Assetivo

Case Studies

Case Study: Asset RAM Study & Weibull Analysis of Repetitive Failures at a Steel Plant

Introduction

This case study aims to demonstrate the practicality and usefulness of reliability engineering analytical tools to solve common industrial maintenance-related issues that can impact on a steelmaking company’s profits and return on investment. It takes a look at reliability performance by means of delays, costs and maintenance records, then a reliability engineering study using fault tree analysis and Weibull techniques to derive operating parameters of the item under study. The failure findings feed into the company’s reliability-centred maintenance (RCM) process for the system and item under study and help determine its maintenance strategy.

Steelmaking

The steelworks is an integrated plant that converts raw materials into coiled, steel strip which is then coated at a sister plant and sold to automotive, construction and packaging sectors. At the steelworks, the principal business units are Coke, Sinter and Iron (CSI), Steel and Slab, Hot-Rolled Products and Cold-Rolled Products. Of interest here is the Steel and Slab business unit where the Basic Oxygen Steelmaking (BOS) plant is located. Steel and Slab and CSI form what is known as the heavy end plants where raw materials are converted into steel slabs before they are transferred to be hot or cold rolled into strip.

BOS is a batch process concerned with refining molten pig iron and ambient scrap steel into the required grade to be cast into slabs at the continuous casting plant. The refining process is carried out in a 350 tonne capacity, barrel-shaped converter vessel in batches called ‘heats’ every 45 minutes or so. It does this by using a water-cooled lance to blow high purity oxygen on to the surface of the hot metal and scrap bath at supersonic velocities. Fluxes such as burnt lime and dolomitic lime are added during the initial stages of the blow to control chemistry and the sulphur and phosphorus capacity of the slag which forms on top of the bath. The oxygen blowing is a combustive process whereby the carbon is removed mostly in the form of carbon monoxide and reduced from 4% to less than 1%; the process also creates significant heat energy to melt the initial scrap charge and raise the temperature of the bath.

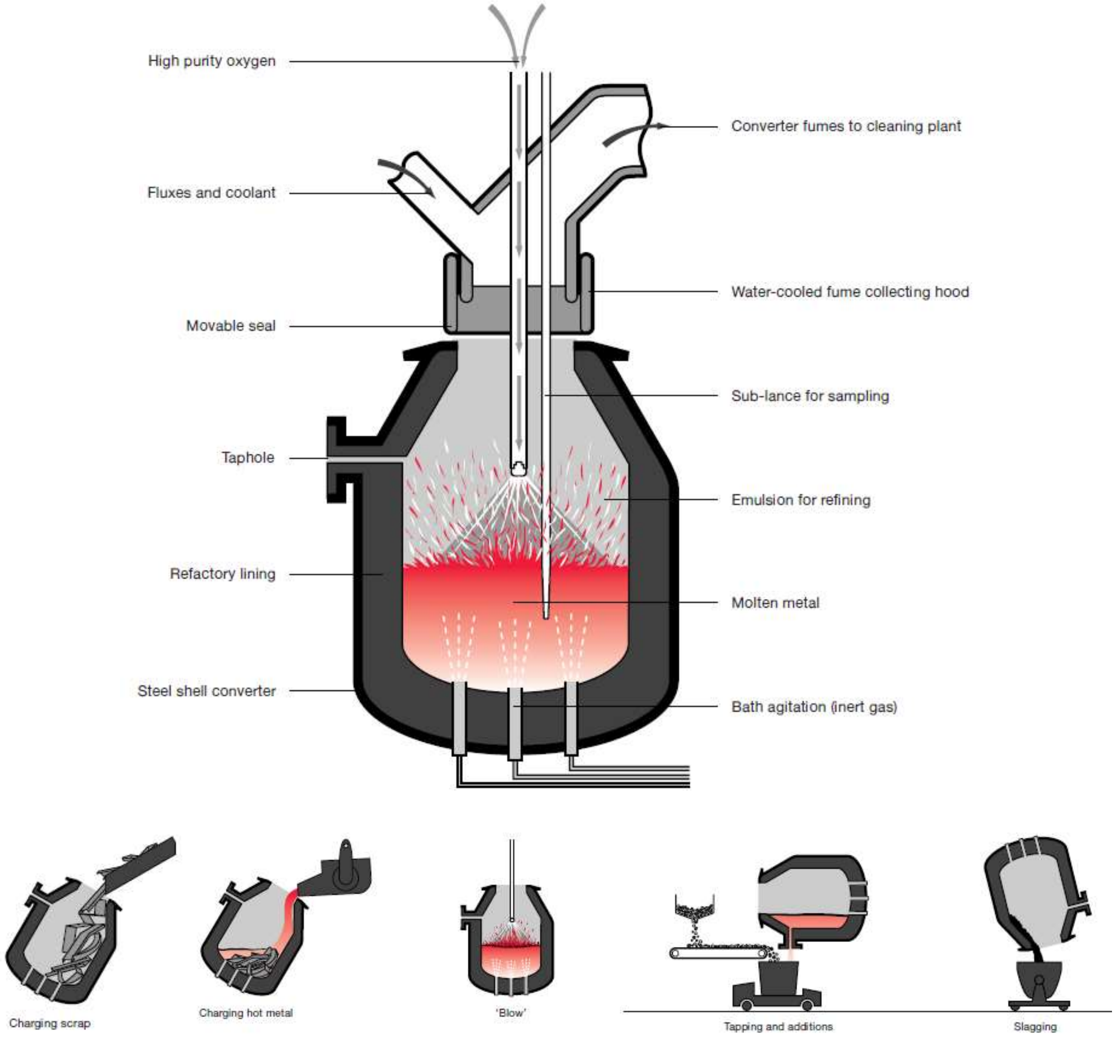
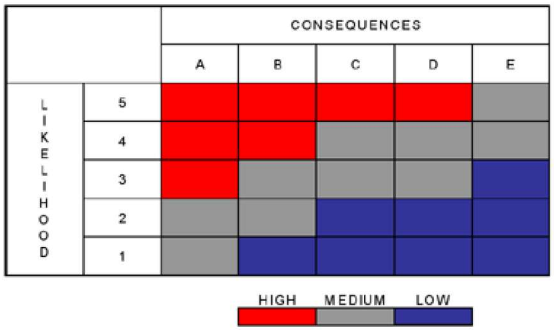


Figure 1: The steelmaking process in a BOS converter vessel

Criticality and Reliability Performance at the Steel Plant

At the time of the case study, the steel plant was in the process of rolling out a streamlined RCM program as part of its asset management framework to derive new maintenance strategies for its critical plant and equipment in terms of safety, environmental hazards, operational risks, quality, and maintenance costs. Criticality is the key to understanding the importance of a plant unit to a business in the event of its failure and the consequences of that failure (Marquez, p.107, 2007), and therefore its prime concern is in managing the risk.



		CONSEQUENCES				
		A	B	C	D	E
LIKELIHOOD	5	🟥	🟥	🟥	🟥	▨
	4	🟥	🟥	▨	▨	▨
	3	🟥	▨	▨	▨	🟦
	2	▨	▨	🟦	🟦	🟦
	1	▨	🟦	🟦	🟦	🟦

HIGH	MEDIUM	LOW
🟥	▨	🟦

Figure 2: A typical criticality matrix.

Figure 3 is an example of the criticality analysis result carried out by plant personnel and the top ten most critical equipment at the steel plant. For this reliability study assignment, it was decided to choose the sub-lance system since several of the other top ten critical plant had already had their RCM projects started or were well under way. The sub-lance system and its related components were also one of the few areas to have some recorded and reliable failure data available due to it having some costly and troublesome events having impacted operations in the previous two years.

Area	Asset Description	Criticality Score
Oxygen Lance	Oxygen Gallery & Supply Lines to Lance Carriages (inc. Control Valves etc.)	42
Cranes	North Casting Crane (North Teeming Crane)	41
Cranes	South Casting Crane (South Teeming Crane)	41
Cranes	63T RD Degasser	41
CAS 2	Oxygen Lance	38
Cranes	North Charger Crane	38
Cranes	South Charger Crane	38
CAS 2	Cooling Water System	37
Sub-lance	Sub-lance Mast & Carriage (inc Hoist)	36
Converter Additions	635 Conveyor	36

Figure 3: Steelmaking plant top ten critical plant list

Reliability of the sub-lance system

The principal reason for installing a sub-lance is as a dynamic process control tool to achieve the specific end blow aims of temperature and carbon. Vortrefflich (2010, p.63) argues that there are also substantial financial savings because of improved productivity, reduced energy and flux consumption and improved quality levels due to more accurate data. These gains are achieved because sub-lances replace manual sampling which involves tilting the converter vessel and interrupting the oxygen blow for an employee to collect a sample at the end of a lengthy rod dipped into the molten bath. Apeldoorn and Gootjes (2006, p.97) claim manual sampling can add 15% to the overall process time for steelmaking if a sub-lance system is not installed.

The sub-lance plays an intermittent – but vital – role in the process. During the twenty minute oxygen blow, the sub-lance will take an in-blow measurement after 90% of the oxygen volume has been blown. This is a Temperature, Sample, Carbon (TSC) measurement using a disposable probe and these data are fed to the BOS process computer to calculate the remaining oxygen to be blown and coolant to be added. The second measurement is taken after all the oxygen has been blown using the Temperature, Sample, Oxygen (TSO) probe and this confirms the end temperature and carbon and bath levels.

The sub-lance system consists of several interrelated mechanical and electrical components which navigate the lance body, replace probes and analyse the samples. The component parts are:

- The slewing platform with winch system to position horizontally the sub-lance body, and raise and lower the lance body into the converter vessel.
- An automatic probe charger to select and attach probes to the sub-lance body, as well as removing and disposing of spent probes. There is also a probe chamber for storage.
- TSC and TSO disposable probes.
- A seal cap which is a water-cooled slide that covers the entry hole to the converter vessel in between sample taking and thereby prevents process off gases from escaping.
- A skull remover to remove solidified slag skulls that adhere to the lance body on withdrawal from the converter vessel.
- Electrical and instrumentation equipment such as the Digital Interpretation and Registration Computer (DIRC) which collects and interprets the probe measurements.

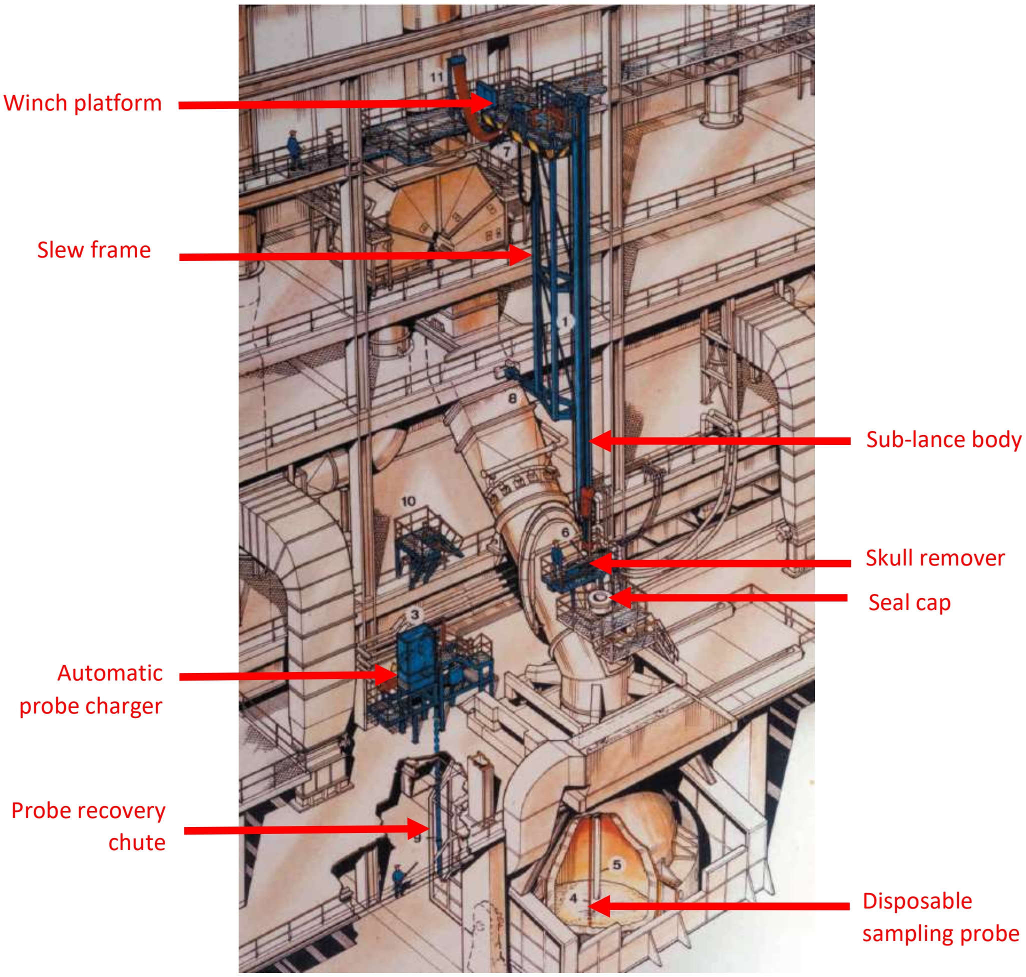


Figure 4 Three-dimensional impression of the sub-lance system

Included in these hardware systems are motors, encoders, gearboxes, valves, cylinders and sensors playing a crucial role in the correct functioning of the sub-lance. Water is used for cooling the sub-lance, and nitrogen for purging purposes and actuating cylinders. Although the sub-lance is used intermittently, its importance cannot be overstated and its reliability needs to be maintained because as Fruehan et al (1998, p.518) point out, the drawbacks of the sub-lance – apart from substantial capital costs – are engineering and maintenance problems and these are rarely mentioned in literature originating from system suppliers (Apeldoorn & Gootjes, Vortrefflich).

Reliability Performance

Reliability is defined by Blischke and Murthy (2003, p.3) as:

> *The reliability of a product (system) is the probability that the item will perform its intended function throughout a specified time period when operated in a normal (or stated) environment.*

This generally-accepted definition conveys the probabilistic and relative nature of the field of study, that is to say, there is never a 100% certainty that an item will perform its function and then fail right on time as per the analysis. This uncertainty pervades reliability engineering and stands it apart from almost all other engineering disciplines as O'Connor (2002, p.2) explains: 'because of the high levels of uncertainty involved these (reliability methods) can seldom be applied with the kind of precision and credibility that engineers are accustomed to when dealing with most other problems'. Despite the contributions of mathematical and statistical methods, he also urges that practical engineering must be the principal tool for determining the causes of problems and arriving at their solutions. There are many subsets of the reliability field of study such as reliability modelling, optimisation, theory, management, test design, and science. The focus of this case study will now be on reliability performance analysis to highlight potential areas for engineering improvement.

RAM: Reliability, availability & maintainability

Reliability, availability and maintainability are three important and intrinsically related quantitative concepts usually employed to guide maintenance decision-making. RAM values are vital for equipment reliability performance measurement and can be used to target areas for long-term reliability improvement and growth. Operational and downtime data can provide typical indicators such as mean time to failure (MTTF), and mean time to repair (MTTR). Table 1 displays sub-lance downtime frequency and duration information which was transferred from the steelmaker's proprietary and legacy operational downtime reporting system.

Table 1: Sub-lance downtime by duration and frequency over a two year period

Reason	Total Delay (minutes)	Frequency (occurrences)
Sub-lance change: leakage	2603	41
Sub-lance change: bent	2344	28
Sub-lance fail to measure: seal cap not open/shut	1870	77
Sub-lance: other	770	36
Sub-lance: DIRC: fault in connection	763	34
Sub-lance fail to connect/disconnect: ring scull	692	78
Sub-lance fail to connect/disconnect: tilt arm	576	47
Sub-lance fail to connect/disconnect: other	497	34
Sub-lance fail to connect/disconnect: tip broken	434	54
Sub-lance fail to connect/disconnect: APC probe transport conveyor	415	52

Reliability

In the RAM sense, reliability is a *quantitative* analysis using known failure data to highlight the average or mean time to failure of a component, item or system. In the case of the sub-lance,

$$MTTF = \frac{Total\ productions\ hours}{No.of\ failures}$$

Where *total production hours* = 8760 (one year) x 2 = 17520 hours.

But there are six monthly, two week shutdowns for re-lining the converter vessels, therefore, two weeks lost production = 24 hours x 14 days = 336 hours, and so *total production hours* = 17520 – 336 = 17184 hours. No. of failures for the sub-lance are the total occurrences for all the failure modes in column 3 of Table 1, i.e. 481 occurrences. Therefore,

$$MTTF = \frac{17184}{481}$$

$$MTTF = 35.7\ hours$$

This value demonstrates that the sub-lance alone as one section of a complex, steelmaking system is likely to fail every 35.7 hours or 1.5 days approximately and consequently stop or slow down production of steel. There is clear room for improvement here to try to increase the sub-lance reliability by growing the MTTF.

Maintainability

This can be defined as the mean time taken to repair a failure for the item under investigation. For a detailed investigation, the number of non-productive hours (downtime) would be broken down in to ‘active’ repair time and ‘waiting’ time. For this case study this data is not available, though it is interesting to note that the ‘waiting’ time can also be targeted to improve MTTR in more in-depth studies by studying spares holding, resourcing, permitting arrangements and tool placements, etc.

$$MTTR = \frac{No. of\ non - productive\ hours}{No. of\ failures}$$

Where *non-productive hours* is overall downtime, i.e. the addition of all the durations in column 2 of Table 1, i.e. 10964 minutes or 182.7 hours.

Therefore,

$$MTTR = \frac{182.7}{481}$$

$$MTTR = 0.38\ hours\ or\ 22.8\ minutes$$

This MTTR of 22.8 minutes for the sub-lance shows that when this item fails during production it means significant financial losses. The cost of lost steelmaking production (£4200 p/hour) for an average sub-lance failure is (0.38 x 4200) = £1596.

Availability

This is usually defined as the long term average ratio that the item under study is available and capable for use, and the indicator is heavily influenced by the reliability and maintainability of the item:

$$Availability = \frac{MTTF}{MTTF + MTTR}$$

$$Availability = \frac{35.7}{35.7 + 0.38}$$

$$Availability = 0.989 \; or \; 98.9\%$$

The availability of 98.9% can be considered high over the long term, but it must be stressed that the sub-lance is one small section of a complex, interrelated electro-mechanical steelmaking system where all the other components have individual reliabilities and it is understood that there are few - if any – active parallel (redundancy) paths in place. In this sense, the entire system (considered as a series reliability) will always be less than 98.9% availability (Lusser's Rule).

Sub-lance delay analysis

Delay analysis was achieved by investigating the company's proprietary delay reporting system as seen in Table 2. It was decided to investigate a two-year period to coincide with the fact that the enterprise resource planning (ERP) system had been active for two years and therefore costs data were researched for that period. Also, impacting upon the steel plant's vessels' reliability, sub-lance 'bursts' caused lost production costs of £4200 per hour as previously mentioned. There had been an unusual number in recent times with eight recorded 'bursts' over two years. The eight bursts had totalled a production stoppage of 360 minutes at a cost of £25200 to date; the exact details of how downtime is calculated are unknown and it is possible that in real terms it may be much higher if all secondary effects are added in (wasted energy, lost product, overtime, extra spares usage, slowdown effect on previous and subsequent process operations, etc.). The sub-lance 'bursts' can be seen in Table 1 and 2 as part of the 'sub-lance leakage' fault, and, although the 'bursts' only account for 13.8% of the leakage downtime, they were chosen due to the high secondary costs associated with sub-lance replacement/repair and the potential safety risks and consequences of having water temporarily pumped into molten steel in the converter vessels.

Table 2: Sub-lance delays by downtime over a two year period

Fault	Code	Cumulative % of systems	Downtime (mins)	% of total downtime	Cumulative % of downtime
Sublance change: leakage	A	10	2603	23.7	23.7
Sub-lance change: bent	B	20	2344	21.4	45.1
Sub-lance fail to measure: seal cap not open/shut	C	30	1870	17	62.1
Sub-lance: other	D	40	770	7	69.1
Sub-lance: DIRC: fault in connection	E	50	763	6.9	76
Sub-lance fail to connect/disconnect: ring scull	F	60	692	6.3	82.3
Sub-lance fail to connect/disconnect: tilt arm	G	70	576	5.2	87.5
Sub-lance fail to connect/disconnect: other	H	80	497	4.5	92
Sub-lance fail to connect/disconnect: tip broken	I	90	434	4	96
Sub-lance fail to connect/disconnect: APC probe transport conveyor	J	100	415	3.9	99.9
		Total downtime (mins)	10964		

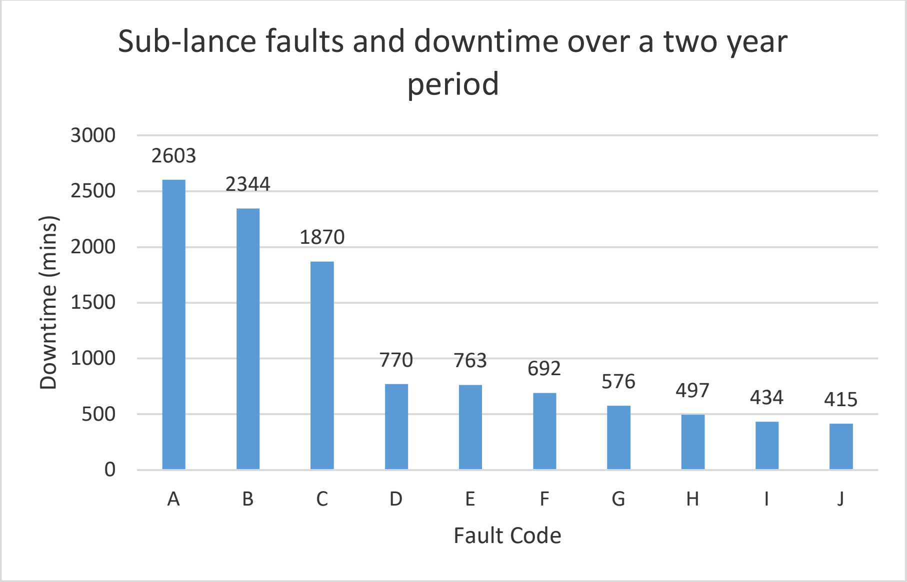


Figure 5: A histogram of the top 10 sub-lance faults by type and duration: two year period

Figures 5 and 6 are a simple decision analysis representation of the reliability issues of the sub-lance. Firstly, a histogram highlights how the sub-lance leakages are the leading cause or failure mode of sub-lance downtime at 2603 minutes (43 hours) over a two year period. Secondly, the Pareto chart shows the cumulative contribution of the sub-lance failure modes to overall downtime, although it does not closely represent the 80/20 Pareto principle. In this instance, it closer represented that 80% of the downtime was caused by 55% of the failure modes.

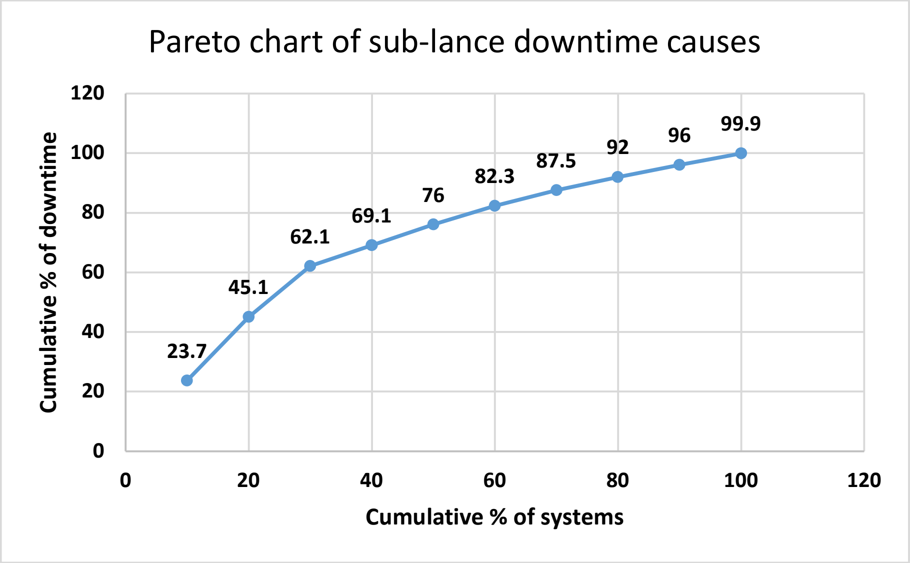


Figure 6: Pareto chart of sub-lance downtime causes

Maintenance records and costs

For this assignment, maintenance records from the ERP system had been studied over a two year period. Over this period the cost of maintenance labour details in Table 3 were recorded for reactive maintenance. Please note that the cost of spares are incorporated into the financial figures in Table 3, but, due to basic access level to the ERP system, specific lists of the spares used could not be accessed at this time.

Table 3: Sub-lance reactive maintenance instances, hours & costs over two years

Equipment	Reactive Maintenance Instances	Maintenance resource hours	Cost of reactive maintenance resource hours and spares (£)
Converter 1 Sub-lance System	379	745.1	24,776.77
Converter 2 Sub-lance System	438	906.8	31,701.66
Totals	**817**	**1642.1 hours**	**£56,478.43**

The data in Table 3 demonstrates that on each sub-lance there is an average annual maintenance resource spend of approximately £14,000 from reactive maintenance and a downtime of 200 hours. For one converter alone, and over a year, the data suggests that it will be out of operation for reactive maintenance for 2.3 % of all available operating time. However, this unavailability of 2.3% or availability of 97.7% is somewhat different to the 98.9 % calculated earlier. This suggests discrepancies between the ERP feedback and the proprietary reporting system. Further, Figure 7 is a comparison between the costs of reactive maintenance and the occurrences at each functional location. Unfortunately, the most noteworthy point here is that most reactive maintenance data are logged under the ‘sub-lance’ functional location and therefore unhelpful in defining specific items of high cost plant. This point alone is a clear indicator of a poor practice in ERP usage as suggested earlier and highlights a clear performance gap in failure and fault recording.

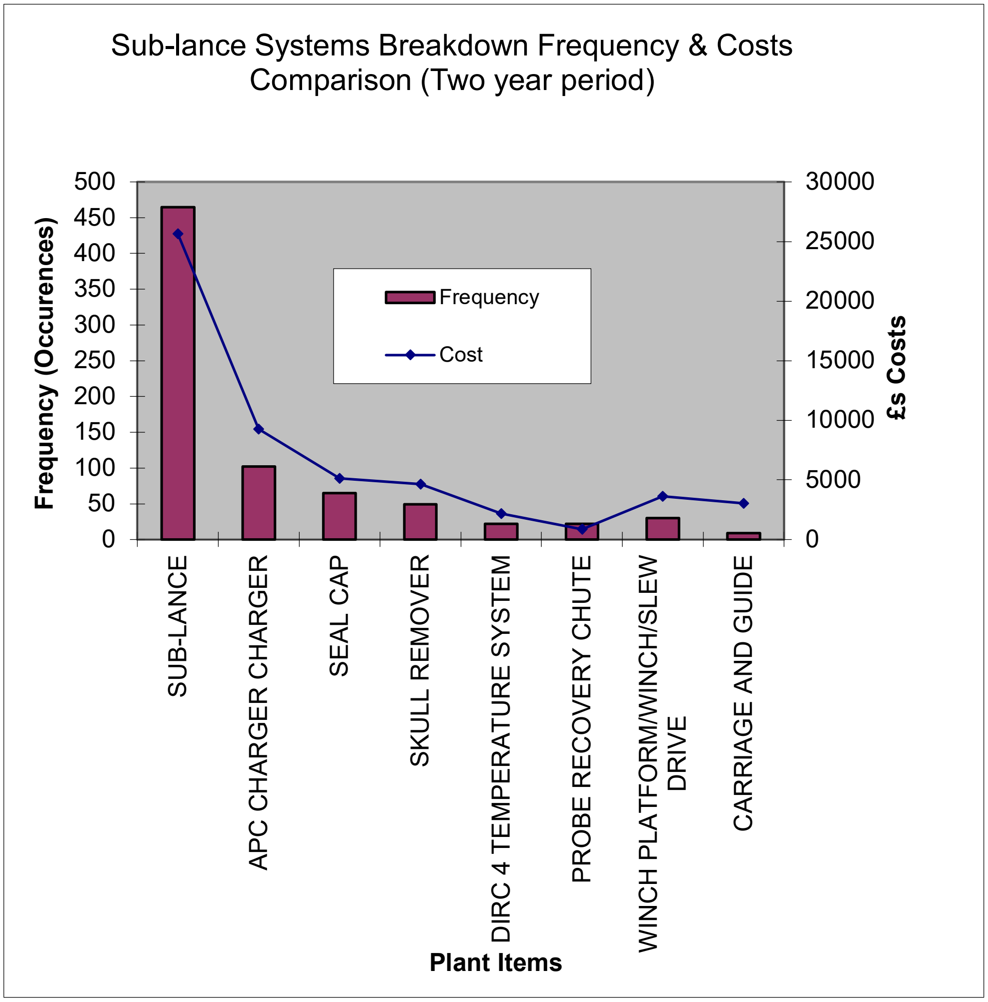


Figure 7: Sub-lance systems breakdown frequency & costs

It must be noted that anecdotal evidence suggests that there is some distrust in the accuracy of the maintenance reporting data in the ERP system due to perceived discrepancies in inputs, *viz*., the number of craftspeople on specific jobs, hours spent on specific jobs, quantity and accuracy of spares used, etc. This is backed up by investigating ERP work 'confirmations' which show a poor or non-existent level of communication with regards to feeding back information from reactive maintenance work. The steel company is currently addressing this pressing issue by way of widespread re-training in the use of basic ERP functions for maintenance personnel.

Given the serious and costly nature of the sub-lance 'bursts', these were then put through a more in-depth engineering analysis which forms the basis of the following sections.

Reliability Analysis - Sub-lance copper section failures

The following images in Figures 8 and 9 are a sample post-failure images taken at the steel plant workshop of the failed copper sections of the sub-lances. Molten steel from the converter vessel has adhered to the copper section and there has been a longitudinal rupture of the water-cooled tubular wall thickness. It is unknown whether the metal adhered to the copper section as a result of the 'burst' or as a potential cause of it.

Figure 8

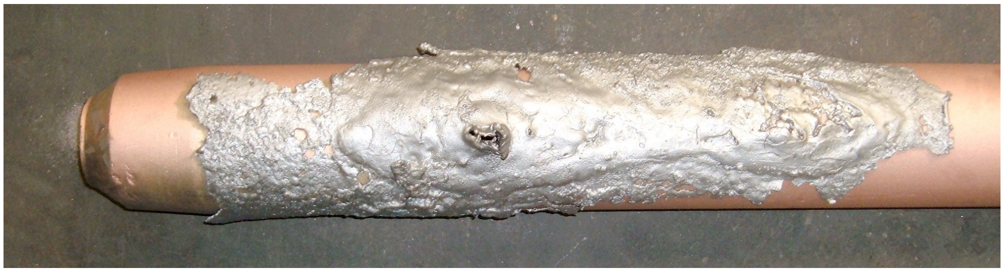


Figure 9

Fault Tree Analysis

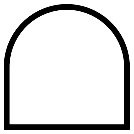
> *Fault Tree Analysis (FTA) is a deductive method in which a hazardous end result is postulated and the possible events, faults, and occurrences which might lead to that end event are determined. Fault Tree Analysis is a "top–down" analysis that is basically deductive in nature. This (top) event is the undesired event or ultimate disaster. From there, the analyst endeavours to find the immediate events that can, in some logical combination, cause the top event.* (Geitner & Bloch, 2006, p.156)

This succinct description of FTA demonstrates it simplicity and usefulness in reliability engineering analysis as a qualitative tool that is ideal at stimulating logical thought processes. It is not a perfect method, however, as the same authors warn that, 'the major drawback of the fault tree is that there is no way to ensure that all causes have been evaluated consistently', that is to say, mistakes and omissions can be made due to the sometimes subjective interpretation of those involved in the analysis. The following in Figure 10 is a fault tree analysis derived for a sub-lance copper section 'burst' which aims to derive the possible combination of events that can lead to a 'burst'.

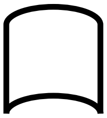
Fault Tree Symbols Key:

= Top Event (the undesired event under study)

= Fault Event (typical malfunction caused by basic fault events)



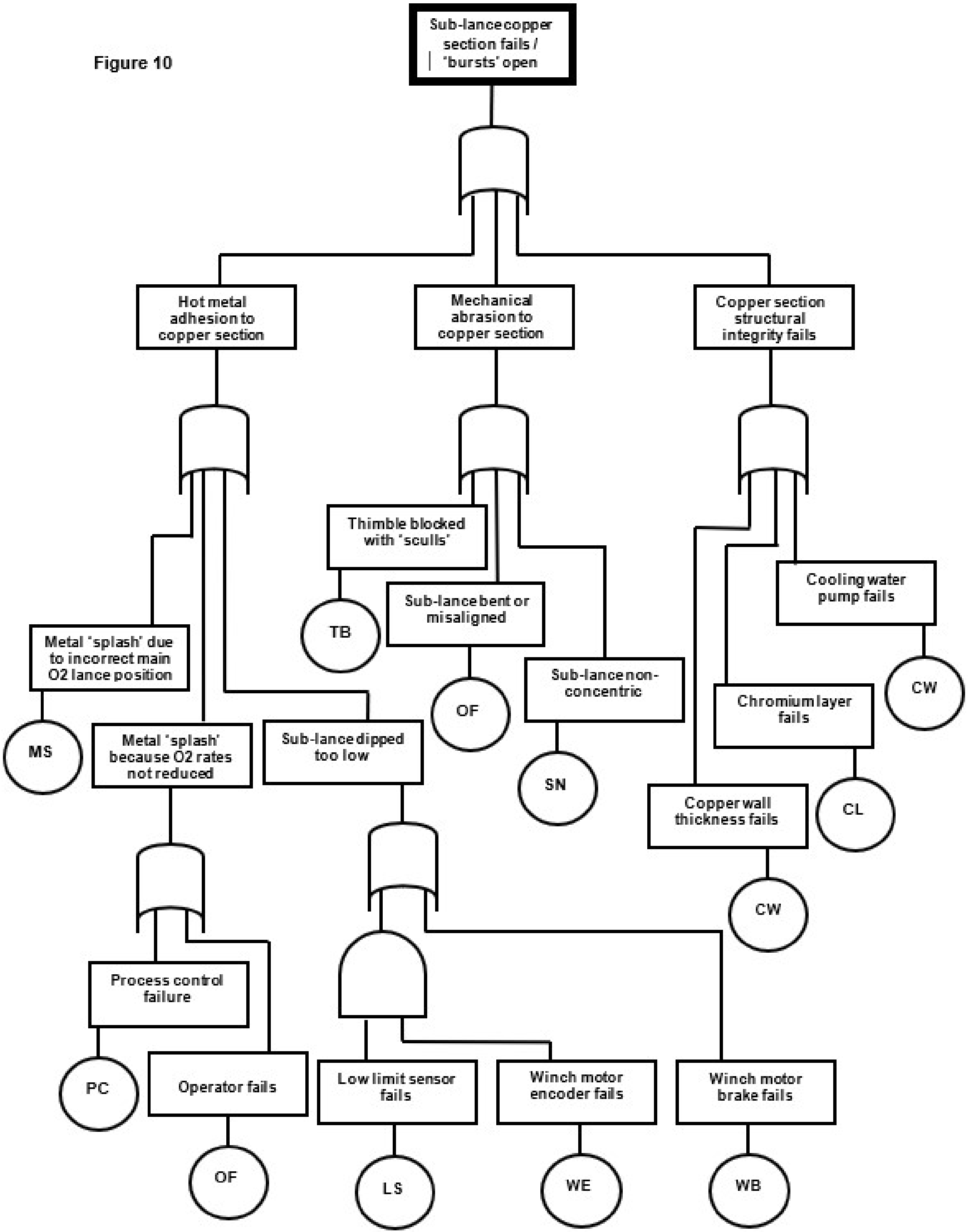
= AND Gate



= OR Gate

○ = Basic Fault Event (component failure, etc.)

Figure 10



From the FTA there is a clear lack of AND gates present and this signifies that there is little redundancy in the system to stop a sub-lance 'burst', that is to say, it will be difficult to stop this occurrence if any of the basic events in the FTA are present. The basic events can be divided into component failures and simple human error and this at least gives the steelmaking company a good idea of areas to target for a reliability improvement of the sub-lance copper section.

Weibull Analysis of a small and incomplete sample of data

For failure investigations and reliability engineering studies, Weibull analysis is an extremely useful diagnostic tool which can be performed on known failure data – large or small. Abernethy (p. 1-3, 2010) concurs that, 'the primary advantage of Weibull analysis is the ability to provide reasonably accurate failure analysis and failure forecasts with extremely small samples', which it is argued is the case here with only eight recorded sub-lance 'burst' failures. The Weibull analysis gives the user a probability distribution function (pdf) which can be translated into an approximation of the failure distribution of the items under study. By failure distribution, it is meant running-in, random or wear out, i.e. something best visually represented by the hazard function Z(t) for a particular failure mode. There are typically three defining parameters to be determined by a Weibull analysis:

Guaranteed Life t0: the time that has passed before items start to fail – most relevant for random and wear out failures. Not applicable to running-in failures, i.e. where t0 = 0.

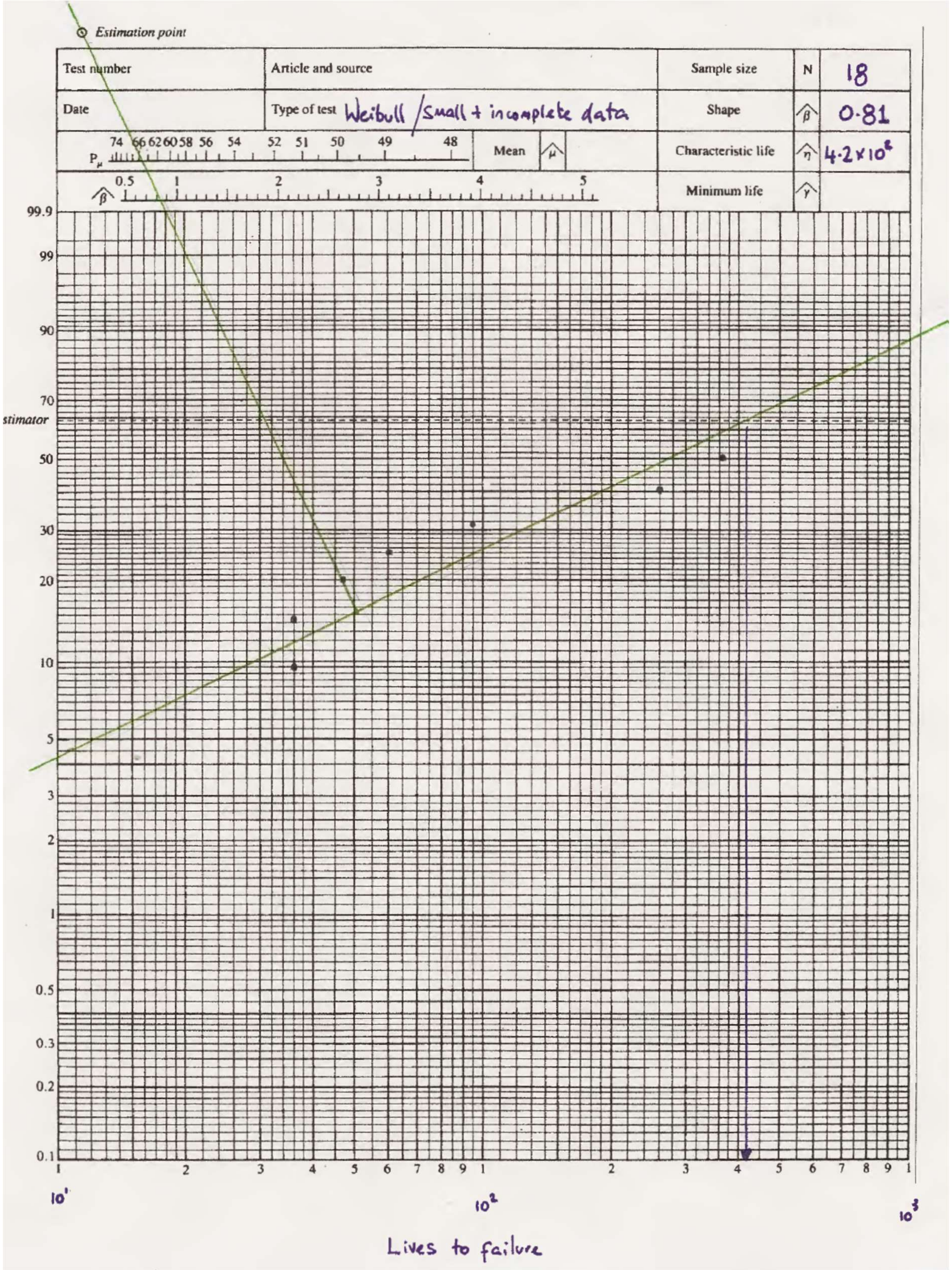
Characteristic Life η: this is the time period after the guaranteed life (t0) at which it is expected that 63% of all items under study will have failed, or 37% will still be operating successfully.

Shape Factor β: essentially this is the slope of the line which determines the typical failure distribution of the items under study. When β is significantly less than one, the pdf is representative of a running-in failure; when β = 1 the pdf then is typical of random failure; when β increases above 2, the pdf then represents a wear-out failure.

The following is a small and incomplete set of data concerning eight sub-lance 'burst' failures and ten 'suspended' sub-lances over a period of two years. The number of lives are recorded and are equivalent to the mean time to failure. One life is one submersion of the disposable (sample taking) section into the steel bath melt. The Weibull technique used is the median ranks method which is most useful when the dataset consists of totally failed items and other items which did not fail in service, i.e. they were either withdrawn for an unrelated reason to the failure mode under study or were still running at the end of the measurement period – and these are both known as 'suspended' items. In the case of all 'suspended' items here, access to data was permitted which detailed each of ten sub-lance's least and most lives and therefore the mean value was taken for each one as a typical, average life.

Table 4: Weibull analysis data using the Median Ranks Method

Sublance No.	No. of lives at point of failure	Suspended of failed s/f	New Increment	Order Number	Median Rank
6	2	f	1	1	0.038
5	36	f	1	2	0.092
2	36	f	1	3	0.147
5	47	f	1	4	0.2
7	62	f	1	5	0.256
9	95	f	1	6	0.31
9*	140	s	-	-	-
4*	181	s	-	-	-
5*	217	s	-	-	-
1*	248	s	-	-	-
4	263	f	1.44	7.44	0.39
2*	325	s	-	-	-
1	367	f	1.71	9.15	0.48
10*	377	s	-	-	-
3*	391	s	-	-	-
6*	614	s	-	-	-
7*	872	s	-	-	-
8*	1459	s	-	-	-



Test number	Article and source	Sample size	N	18
Date	Type of test Weibull /small + incomplete data	Shape	$\hat{\beta}$	0·81
		Characteristic life	$\hat{\eta}$	$4{\cdot}2 \times 10^2$
		Minimum life	$\hat{\gamma}$	

Figure 10: The two parameter Weibull pdf for the sub-lance 'burst' failure data

In the Weibull analysis performed, the following assumptions were made: all failure modes were of the same type; guaranteed life t0 = 0, and failed units had totally failed, and not partially failed. This two parameter (η and ß) Weibull analysis provided the following results for a sample of eighteen failed and suspended sub-lances: a characteristic life η of 420 lives, i.e. by 420 lives approximately 63% of sub-lances will have likely failed in service. The shape factor ß equated to 0.81 and, as mentioned, values below 1 indicate a running-in failure distribution. Given that this is a graphical technique and that industrial data – as opposed to highly-controlled laboratory tests – are collected under varying external conditions, there exists the possibility of errors and statistical uncertainty in what is already a probabilistic rather than deterministic or absolute technique. Blischke and Murthy (2003, p.360) also duly point out that, 'the assumption of a single failure rate pattern, as implied by fitting a two-parameter Weibull distribution, can obscure the fact that wearout often becomes a factor late in the life of components. This can become visually apparent on a Weibull plot, but the highly nonlinear scale of Weibull probability paper may obscure the wearout effect'. Having said this, the Weibull data presented in Figure 11 clearly indicate a running-in failure mode for the sub-lance 'burst' and this can aid greatly in searching for a root cause.

Running-in failures

Running-in failures mean that the probability of failure reduces with component age for those items that have made it through this hazardous early period. Most commonly seen in electronic items that have to be burnt in, it is also often seen in mechanical items where it occurs when they are brand new or after a maintenance overhaul. In John Moubray's important text RCM II (1997, pp.247-249), he describes running-in (infant mortality) failure patterns as usually being attributable to one or more of the following causes:

- Poor design
- Poor quality manufacture
- Incorrect installation
- Incorrect commissioning
- Incorrect operation
- Unnecessary maintenance
- Excessively invasive maintenance
- Bad workmanship

To add to this, Geitner and Bloch (2006, p.54) are in general agreement and similarly suggest assembly errors or material and manufacturing flaws to be the causes of running-in or infant mortality failures. The general trend of this reliability analysis of the sub-lance 'burst' failures pointed toward a maintenance issue with the sub-lance copper sections *before* they were put into service.

Recommendation for engineering improvement

The reliability analysis carried out has highlighted that the costly sub-lance 'bursts' are running-in failure modes. The recommendation is for further engineering investigation of the information contained here. This is because it serves greatly to direct a root cause analysis effort to eliminate any re-occurrence of the failure mode by investigating each potential basic event of the fault tree and the likelihood of it being a running-in failure mode. The recommendation in particular is to investigate the following areas:

- The standard operating procedure for re-conditioning of the sub-lances prior to installation.
- A review of quality assurance and quality control procedures for the sub-lance reconditioning process.
- Design specifications for the sub-lance batch.

Upon reaching the root cause of the sub-lance 'bursts' and taking action to prevent future repeats by way of redesign, change of procedure or maintenance, the following is recommended:

1. Target the next prime failure mode in Table 1, i.e. the 'sub-lance bent' problem. This is typical of the reason Pareto analysis is carried out which is to target the important few as opposed to the trivial many. Repeated targeting and elimination of regular failure occurrences will help to achieve reliability growth for the sub-lance system in the steelmaking plant.
2. On all future capital expenditure equipment purchases, carry out a Design for Reliability project – with the input of operators and maintenance personnel - to ensure the equipment will have high reliability, availability, and low maintainability times and ensure a good return on investment over its life cycle.
3. Continue with the current streamlined RCM strategy on all critical equipment and feed the results of all reliability improvement studies in to the RCM program.
4. Record and track as key performance indicators the following on all critical equipment: reliability, maintainability and availability.

5. Invest in reliability software to aid in professional reliability engineering analyses (e.g. Reliasoft, Isograph Availability Workbench, etc.).

Whilst it is difficult to estimate the costs of implementing these specific actions at the steelmaking plant, it would require at least two full time reliability engineers to be employed. In today's market, this may equate to £60,000 to £90,000 annually. However, given the significant costs of downtime (£4200 p/h), this outlay on technical specialist and subject matter experts can be made back rapidly with even small improvements in equipment reliability and more so with gradual reliability growth over many years.

The steelmaking company has reasonably good data collection systems in place. However, because it is currently using a legacy system for its failure reporting, it is recommended that the company move this activity into its ERP system for optimum efficiency and effectiveness. As mentioned earlier, ERP feedback reporting requires improvement in factual accuracy, and this should be achieved with ongoing training.

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