested model is:

$$\text{Percentage availability (A)} = A_{max} \times A_{overtime} \times (1 - e^{-m}) \times 100$$

'A_{max}' is the maximum possible availability based on calibration frequencies and duration, necessary routine/planned maintenance involving the analyser being taken off-line, and mean time between failures (MTBF) and mean working time to repair (MWTR).

'$A_{overtime}$' is the effect of use of overtime for breakdown work on availability. Analyser faults occurring out of normal working hours incur an additional penalty. This is either from having to wait until normal hours for corrective action or, if overtime is agreed for call-outs, additional hours lost in personnel reaching the site. The overtime factor will be affected by analyser mean times between failures (MTBF), mean working times to repair (MWTR), normal cover times, numbers of analysers and numbers of technicians.

'm' is the exponential index which covers the maintenance effort aspect which is essentially related to the effect of under manning, training/experience and overtime for scheduled work.

6.4.7.2 Maximum availability (A_{max})

'A_{max}' depends on the mean time between failures (MTBF), mean working time to repair (MWTR), calibration time (C_t), calibration interval (C_i), routine maintenance time (RM_t) and routine maintenance interval (RM_i):

$$A_{max} = 1 - \left(\left(\frac{365 \times \text{MWTR(hours)}}{\text{MTBF(days)}} \right) + \left(\frac{365 \times C_t\text{(hours)}}{C_i\text{(days)}} \right) + \left(\frac{365 \times RM_t\text{(hours)}}{RM_i\text{(days)}} \right) \right) \times R_A$$

The variable 'R_A' will depend upon which basis the MWTR, MTBF, C, and RM values are derived. If based on actual average values for the group of analysers concerned, then R_A = 1 but if based on values attributed to an equivalent analyser then R_A will be the ratio of equivalent analysers (N_{EQA}) to actual analysers ($N_{analysers}$).

6.4.7.3 Availability breakdown overtime factor ($A_{overtime}$)

The use, or to be exact the non-use, of breakdown overtime can have a significant impact on availability because breakdowns during weekends/nights have to wait till normal working days for attention. With no overtime and considering purely random breakdown scenarios then the proportion of breakdowns out of hours will be:

$$\left(\frac{\text{hours in a year} - \text{normal cover hours}}{\text{hours in a year}} \right) = \left(\frac{8\,760 - 1\,880}{8\,760} \right) = 0{,}785$$

Therefore extra yearly downtime per analyser that can be expected with no overtime worked (allowing for weekends and assuming on average that the breakdown occurs in the middle of each 'out of hours' time) is as follows:

$$\left(\frac{24 - \text{working day} \times \frac{5}{7}}{2} \right) \times \frac{365}{\text{MTFB (days)}} \times 0{,}785 \times R_A \text{ hours per analyser}$$

which equals (assuming an 8 h work day):

$$(9{,}14)\times\frac{365}{\text{MTBF}}\times 0{,}785\times \text{R}_\text{A}\,\text{hours per analyser}$$

Therefore the maximum effect on availability will be the additional down time per analyser as a proportion of the total yearly hours which equals:

$$(9{,}14)\times\frac{365}{\text{MTBF}}\times 0{,}785\times\frac{1}{8\ 760}\times \text{R}_\text{A}$$

To counteract this effect on availability requires use of overtime and the theoretical maximum overtime requirement will be:

$$\frac{365}{\text{MTBF}}\times\text{MWTR}\times(\text{proportion of out of hours breakdowns})\times\text{R}$$

which equals:

$$\frac{365}{\text{MTBF}}\times\text{MWTR}\times 0{,}785\times \text{R}_\text{A}\,\text{hours per week}$$

From the above, and knowing the number of analysers and technicians, the theoretical maximum overtime required can be estimated and depending on what proportion of overtime between zero and the maximum required is employed the effect of overtime on availability can be calculated and related to the overtime factor as follows:

$$\text{therotical maximum overtime per technician} = \frac{365}{\text{MTBF}}\times\text{MWTR}\times 0{,}785\times\frac{N_\text{analysers}}{N_\text{TA}}\times\text{R}_\text{A}$$

where

$N_\text{analysers}$ is the number of analysers;

N_TA is the actual number of technicians employed.

Each technician normal working year is 1 880 h, therefore the proportion of overtime required is:

$$\frac{365}{\text{MTBF}}\times\text{MWTR}\times 0{,}785\times\frac{N_\text{analysers}}{N_\text{TA}}\times\text{R}_\text{A}\times\frac{1}{1\,880}$$

Using these last two equations will enable A_overtime to be calculated from:

$$\text{A}_\text{overtime}=1-\left((3)\times\left(1-\frac{O_\text{A}}{(4)}\right)\right)$$

where

O_A is the actual overtime expressed as a fraction, i.e. % / 100

which for standard times of 1 880 h per year for technicians, a working day of 8 h and hours in a year as 8 760 (365 days) reduces to:

$$\text{A}_\text{overtime}=1-\left(0{,}3\times\frac{\text{R}_\text{A}}{\text{MTBF}}\left(1-\frac{O_\text{A}\times\text{MTBF}\times N_\text{TA}}{0{,}1524\times\text{MWTR}\times N_\text{analysers}\times\text{R}_\text{A}}\right)\right)$$

The variable 'R_A' will depend upon which basis MWTR and MTBF values are derived. If based on actual average values for the group of analysers concerned, then $R_A = 1$ but if based on value attributed to an equivalent analyser, then R_A will be the ratio of equivalent analysers to actual analysers.

6.4.7.4 The exponential index '*m*'

The exponential index is derived as follows:

$$m = \frac{N_{TI}}{N_{TI} - (N_{TA} \times \text{skill factor} \times \text{overtime factor}} - 1$$

where

N_{TI} is the ideal number of technicians required;

N_{TA} is the actual number of technicians employed.

This equation represents the degree of under manning expressed in a way to produce a number of between zero and infinity for '*m*' for manning levels varying from 100 % to 0 % of the ideal. This means a range of 0 to 1 for e^{-m}. For manning levels that exceed 100 % of the ideal, the value of 'm' is limited to zero (negative values are not allowed). Note that with this algorithm, significant effect on availability only starts when manning drops to below 90 % of the ideal which is not unreasonable as the ideal number would be expected to cope with such short falls of up to 10 % (e.g. leave cover) in the short term. However this is not an indicator that manning level reduction to 90 % of the ideal can be justified as a long term measure because in this case leave and sickness is putting availability at much higher risk (e.g. a further 5 % reduction in manning (to 85 % ideal) will have an effect of 0,3 % and 10 % reduction (to 80 % ideal) an effect of 1,8 %).

The 'skill factor' is an indicator of training/expertise of the technicians and ranges from 0 to 1. For a work force that is well trained and who all have at least three years' experience, the number 1 is applicable. The number will reduce proportionally to a level of experience and to numbers of technicians with less experience.

The 'overtime factor' is an adjustment for overtime used to improve maintenance effort over and above that allowed for out of hours breakdowns, i.e. that overtime which is allocated for general maintenance such as increasing cover at weekends where scheduled work (calibrations, routine maintenance, etc.) is performed. This boosts the effective manning level and is entered into the equation as a factor greater than unity, for example 20 % overtime gives a factor of 1,2.

6.4.7.5 Ideal number of technicians (N_{TI})

In order to derive the ideal number of technicians required the procedure is simplified if the concept of equivalent analysers is used.

The 'number of equivalent analysers' is based on analysis of all the site analyser installations. Its derivation is covered in detail in 5.5.2.

In summary, this method looks at individual parts of the installation (analyser, application, sample system, signal interfacing, numbers of outputs) and allocates numbers ranging from 0,1 to 2 (depending on the part) which are then added together to arrive at a value for each installation. The total points are then added up for the site and then this total is adjusted for additional aspects of maintenance work (project work, commissioning, remedial work, etc.). Corrections can be positive or negative depending on whether the additional aspects are supplied by the analyser maintenance group or the support is supplied by a third party. The points are related to a standard analyser equalling 1 and the number of these analysers which can be maintained by a single technician.

The number of equivalent analysers (N_{EQA}) requires a number of analyser technician hours per year to maintain. From this can be derived the ideal number of technicians required (N_{TI}).

6.4.8 Analyser maintenance cost against benefit

Having derived a formula for relating availability to maintenance effort, the effects of cost of manning levels against the benefit derived from achieving analyser availability targets can be looked at.

Overall cost of maintenance, whilst obviously of importance, is not an issue in optimising availability. Costs such as spares, fixed overheads, have no impact on availability and the cost of achieving desired changes in availability. It is the relationship between the cost of increasing or decreasing present levels of availability through manning level adjustments or overtime adjustments against improvements in benefit that is of relevance in optimising availability.

Knowing man-hour rates, overtime rates, and the benefit the analyser gives to the process in monetary terms, a spread sheet can be constructed to compare incremental cost to incremental benefit and to look for the optimum availability. Ideal manning levels or increased overtime may not necessarily be the most cost effective solutions depending on the incremental benefit derived and the best solution may be to set lower availability targets.

The above equations can be applied in the cost benefit analysis to look at single analysers, specific groups of analysers or the total analysers on site as long as the relevant data on benefits, MTBFs and MWTRs used are specific to the groups considered. For groups of analysers, the use of simple average values is envisaged. If analysers are reduced to equivalent analysers, care should be taken to use the MTBF and MWTR for the equivalent analyser along with the ratio of numbers of equivalent analysers to actual analyser numbers.

Annex E shows an example derived from using the equations developed in 6.4.7 with typical average analyser maintenance data and typical refinery analyser overall benefit to operations of 12 cents in the barrel. The effect of overtime for breakdown maintenance is shown along with comment on use of general overtime to make up for under-manning. It can be seen that overtime for breakdown maintenance, whilst improving analyser availability, is not necessarily cost-effective if applied to all analysers. Only on high benefit analysers will the overtime curves start to increase benefit – the break point will be dependent on labour costs and contribution of value by the analyser to the process.

6.5 Analyser performance reporting

A key element in gaining management awareness and operator acceptance of analysers is in the way analyser performance and benefit data is fed back by formal reporting.

Reporting should emphasise the positive aspects of analyser performance and value to the plant operation and profitability. Negative aspects such as benefit lost due to downtime or cost of analyser failure give strong messages that change needs to be made in maintenance.

Monthly uptime calculations can be quickly collated for an area or group of analysers if the analyser log includes plant downtime. Once collated and presented as a table with possibly a bar chart above it (see Annex F for an example) this can be distributed accordingly to operators and technicians. Seeing actual values locally in this fashion allows the values to be challenged/verified and can help address any dissatisfaction with the yearly results when collated. Operations are often surprised initially at the relatively high uptime values that occur from apparently 'troublesome installations' and this may help avoid un-called for dissent.

Local distribution also highlights problem areas to the technicians that allow proactive strategies to be focused earlier in the year rather than as a result of a year-end review.

An example of a way to present uptime data to an annual, or similar periodic, review meeting is to compile the monthly information into a matrix (see Annex F for an example). The matrix offers an excellent overview of the year's performance for the complete range of analysers on a designated area.

If months of high uptime are left blank (typically > 99 %) it is easy to highlight key areas of concern and effort to higher management.

The matrix is especially effective if presented with the monthly data in the document so as to allow the highlighted problem areas to be referenced or 'drilled down to' for a more complete and detailed picture of the problem.

The matrix allows further data to be ascertained from it by calculating average monthly uptimes for groups or individual analysers and when allied to the number of monthly breakdowns, shift calls, call-outs, etc. (see Annex F for an example) a complete overview is possible.

When previous years' data is available, the trends offer an insight into the general analyser management performance, i.e. becoming better or worse.

If analyser effectiveness data is available as a result then this completes the contribution of the analysers and may show areas for improvement or encourage further investment in problem areas based on fact.

Conversely, as market situations change, opportunities for mothballing or removing non-effective analysers may be highlighted, offering the chance to focus resources elsewhere.

Annex A
(informative)

Equivalent analyser per technician (EQAT)

A.1 Part 1 – Calculated technician number worksheet

Manufacturing site/business unit: ______________________________ Date: ____________

		Number of technicians	Comments
1)	Dedicated to analysers (permanent employees)	______	
2)	Part-time on analysers[3] (permanent employees)	______	
3)	Technicians on contract	______	
4)	Vendor maintenance contracts[4]	______	
5)	Multi-craft effort[5] (permanent employees)	______	
	Total calculated technician number	______	

NOTE

1) Use decimal fractions to indicate part-time involvement i.e. 0,5 for 6 months, 0,25 for 3 months. Do not discount vacations.

2) Report all staff involved in maintenance/validation functions on permanently installed equipment which will be included in the equivalent analyser list. This does not include laboratory analysers, portable monitors and personal safety monitors.

3) Report here maintenance personnel who do analyser work but are not dedicated to analysers.

4) Report here any effort from ongoing contracted vendor maintenance and repair services. Note the vendor name(s) in the comment field.

5) Report here non maintenance personnel who carry out analyser work (scheduled validations, etc.) and note the type of work in the comments field.

A.2 Part 2 – Equivalent analyser inventory worksheet calculation methodology

Manufacturing site/business unit: ______________________________ Date: ____________

Instructions

The equivalent analyser (EQA) inventory worksheet should include all permanently installed analysers. The EQA worksheet should not include portable analysers, personal safety monitors, flame scanners, corrosion probes and laboratory analysers. If analyser technicians are responsible for work carried out on equipment not included on the work sheet then their effort to maintain this equipment should be discounted from the total number of analyser technicians' calculation (refer to Part 1). The site individual analyser tag listing sheets attached to this document can be used to facilitate the EQA calculation and completion of the EQA inventory worksheet.

Correction factors

The equivalency factors given in the table in Clause A.3 (refer to Part 3) are for one analyser, one detector, analysing one stream, measuring one component or property.

If a single analyser is being used but has more than one detector, or more than one internal switching valve, or more than one stream or is measuring/predicting more than one component or property then the correction factors listed below should be used to adjust the equivalent analyser number. The total obtained from the correction factor calculations should be added to the basic analysers' equivalency factor listed in the table to obtain the true equivalent analyser number.

1) Sum all additional detectors and multiply by 0,5.
2) Sum all additional, internal switching valves for gas chromatographs and multiply by 0,1.
3) Sum all additional streams and multiply by 0,5.
4) Sum all additional components/properties being measured and multiply by 0,1.

EXAMPLE Three applied automation chromatographs of which one analyses two streams (1 additional), one has two detectors (1 additional) and 3 internal switching valves (2 additional), and together they measure seven components (4 additional):

Equivalent analysers (EQA) = $3 \times 1{,}5 + 1 \times 0{,}5 + 1 \times 0{,}5 + 2 \times 0{,}1 + 4 \times 0{,}1 = 6{,}1$

A.3 Part 3 – Equivalent analyser inventory worksheet

Manufacturing site/business unit: ______________________________ Date: ____________

		A	xBEF	$+C_{det}$	$+C_{SV}$	$+C_S$	$+C_C$	=EQA
Measurement	**Technique and comment**	**No. of operational analysers / maintained equipment**	**Base equivalency factor**	**Correction for additional detectors**	**Correction for additional switching valves**	**Correction for additional streams**	**Correction for additional components**	**Total equivalent analysers (EQA)**
Acid strength			2,5					
Analyser data systems	For each major component excluding analysers		0,1					
Analyser enclosures								
Enclosed walk-in shelter	Forced ventilated and/or air conditioned		2,0					
Weather protection shelter	Includes three sided shelters with utilities		0,3					
Basic analyser cabinet			0,1					
Calorimeter Wobbe index	Catalytic and open flame		1,5					
CEM – DAS/DHS	Standalone		0,5					
CFPP			1,5					
Chromatographs								
Component analysis vapour injection			1,5					
Component analysis liquid injection			2,0					
GC – PTGC (Temperature programmed)			2,5					
GC – Sim dist			2,5					
GC – Sparger			2,5					

			A	xBEF	$+C_{det}$	$+C_{SV}$	$+C_S$	$+C_C$	=EQA
Measurement		**Technique and comment**	**No. of operational analysers / maintained equipment**	**Base equivalency factor**	**Correction for additional detectors**	**Correction for additional switching valves**	**Correction for additional streams**	**Correction for additional components**	**Total equivalent analysers (EQA)**
Cloud point				1,5					
Colour				0,4					
Composite sampler				0,5					
Crude oil sampler				2,0					
Density									
	Nuclear			1,0					
	Vibration			0,5					
Distillation									
	Atmospheric			1,5					
	Vacuum			3,0					
Dissolved oxygen		Hydrocarbon		1,0					
Fire/smoke detectors				0,2					
Flash point				1,5					
Flue gas in situ									
	Oxygen			0,5					
	Combustibles			0,5					
	IR/UV	Cross stack and in-situ		1,0					
	Particulates	Opacity and electro dynamic		0,5					
Freeze point				1,5					
Gas detectors									
	Flammable	Catalytic, solid state and IR		0,1					

Measurement		Technique and comment	A No. of operational analysers / maintained equipment	xBEF Base equivalency factor	$+C_{det}$ Correction for additional detectors	$+C_{SV}$ Correction for additional switching valves	$+C_S$ Correction for additional streams	$+C_C$ Correction for additional components	=EQA Total equivalent analysers (EQA)
	Toxic	Solid state, electrochem and IMS		0,1					
	Open path	Hydrocarbon and toxic		0,3					
	Oxygen deficiency			0,1					
Hydrogen specific sensors				1,0					
IR/Vis/UV spectroscopic									
	Basic IR/UV absorption			1,5					
	Chemiluminescent			1,5					
	Diode array			1,5					
	FTIR/FTNIR			1,5					
	Sulphur plant feed, tail-gas and sulphur pit			2,5					
	Tunable diode laser (TDL)			1,0					
Liquid sample recovery unit				0,5					
Manual sample point (not part of analyser sample system)		Where maintained by analyser group		0,2					
Mass spectrometer				2,0					
Mercury		Atomic fluorescence/ absorption		3,5					
Moisture		Vibrating crystal		1,0					
Moisture probe		Capacitance or solid state		0,5					
Octane									
	Octane engine	If maintained by analyser group		10,0					

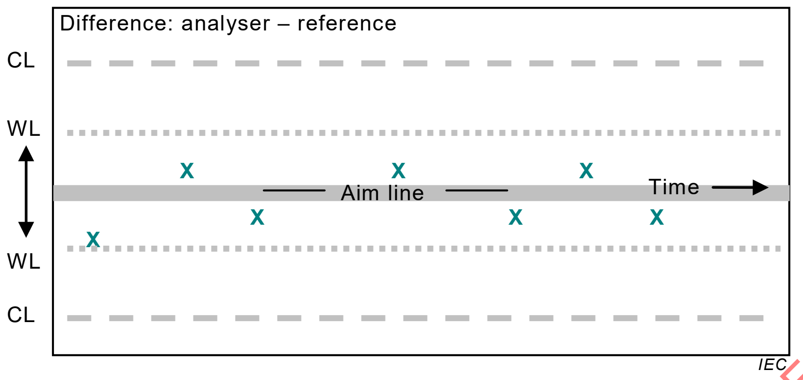
		A	xBEF	$+C_{det}$	$+C_{SV}$	$+C_S$	$+C_C$	=EQA
Measurement	**Technique and comment**	**No. of operational analysers / maintained equipment**	**Base equivalency factor**	**Correction for additional detectors**	**Correction for additional switching valves**	**Correction for additional streams**	**Correction for additional components**	**Total equivalent analysers (EQA)**
Octane engine comparator system			4,0					
Engine protofuel tank system	Only count once per system		4,0					
FTIR/NMR			1,5					
Oxygen (process, extractive)	Paramagnetic, electrochem and fuel cell		1,0					
Paper tape			2,0					
pH (process)			1,0					
Pour point			1,5					
Raman			1,5					
Refractive index			1,0					
Rheometers			3,0					
Rubber moisture			1,0					
Sulphur in liquids	UVF, XRF and X-ray absorption		2,0					
Thermal conductivity			1,0					
Titrators			2,0					
Vapour pressure			1,5					
Viscosity	Capillary, rotational, vibrational and falling object		1,5					
Water quality								
pH			0,5					
Conductivity			0,5					
Dissolved O_2			0,5					

			A	xBEF	$+C_{det}$	$+C_{SV}$	$+C_S$	$+C_C$	=EQA
Measurement		**Technique and comment**	**No. of operational analysers / maintained equipment**	**Base equivalency factor**	**Correction for additional detectors**	**Correction for additional switching valves**	**Correction for additional streams**	**Correction for additional components**	**Total equivalent analysers (EQA)**
	Turbidity			0,5					
	TOC/TOD/COD			2,0					
	Silica/hardness			1,5					
	Specific ion			1,5					
	Oil in water			1,5					
Water in oil				1,5					
					Total number of equivalent analysers				

Annex B
(informative)

Example interpretation of control chart readings

Examples of interpretation of control chart readings are given in Figure B.1, Figure B.2, Figure B.3 and Figure B.4.



This chart pattern is ideal showing **differences distributed above and below the aim line** within the warning limits.

Cause: Successful system

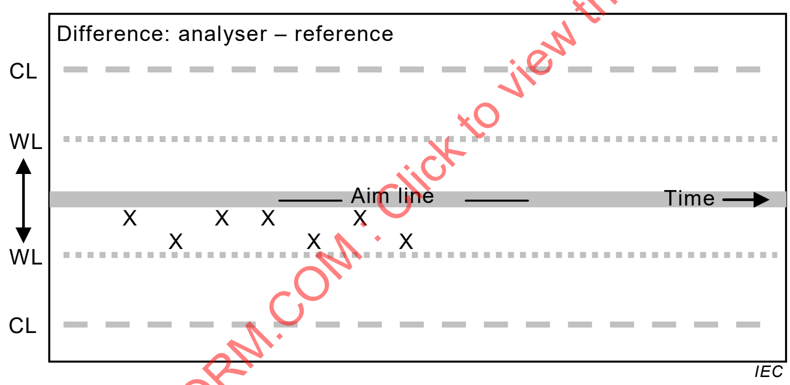
Action: None

Key

CL = control limit

WL = warning limit

Figure B.1 – Example of accurately distributed control chart reading



This chart pattern has **six or more readings on one side between the Warning Limit and the Aim Line**.

Cause: Zero shift/bias indicated

Action: Adjust zero

Key

CL = control limit

WL = warning limit

Figure B.2 – Example of biased control chart reading