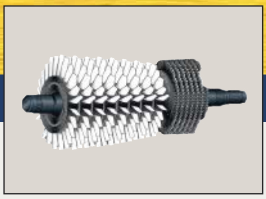
Compressor Systems in the UK Continental Shelf

ADDRESSING THE $2BN ANNUAL LOSS FROM THE GAP BETWEEN MANAGEMENT AND TECHNICAL PERSPECTIVES

January 2015

Aberdeen, UK



Version 2.0

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This document has been produced on behalf of the Unplanned Losses Working Group (ULWG) by Schlumberger Business Consulting. Its objectives are to identify the causes of unplanned losses in the North Sea and to push for action within and between companies to reduce them. The Members of the ULWG are Chevron, Talisman Sinpoec Energy, Taqa, and Schlumberger Business Consulting. The ULWG would like to thank all those operators who commented on the previous document. We have considered all comments received but take responsibility for the content of this document – given that this is a thesis about the gap between the management and technical perspective we have not necessarily accepted all the comments received. We would also like to thank Cameron Gauld and colleagues from Petrofac for assistance in reviewing the content and providing technical input. For questions, please contact **compressor-systems@slb.com**

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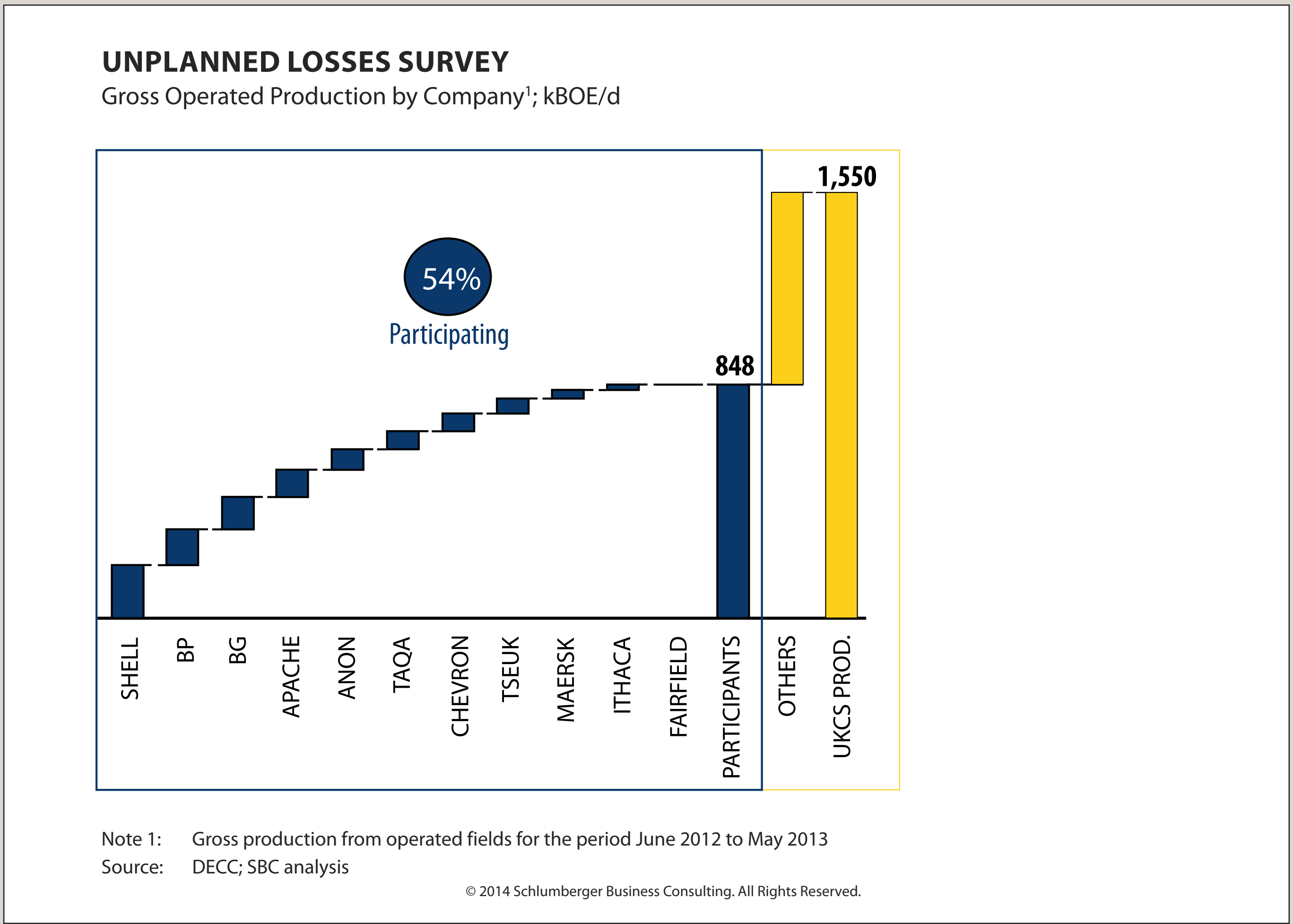


Why both Managers and Technical Experts need to read this document

This document is about compression systems, not just compressors. Such systems cause approximately 35 MBOE[1] of losses and $1.9 billion[2] erosion of revenues in the United Kingdom Continental Shelf (UKCS) per year. Compression systems are not only one of the single biggest equipment causes of production losses but also one of the fastest growing.

This is a management document informed by technical understanding, not a technical document (for which there is already at least one good example [ref 1]).

It explores the paradox we have observed that:

- There are many experts in rotating equipment/ compressors and many guidelines in existence
- At the same time compression systems cause the biggest losses by equipment type in the North Sea

This document tries to address this paradox.

Its thesis is that problems stem as much, or more, from management/ organizational issues than technical ones.

Its intended audience is therefore Executive Management and Operations Managers "looking down" and Operators, Maintainers and Technical Experts "looking up".

Nine best practices are proposed, and these are presented in terms of 3 categories – "getting priorities and accountabilities right", "understanding your compressor system", and "taking the right actions". Much of the content will also be applicable to other categories of rotating equipment.

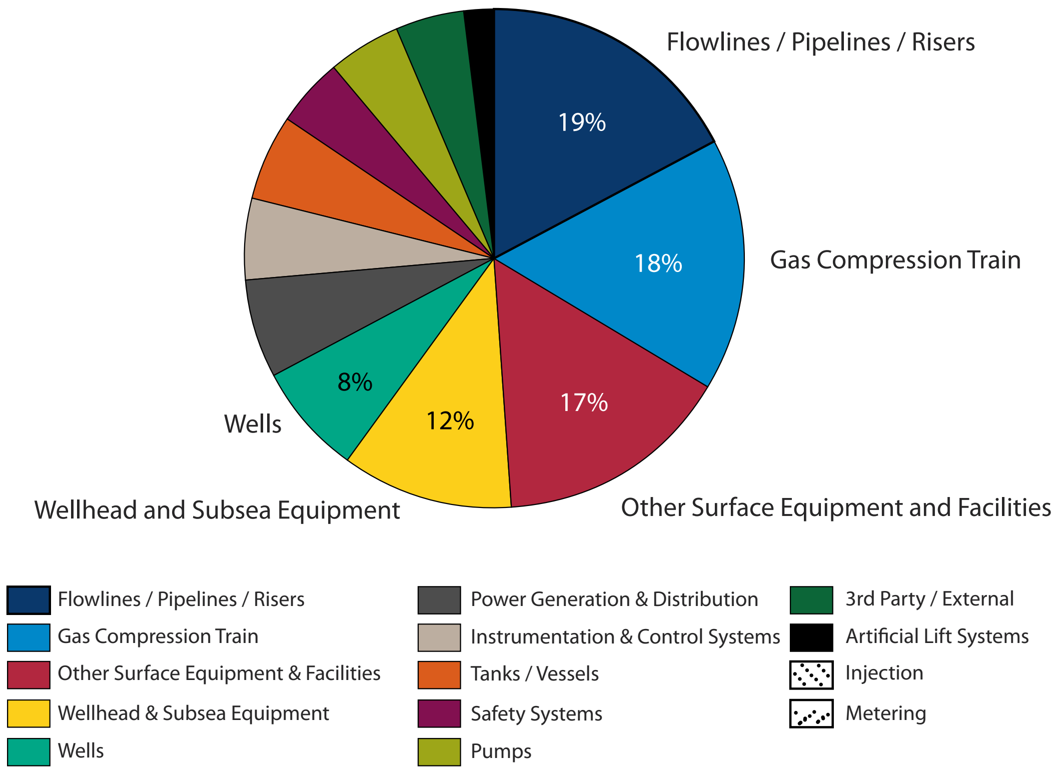
Our message is that you do not need to accept the status quo: there are operators in the North Sea running compression systems with good availability and losing fewer barrels and less money. You should be one of them!

Given the value at stake, we also hope this document provides material for supply chain companies to develop new innovative solutions.

1. Losses grossed up to the industry according to operators participating in the ULWG 2014 survey
2. 55/45 Oil/Gas 2013 UKNS production ratio (SBC North Sea Model/DECC), Crude price = 85 $USD/bbl (October 2014), Gas price = 3.6 $USD/MMBtu (October 2014)

SOURCES OF UNPLANNED LOSS FROM THE 2014 ULWG SURVEY

% of total unplanned losses, 2013



Executive Summary

The benefits of improving compression system performance in the UKCS are huge and achievable.

While there are usually people in your organisation who know what needs to be done to improve compressor performance, the necessary work often does not get done. The reasons for this are typically more managerial than technical.

This document is based on experience and examples from Oil and Gas, but also draws on best practices from other industries, including the industry that leads the world in the management of physical assets – Civil Aviation.

This document sets out 9 best practices:

GET PRIORITIES AND ACCOUNTABILITIES RIGHT

1. Don't accept the status quo
2. Prioritise based on value and barrels
3. Have one "throat to choke"/"chest to pin the medal to"

UNDERSTAND YOUR COMPRESSION SYSTEM

4. Don't assume yesterday's compressor is fit for today's conditions
5. Measure and Monitor: if ain't broke, don't fix it
6. Root cause analysis is about asking the people who know, not feeding the data monster

TAKE THE RIGHT ACTION

7. Don't just focus on the compressor - look after ancillaries and inputs better
8. Ensure completion of high-priority actions
9. Collaborate across companies

The first step is for managers to challenge the status quo: you do not need to accept poor performance! Management and technical staff then need to collaborate to understand the value of potential improvements, avoiding at this stage, being drawn into detailed technical discussions. It is then important to set clear accountabilities for solving the problem: one "throat to choke"/ "chest to pin the medal to". The concept of a Decision Support Centre comes in here.

To understand your compression system it is necessary to understand what is causing the problems: has the compression system or the environment in which it is operating changed? Managers should also challenge their maintenance regimes: unnecessary overhauls all too often cause problems and add cost; explore whether condition based maintenance could be more effective, or whether you are leveraging the full value of your condition based investments. In addition, to understand the root causes of issues, problem solving should be carried out between managers and technical staff. Too often this is replaced by IT systems and re-reviewing reports.

Finally, all the understanding in the world is not enough, if the required actions stay on the maintenance ticket or list of investment possibilities. Significant improvements can often be achieved without big investments but simply by looking after ancillaries better. It may sound simple to state that a manager's role is to ensure that the high-priority actions are completed; but too often this does not happen. Few companies have a "production critical" backlog category, akin to "safety critical". However, given the value at stake, managers need to treat compression problems as "production critical" and ensure action. Finally, you are not the only one experiencing this problem. Rather than trying to solve it on your own, connect with your peers at management level and explore the opportunities for collaboration: joint decision support centres, shared expertise, shared spares, a joint approach to suppliers, … Of course, there are challenges with all of these options. But the problem is sufficiently large to explore big new solutions. Continuing in the way we are will only lead to the same outcomes.

The sections below explore these points in greater detail.

Introduction

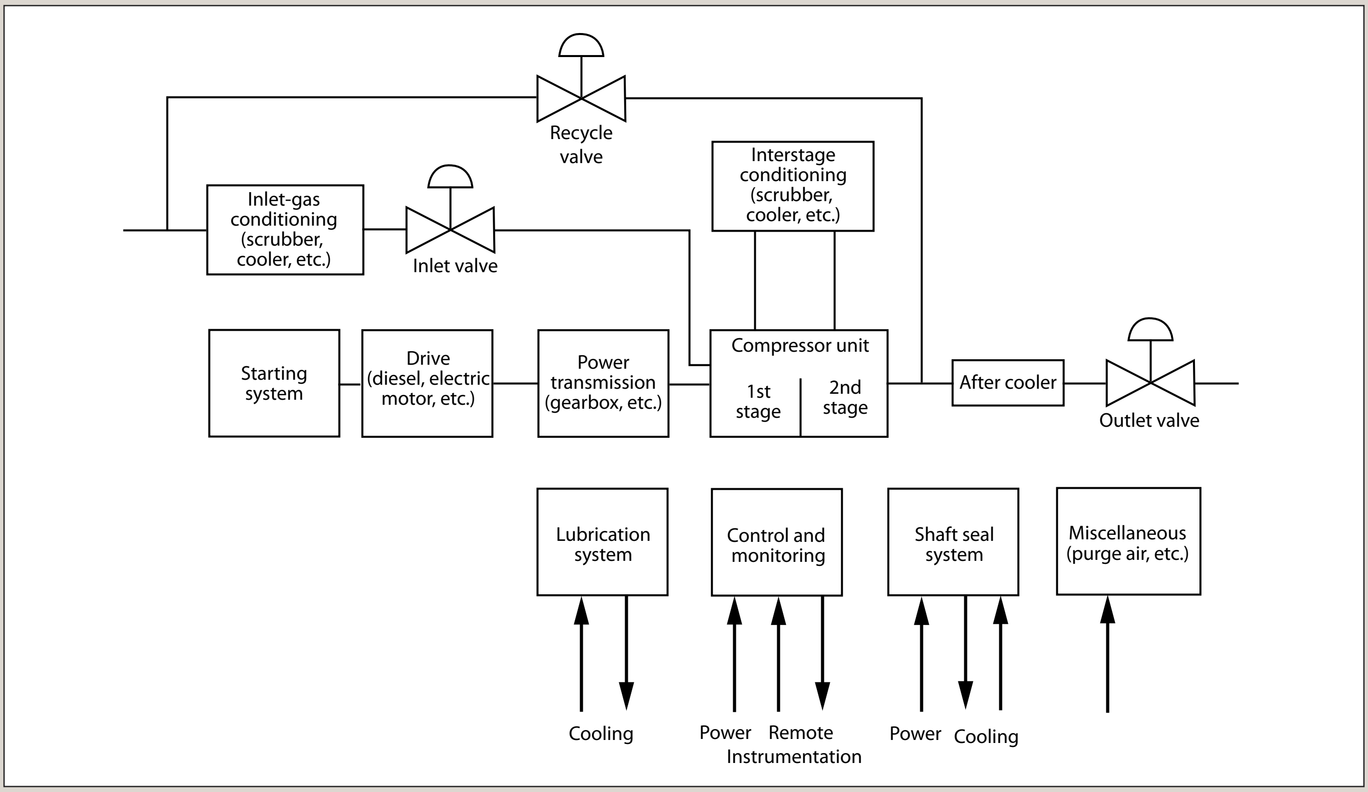
SCOPE

The Compression System

Whilst many production losses find themselves allocated to the "compressor" category, they are often the manifestations of problems in the wider compression system: for example, the drive or prime mover; or ancillary equipment such as coolers, fans, separators, knock-out vessels, lube oil systems, fuel gas systems, seal gas systems, couplings, gearboxes and even slug catchers. Indeed there is strong evidence to suggest that a significant part of the answer to our compression problems is to keep such ancillary equipment in good condition (see below).

Consequently, it is important to focus on the compression system rather than just the core compressor itself: to improve availability of the compressor, we must also consider the components and systems listed above.

The diagram below (based on the one used in ref 1) lays out the typical components in a compression system, all of which fall under the scope of this document



Applications of compressors and consequences of failure

Compressed gas may be used as fuel gas, for gas injection or gas lift, or gas export. Compressors are also used to boost the pressure of gas in pipelines to restore pressure drop resulting from friction losses, and in fields that are experiencing pressure decline. The consequences of compressor failure obviously depend on the application. A compressor which is offline for any reason will not receive gas - which may then have to be flared - and it will not deliver gas to the next stage of the process. If additional flaring is not an option, compressor unavailability can have a knock on effect on oil production.

For some applications (including gas injection) a short period of compression downtime may have little effect on output. However, one feature of many compression systems is that there can be many elements in series, so any failure can have a knock on effect on the whole system. This is a possible reason why compression system losses are high – not necessarily because they are unreliable (although they often are), but because the consequences of downtime are high, and are often felt immediately.

Another characteristic of many compression systems – which contributes to further losses – is that there may be a delay between the system becoming available after a failure and the resumption of full production, perhaps due to difficulties starting up, or knock on effects in the wider system, such as process line up issues which are typically not a direct compression problem but are often included in the compressor system loss calculations.

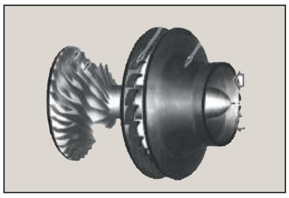
An additional, and extremely important consequence of certain compressor failure modes, which is covered in detail in ref 1 – and is therefore not addressed further here – is loss of containment.

Common Compressor Types

The principle of operations of four main compressor types – centrifugal, axial, reciprocating and screw – is shown in the diagram below. An informal survey of users suggests that all four types are used in the North Sea, but that centrifugal compressors are the most common. These tend to be the preferred choice for higher flow applications, and the most common driver for such machines is a gas turbine.

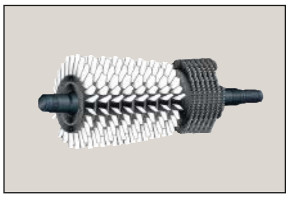
Compressor Types

CENTRIFUGAL



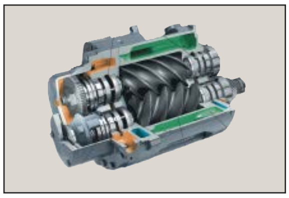
Gases enter at centre of a spinning rotor and exit at higher velocity outside

AXIAL



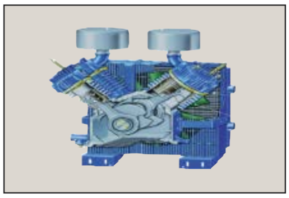
Gases compressed by rotating elements while they travel along axis of machine

SCREW



Gases are compressed by two interlocking rotating screws

RECIPROCATING



Similar in principle to a car engine – piston compresses gases in a cylinder

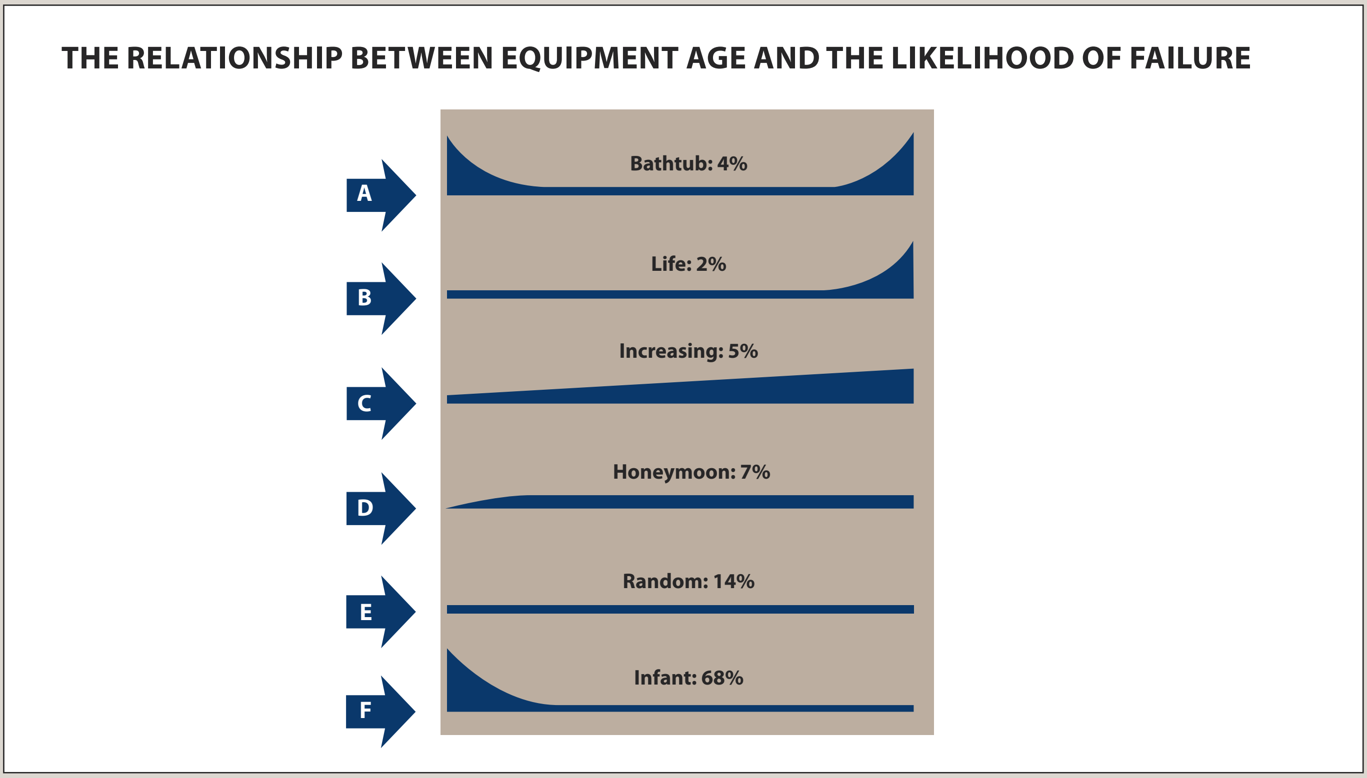
Lessons From Another Industry - Aviation

One of the characteristics of the oil and gas industry is its relative insularity. But there are lessons to be learnt from others. The aircraft industry is widely recognized as the "best of the best" in the management of physical assets. And while there are clearly consequential differences between aircraft and industrial equipment, the aircraft industry has not always been as good as it is now, and it has learnt valuable lessons that can be applied to Oil and Gas failure.

Furthermore, an area of prime importance to them is the management of Gas Turbines, without which modern airliners could not fly. Many of these engine types will also be found driving rotating equipment on oil platforms.

One such insight concerns the impact of invasive maintenance. Research carried out in the aircraft industry over 40 years ago into the relationship between equipment age and the likelihood of failure for a large number of components, showed that maintenance – particularly invasive maintenance – is not always a force for good (ref 2).

The chart below shows the relationship between the probability of failure (y-axis) and equipment age (x-axis) for a large number of components. Six distinct patterns were identified. The percentages are the proportions of components that conformed to each of the patterns and the titles are names given to each of the patterns. The research showed that 14% of components failed at random: there was no change in the probability of failure with age, which means that scheduled replacement would do nothing for reliability. It also showed that 68% of components failed when they were new or had been overhauled: hence, scheduled replacement of these components would actually decrease reliability. While the percentages for other industries may vary, the principle is the same – that excessive interference can cause failures (note this statistic does not differentiate between component manufacture/design issues or poor workmanship).



This caused a dramatic rethink in the way the aircraft industry approached maintenance and one of the outcomes was the avoidance of interference by placing a much greater emphasis on predictive/condition-based techniques. Such techniques include performance monitoring and condition monitoring such as vibration, temperature and oil monitoring, the objectives of which are to determine if there are 'potential failures' or warnings that something is failing.

Compared to maintenance programmes in the past, those for modern aircraft have far fewer fixed time replacements/ overhauls. Instead, a whole range of parameters are monitored, including engine temperatures and pressures, bearing temperature and vibration, and oil condition. Many measurements are continuous and automatic and the information analyzed in real time – often being sent back to a central Decision Support Centre via satellite. This approach has helped to yield a spectacular improvement in reliability: the rate of fatal accidents due to equipment failure on modern aircraft is 1/1200th what it was in the late 1950s. This has been accompanied by a significant real fall in aircraft maintenance costs.

Obviously, with so many lives at stake, aircraft operators demand seamless performance. Our view is that there is no reason why managers in the North Sea should not do the same of their compressors.

Nine Best Practices For Effective Compressor Management

A. GET PRIORITIES AND ACCOUNTABILITIES RIGHT

1. Don't accept the status quo

What is the paradox?

Whilst the full extent of the issues caused by compression systems shown in the ULWG report may be news, the fact that compression systems cause significant losses should not be a surprise to operators. Also, many of the technical solutions are known in the operators' organizations. Why then do managers accept the status quo?

What are the issues?

There are a number of issues that lie behind this paradox. Managers may not know the improvement potential which they could ask for. If so, the ULWG survey can show them the difference between good and bad performance and help them set targets. The systems that manage losses can also play a part: with some systems the data is compiled at such a detailed level that managers cannot see the wood for the trees (i.e., that it is the compression system that is their biggest issue). In other cases, the data is not granular enough, only highlighting 'compressors' without going down to sufficient detail to identify the subsystem or component where failure is manifested or more importantly where the root cause lies.

At the front line the issue may be a cultural acceptance of imperfection – having to live with, and tolerate an environment that is not optimal. Some imperfection is inevitable in older, declining assets where costs need to be controlled. However, because some imperfections must be tolerated, there is often the temptation to tolerate all imperfections. The culture of imperfection becomes ingrained and self-fulfilling.

Exacerbating both of these issues is a disconnect between management and operators. Manager may not feel comfortable discussing technical issues and simply delegate such issues to their experts, even when the main problem is a "business" one around necessary investment. However, a common and hopefully reassuring theme from many of the best practices covered later in this document is the importance of basic maintenance and housekeeping. Keeping ancillary equipment in good condition is not rocket science and many failures occur because of straightforward issues. These can include poor oil management, failure to check gauges and readings such as differential pressures across filters (and act upon them), failure to fix failed instruments and valves, lack of appropriate spares (sometimes even simple things like o-rings), failure to spot a small leak before it becomes a large leak, failure to check levels, or to clean local level indicating instruments, failure to properly protect equipment if sandblasting is carried out on other equipment nearby etc. While time pressure to resume production can also play a part, fixing these is a matter of good management – not something to be delegated to experts with no direct control over the operating environment or maintenance activity.

What should you do?

We recommend that Executive Management and operations managers get smarter on their compression systems, learn to set realistic yet stretching improvement targets, demand action, but also provide funds where it makes sense. There are six sets of questions that they can use to challenge their teams:

1. What type of compressor is used? What is it driven by? What are the other critical components of the compression system?
2. How are failures recorded? What are the KPIs? How is mean time between failure calculated and recorded? What is the quality of the data?
3. How does performance compare to peers? Do we know? What explains the gap? What should our target be?
4. Who operates the compressor and maintains it? To what extent are manufacturers involved? Are specialists available? Which people are responsible for compressor reliability?
5. What are the biggest problems with the compressor system? How are these manifested? What are the main concerns looking forward?
6. What are the root causes of the problems? What actions could be taken to deal with them? What is the return on cost of these actions? Who should be responsible for implementing them?

At the same time, frontline managers, operators and technical experts can also challenge the status quo by spotting technical, organizational and management issues and escalating them to senior management for resolution, rather than accepting the situation and falling into cynicism.

2. Prioritise based on value and barrels

What is the paradox?

Many activities are not carried out even though it would make economic sense to do so.

What are the issues?

Given the scale of the problem, compression system problems typically generate many improvement initiatives – each of which can generate many more actions - and these initiatives are often dispersed around the organization. With their different perspectives, different parts of the organization may have conflicting views about priorities for implementing all the things that need to be done. As highlighted above, the issue is often seen as too difficult and is handed over to the technical experts to resolve as a technical, rather than a business, issue.

In other cases the decision-making framework for resolving issues is not clear. For example, asset strategies do not exist or are not up to date and do not specify whether the asset – and its critical equipment – are priorities for economic growth, candidates for investment when the business case makes sense, or low priorities where only necessary HSSE investments are justified. Amazingly, in some cases, assets which are due to be decommissioned in 1-2 years are still undergoing shutdowns and overhauls, draining resources from assets which have longer-term potential. This represents a breakdown in communication between management and operations.

This lack of prioritization can lead to a situation where everything is top priority (which of course means that nothing is top priority) so things do not get done, or are late getting done, reinforcing a culture of non-delivery. Alternatively, priorities are set based on whoever shouts the loudest, is the most persuasive, or has management's "ear" at the right time.

Setting priorities in any of these ways is not optimal for the business.

Unfortunately because technical people frequently do not shout the loudest, they are often not well placed to communicate the full operational and economic benefits of an improvement opportunity, and are not always the best at putting across their arguments (for example, providing reams of technical data, but limited economics), sometimes their recommendations do not receive the priority they deserve.

What should you do?

Our recommendation is that Executive Management and Operations Managers need to take ownership of an issue which may comprise up to a third of their losses and which may lose their companies tens of millions of dollars a year. They should insist on business cases for solutions, backed up by hard numbers, and take time to consider the different options available and their pros and cons.

On the other hand, although it could be argued that technical people are not best placed to compile financial information into a digestible management format, they can help themselves by presenting their recommendations to management better. This means:

- Presenting recommendations concisely and objectively and in a language that management understands (and cares about) – i.e., losses and money – rather than in technical jargon
- Quantifying what happens if the recommendation is not carried out and comparing it to the cost of addressing the issue, to demonstrate the value and priority of the recommendation
- Presenting recommendations, as much as possible as a single consolidated list, with the interdependencies clearly highlighted

3. Have one "throat to choke" / "chest to pin the medal to"

What is the paradox?

Rotating equipment specialists may know what needs to be done to improve compression system performance, but typically they do not control the levers to improve the performance of the equipment they are responsible for.

What are the issues?

In the current job climate, rotating equipment specialists are hard to come by, so companies are unable to distribute them amongst the assets, and often need to embed one or two in a central function. This means that they do not have direct authority in the organizational structure, so have to influence through persuasion.

In highly siloed companies, the operators can feel that these functions do not listen to their needs, and only create academic solutions. Conversely, the experts observe that the demands of daily operations mean that their recommendations never receive the time they deserve. In the worst cases, rotating equipment specialists become "narrators" of the problem and/ or spend their time writing long manuals that operations and maintenance will never read.

This is a difficult problem to fix. Rotating equipment specialists do not grow on trees and it is difficult to make people accountable for performance on assets, operated and maintained by colleagues they do not know and have no line authority over. However, it is important to have one person, such as a rotating equipment specialist, you can point to who owns the "compressor system" and can control the levers to improve it.

What should you do?

This is where the concept of a Decision Support Centre (DSC) comes in. The DSC provides an environment for collaborating and sharing learnings across locations. This is enabled by video-sharing and a single, shared view of the compression process. By bringing together all relevant information about critical equipment in real time, the rotating equipment expert can analyse data more quickly and more accurately and reach appropriate conclusions in good time.

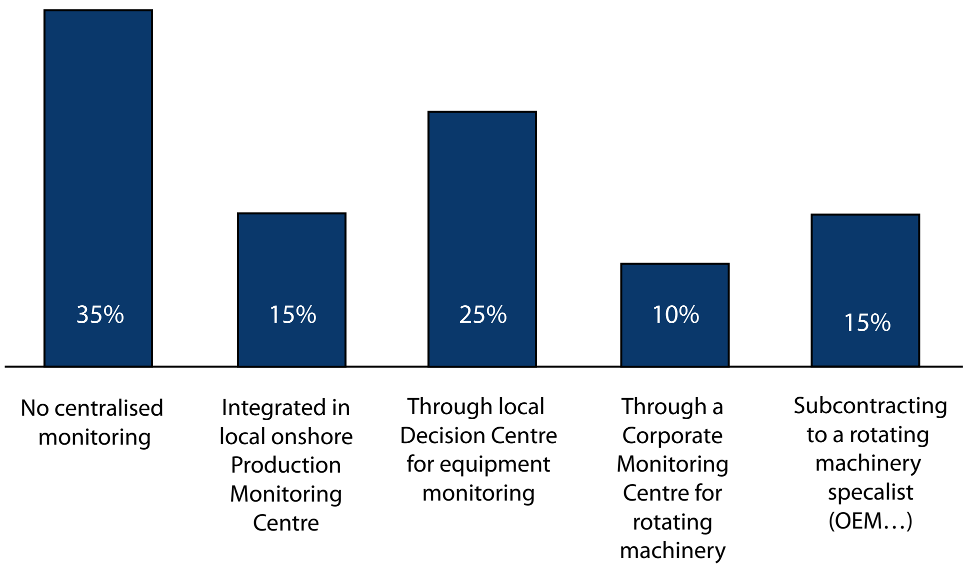
Within a Compression DSC, a Compression DSC Specialist can:

- Monitor processes across fields and assets
- Share a common view of data, trends, models, analyses, results and decisions
- Collaborate with multiple field and local and remote experts to help solve problems
- Work through issues and develop solutions

The DSC is analogous to the remote decision support centres used by Formula 1 racing teams (to ensure technical decisions are made calmly by experts based on data, rather than in the heat of the moment by pit lane crew) and by the civil aviation industry (as highlighted above).

An important aspect of the DSC is that it facilitates cross-functional collaboration and decision making – by providing a common, shared and objective view of the equipment. It brings the expertise of rotating equipment specialists directly to bear on the problem and enables management to hold them accountable for driving solutions where under the control of the technical specialists function. Obviously these centres take time and investment to set up. But you should also remember the significant cost of current failings. If you work for a global company, there can be benefits of sharing the cost and capabilities across regions. For smaller operators in the North Sea, pooling resources to set up a shared compression centre – perhaps with a service provider – could instead make sense. As the chart shows below, current practices around DSCs in the North Sea vary considerably, with a third of companies having no centralised monitoring.

APPROACH TO MONITORING COMPRESSOR DATA IN THE NORTH SEA



B. UNDERSTAND YOUR COMPRESSION SYSTEM

4. Don't assume yesterday's compressor is fit for today's conditions

What is the paradox?

Many people assume that the compression system is unreliable and focus on "fixing" it, when the problem is that the environment has changed.

What are the issues?

Many compressors are unreliable and/or inefficient because they are used in applications that are no longer appropriate for their design. Others have problems because short cuts were taken when they were specified.

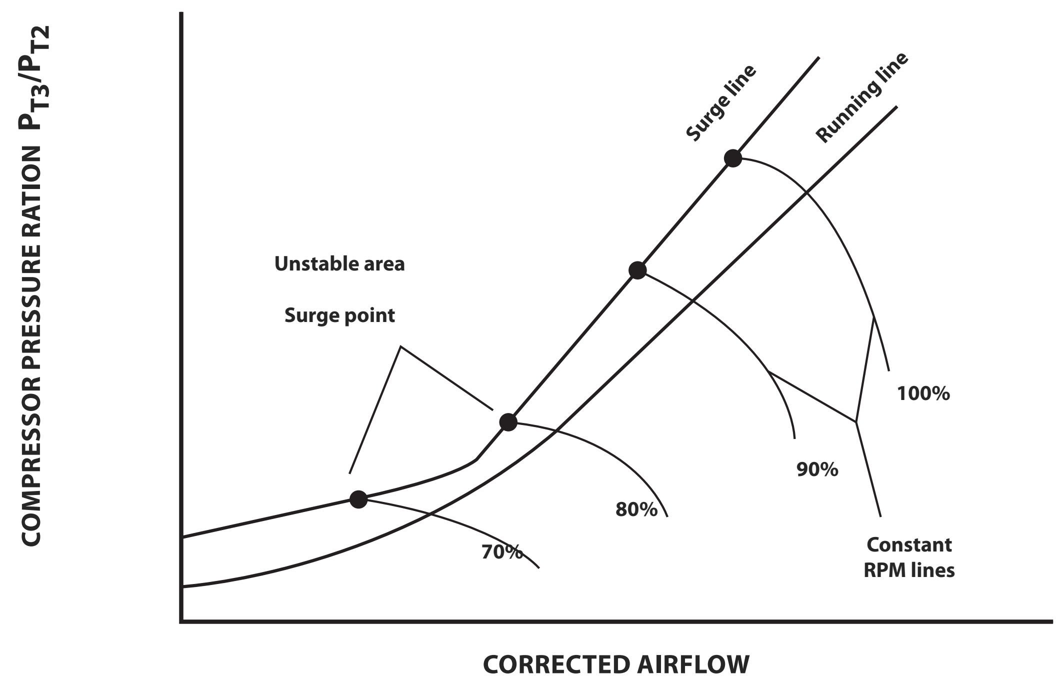
When compressors are specified, they are selected for certain operating conditions, but conditions inevitably change over time. In basins like the North Sea, with very mature fields, these changes can be considerable. It is easy to forget the original design requirements, particularly if the equipment is old, personnel leave, or the operating organisation changes (all very common in the North Sea). Consequently, as conditions change, companies can end up using the compressor in conditions that are inappropriate.

Sometimes the fact that the compressor does not match the application is known, but people decide to live with the problem. On occasion, this is the right answer; but even in these cases, companies should first review the facts and options.

The following examples describe some of the ways in which the compression system may have become inappropriate for its application.

i) Pressure, Molecular Mass and flow rate

Compression systems are specified for certain gas conditions, flow rates and delivery pressures. For example, a centrifugal compressor surge control system is based on a "map" for the compressor design and gas conditions. As producing assets age, parameters such as pressure, molecular mass and flow rate can change such that the compressor is no longer operating within its ideal zone. Furthermore, as the driver is also specified to provide sufficient power for the design case, if conditions change the power demand can also change. The diagram on the following page shows a typical centrifugal compressor surge map.



Clearly, each compression system has a degree of tolerance and the consequences of changes to conditions will depend on the way the compressor control logic works. However, changes to gas conditions can cause changes to compressor system performance. For example, for the same feed condition, compression ratio and compressor speed:

1. If the gas density decreases, the flow rate will decrease, and again the compressor will approach a surge condition

2. If the gas density increases, the flow rate will increase, which will result in more power consumption

Surge testing and subsequent performance mapping allows users to ensure surge protection is set correctly and minimize gas recycling which reduces energy consumption.

ii) Contaminants or corrosive materials

Obviously contaminants or corrosive materials in the process gas can have an effect on the compressor internals. Examples include liquids and particles which can cause deposits and hence vibration. These deposits may then need to be removed by appropriate coalescers or strainers. Other examples are higher levels of corrosive materials such as H2S or CO2, which can cause damage to the compressor internals and require internals made of appropriate materials to be substituted.

iii) Transients

This is another area where the compressor may not be able to cope with the demands of the system. In one company, a fuel gas (screw) compressor tripped because it was not able to respond to fluctuations in system pressure sufficiently quickly. Changes elsewhere in the system had caused transients to become greater and more common. This meant looking into a number of options including loop tuning, linking of control systems and physical changes to upstream equipment to limit load swings.

What should you do?

On assets where compression system issues are common, we recommend that Executive Management and Managers challenge their teams to determine whether the issue is the compression system or the environment within which it operates has changed; and what the implications of this may be. They should make an active choice to live with the situation or do something about it. Sometimes the solutions can inexpensive and can be achieved by changes in operation. In one example, the operator was suffering a high number of trips of the electric motor driving a compressor. This was caused by increases in the power consumption as a result of increased molecular mass. The user was able to make changes to the molecular mass of the gas by changing the way they operated upstream equipment.

Changes can sometimes be more difficult. For example, one user of 30 year old centrifugal compressors found that they suffered excessive recycling due to a decrease in molecular weight. Rewheeling the compressor was one solution but the costs and benefits did not stack up. At the same time living with the current situation is often not painless either. Making these trade offs is a job for managers not technical teams.

For operators and technical specialists it is often a worthwhile exercise to go back to the beginning and establish:

- What was the basis of my initial compressor design?
- What conditions is the system having to deal with today (and into the future)?
- What are the implications of this difference?
- What are the options for managing the consequences, and what changes could and should be made?

5. Measure and monitor: if it ain't broke, don't fix it

Note: There are three categories of maintenance/operating support activity: 1) integrity management (containment, inspection, corrosion management); 2) functionality (including loop checks); and 3) operability. This first two are safety related. Since this document is about loss management, it focuses more on the third category.

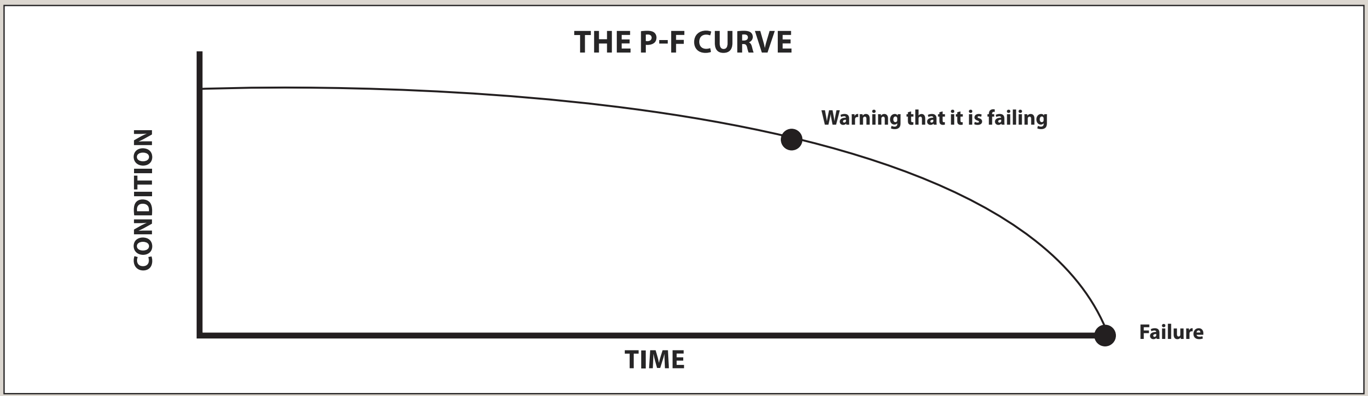
What is the paradox?

The main objective of operability maintenance is to improve reliability and there is often the belief that the way to do this is more maintenance. However, maintenance – particularly if it is invasive – can actually decrease reliability.

What are the issues?

Scheduled maintenance on compression systems should be in accordance with the specific operator maintenance philosophy and should incorporate FMECA type analysis results, however in many cases maintenance programmes are based on the manufacturer's recommendations. These often involve fixed time replacement of parts, and the intervals tend to be conservative, in part because the manufacturer does not know the context of the equipment, so has to err on the side of (perceived) caution. Some operators even suggest that manufacturers have an interest in overly conservative replacement of parts because it enables them to sell more parts and make more money. However this perception is more likely to be a result of OEM's being unwilling to take risks with service life extension where historical maintenance and current equipment health is unknown.

As highlighted above, research from the aircraft industry showed that many components are less reliable after replacement or overhaul. As a consequence, modern aircraft maintenance programmes avoid interference as much as possible by placing a much greater emphasis on predictive/condition-based techniques. Such techniques include performance monitoring and condition monitoring such as vibration, temperature and oil monitoring, the objectives of which are to determine if there are 'potential failures' or warnings that something is failing (see diagram opposite).



This enables action to be taken to avoid or minimize the consequences of failure.

The advantage of such an approach is that, if the equipment is working well, it is not interfered with, and maintenance is only carried out where necessary - massively reducing the risk of maintenance-induced failures. Of course, decreased cost and increased availability are other benefits of not carrying out unnecessary maintenance.

In one recent case an operator with a gas turbine driving two centrifugal compressors, identified that the turbine driven accessory gearbox used for main lube oil circulation was subject to an OEM replacement recommendation every 30,000 hours. However, no previous replacement or maintenance has been conducted and the gearbox has now achieved over 80,000 hours. Based on the above discussion the operator can choose to replace the gearbox simply based on it approaching 3 times the OEM's recommended service life which at best may be a timely replacement of the equipment or at worst may create an infant failure. Alternatively they may opt for a condition based approach and monitor the current gearbox health via vibration analysis, internal inspection, oil sampling, etc. to determine if replacement is actually required regardless of hours achieved.

Another benefit of condition based maintenance is that it fosters an understanding of the condition of the equipment. Our experience is that, in the North Sea, few operators, maintainers and technical staff can honestly answer the question "Do we know what condition our equipment is in?"

Modern maintenance practices for assets in other industries follow a similar approach to the airlines. Many operating parameters are available through the Distributed Control System and these can be supplemented by additional condition based measurements. For us in oil and gas, a number of compression system maintenance activities, many of which are condition based, are suggested below:

- Monitoring compressor and driver bearing vibration and temperature
- Monitoring separator levels
- Monitoring Dry Gas Seal leakage rates
- Checking lube oil and process gas temperature before and after coolers
- Lube oil analysis
- Monitoring fuel gas quality
- Monitoring cooling fan bearing vibration and temperature
- Checking operation of instruments and protective devices
- Checking differential pressures on gas and oil filters
- Cleaning and inspecting separator/ knock out vessel internals
- Cleaning fans and heat exchangers
- Monitoring system delivery pressure and output
- Boroscoping of the turbine

Furthermore, a knowledge of the equipment condition from past equipment teardowns, can be used to increase the period between equipment overhauls, beyond manufacturers' typical recommendation – a key being knowledge of the elastomer sealing (e.g., o-rings) which are dependent on the material and operating temperature, and can be the life limiting factor.

What should you do?

We encourage senior managers – including Executive Management and Operations Managers – to challenge the maintenance programmes for their major pieces of equipment: especially when they are major causes of losses, where it is fairly clear that the status quo is not proving very effective. This means managers getting out into the field and challenging activities. Below is an example of a conversation on a North Sea asset:

- Senior manager: "What are you doing?"
- Maintainer: "Overhauling the compressor. I do it every 6 months"
- Senior manager: "Did you find anything wrong with it?"
- Maintainer: "Nope"
- Senior manager; "Did you find anything wrong with it 6 months ago?"
- Maintainer: "Nope"
- Senior manager: "Did you find anything 12 months ago?"
- Maintainer: "Nope"
- Senior manager: "Have you ever told anyone that this is the case?"
- Maintainer: "Nope"

These sort of interactions should cause managers to demand a change. But if you don't ask the questions, you will not know. Our view is that maintenance regimes should be based primarily on condition based techniques and we recommend that managers ask whether these can implemented.

Operators and maintainers should also challenge traditional, more invasive maintenance programmes. If a condition monitoring programme has been introduced, (such as the Prognost system on reciprocating compressors), some invasive maintenance tasks from the past can often be removed from the maintenance programme.

One operator in the Middle East did just this. They were using compressors dating back to the 1960s (not a bad thing in itself) but despite investing in many condition-monitoring technologies, the core of their maintenance programme (6 monthly and annual Shutdowns) had not changed since the OEM wrote the Maintenance Manual in the 1960s (definitely a bad thing). Regular interventions involved dismantling the reciprocating compressors – to take measurements and replace components – and rebuilding them, an approach that data analysis showed caused more failures than it prevented. By looking at the likely failure modes addressed in the shutdowns and selecting the best maintenance techniques for each (these were mainly condition based and ranged from the use of the human senses to vibration and rod-drop monitoring), the maintenance programme was revised, the invasive preventive interventions were eliminated and compressor reliability and maintenance costs improved significantly.

We have found many instances where Companies have invested heavily in condition-based technologies, yet only use them to give warning of otherwise unanticipated failure "between overhauls". Whilst this is very effective, most organisations miss the corollary of this – if the machine is not showing any signs of impending or incipient failure, then why go ahead and overhaul it?

The concept of a Decision Support Centre (DSC) highlighted above can also form a part of a condition-based solution. While any CBM strategy is dependent on the correct instrumentation being available which may be limited given the age of some UKCS equipment and also relies on the results being effective in identifying the failure modes, information brought together includes process data, work order management, SCADA, production reporting and management of change systems. Sometimes DSCs have additional software such as SmartSignal which is web-based, real-time pattern recognition application which provides continuous monitoring and reports on exceptions for abnormal compressor performance. This allows early identification of abnormal equipment behaviour and more effective and efficient prioritization of maintenance activities.

6. Root cause analysis is about asking the people who know, not feeding the data monster

What is the paradox?

Many operators place great emphasis on root cause analysis, but in many cases the results are not there to justify their efforts.

What are the issues?

As discussed above, it is common, when equipment fails, for symptoms manifested in one place to have root causes that are failures elsewhere. This is particularly the case with compression systems. Clearly, to solve intractable problems, it is necessary to deal with causes of failure rather than their effects.

Most operators are placing great emphasis on root cause analysis programmes as a lever to improve losses. However, they are not always able to point to the results (more barrels/ fewer losses) to justify their investments. There are two things that get in the way: firstly, not taking the actions that need to go together with root cause analysis; and secondly, not doing root cause analysis correctly.

The first thing that gets in the way is that root cause analysis is not seen as a part of a holistic improvement programme, and becomes an end in itself. For better understanding of issues that would lead to barrel improvements, managers have to be ready to follow up on the findings with actions – whether in terms of investment or new practices, such as maintenance. Otherwise the findings just add to "analysis paralysis". In the worst case, front line employees asked to fill in root cause analysis findings into the IT system, and seeing no action resulting, become cynical and treat the activity as a "box ticking" exercise.

The second thing that gets in the way is paying lip service to root cause analysis rather than delivering the essence. This can be because the immediate concern is to deal with symptoms and get the equipment running again, given the pressure to resume production quickly. If the organization is stretched, things may often stop there, because other urgent issues will arise. In addition, many companies are overly reliant on interrogating IT systems for root cause analysis rather than human interactions. The best information about root causes often resides in people's heads and this is not recorded on any data system. You will only find it if you talk to them. If the system relies excessively on recorded data, the real root causes may not be uncovered.

Indeed there may often be challenges associated with the way maintenance information is managed in the Computerised Maintenance Management System (CMMS). The asset hierarchy may be poorly constructed, resulting in failures, failure coding and work orders being assigned at the wrong level. Trying to analyse the failure data becomes extremely difficult in such circumstances."

What should you do?

Managers have the responsibility to ensure that root cause analysis forms part of a programme that leads to loss improvements, rather than becoming an end in itself. Given this, it can be better to start the improvement programme – including root cause analysis – with a particular asset or type of equipment (e.g., compression systems), understand what works, get the benefits early, and then roll them out to other areas, rather than trying to solve everything at once and not getting to any impact in terms of reduced losses.

In terms of how root cause analysis is delivered, it is important that managers insist on intelligent problem solving rather than filling in computer forms. For example, one of the UK's best performers uses the following approach: after the initial loss, the OIM and relevant staff and experts problem solve the issue on a white board (engaging brain before opening computer); then one person completes the computer entry; two weeks later onshore managers challenge whether the root cause analysis was of sufficient depth; then every quarter the most significant losses are reviewed and senior managers discuss whether all the appropriate actions have been taken.

Some examples of compressor root causes include the following:

Keep asking "why" until you find the root causes

DIFFERENT ROOT CAUSES FOR THE SAME LOSS EVENT

– EVENT –	WHY?	WHY?	WHY?	WHY?	– ROOT CAUSES –
COMPRESSOR TRIPS	due to vibration	due to liquid carryover	due to inadequate maintenance on separator internals		**due to lack of ownership**
COMPRESSOR TRIPS	due to vibration	due to liquid carryover	due to no liquid level in separators	because operators leave the drain valve open	**because the level control loop does not work**
COMPRESSOR TRIPS	due to vibration	due to liquid carryover in separators	because operators leave the drain valve open		**because there is no level control info in the control room & local control is dirty**
COMPRESSOR TRIPS	due to vibration	due to no liquid level in separators	because operators leave the drain valve open		**because the level control valve is an on/off design rather than a proportional device**
COMPRESSOR TRIPS	due to GT driver trip	due to failed fuel gas regulating valve	due to particles in the fuel gas	due to corrosion caused by high levels of H_2S	**because of failures in the sweetening plant**

In summary, it is easy to adopt the "processes" around root cause analysis. What is more difficult is the mindset. You know it when you see it: if managers are spending all their time reviewing data on root cause analysis compliance, but do not know what the problem is, and no improvements are resulting, you do not have it; if managers are discussing the substance of the losses, making prioritisation decisions, committing capital where required, and tracking actions through to completion and improved production, you probably do.

C. TAKE THE RIGHT ACTIONS

7. Don't just focus on the compressor itself - look after the ancillaries better

What is the paradox?

The reliability of core equipment is crucially dependent on the performance of less glamorous equipment which is often neglected.

What are the issues?

In a survey of two companies, we found that more than a third of compressor trips were caused by ancillaries:

Equipment like fans, coolers, separators (and their associated level control systems), fuel gas conditioning and regulating equipment, lube oil pumps and filters, GT air inlet systems, seal gas filters and valves are often seen as not 'core' to the process. This is reinforced by the fact that many are (relatively) inexpensive. Designers under pressure to reduce costs might see such equipment as good opportunities to save money, and operators and maintainers may believe that they have more important priorities. Consequently it is common to see such equipment not given maintenance or redesign priority, left in a poor condition, or even left in a failed state.

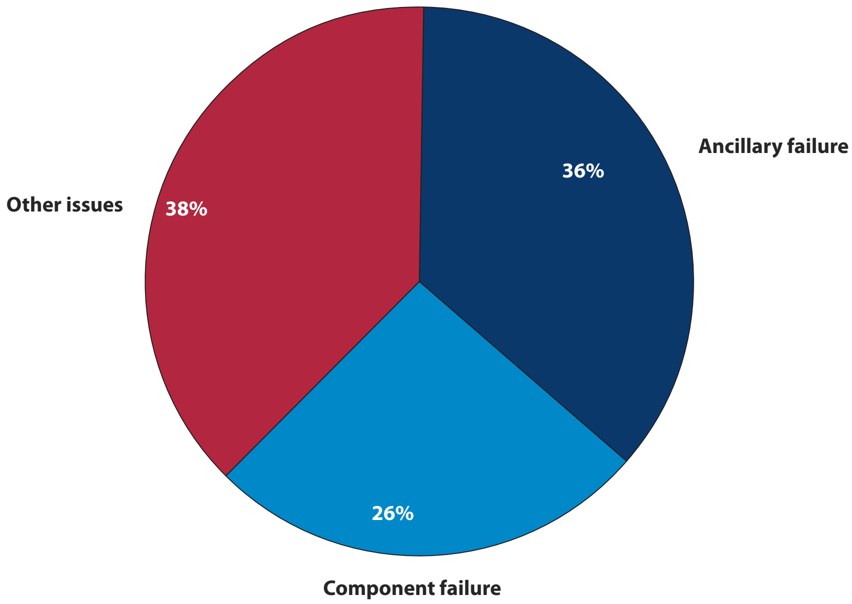
However, these ancillaries are crucial for the long term condition and smooth running of the compressor.

One (but certainly not the only) reason some important ancillary equipment is sometimes not maintained is that nobody sees it as their responsibility, since some equipment and some functions can 'fall through the cracks'. For example, slug catchers and separators are usually regarded as static devices, and in many organizations, the responsibility for their maintenance rests with the static/integrity department. However, the integrity department is often quite small and is fully occupied managing integrity and hydrocarbon containment due to corrosion, erosion etc, on a whole range of ageing equipment. Even if the question of the condition of slug catcher and separator internals has occurred to them, it will not feature very high on their list of priorities. One operator had problems with centrifugal compressor vibration trips due to liquid carryover and had not looked at slug catcher and separator internals for 30 years. When they did inspect the internals there was nothing left!

More than a third of compressor trips are recorded as ancillary failures

PROPORTIONS OF ANCILLARY & COMPONENT FAILURE

% of root causes for the "unplanned loss" benchmarked operators



Another example of equipment that can 'fall through the cracks' is valves. In many organisations the instrument department is responsible for valves, since valves are often associated with the loops and instruments the department looks after. However, what about large valves? Are these covered by the Instrument department too? And, if they are, do the personnel in this department have the experience/ interest in the maintenance of items of equipment that are so different to the equipment they normally work with?

What should you do?

In our opinion, Managers need to dig deeper into the root causes of failures, and challenge operators and technical experts to do the same. Just because the compressor has tripped, does it mean the root cause of the problem lies with the compressor? It is also important to look out for equipment and functions that can get overlooked and ensure maintenance responsibilities are defined and understood, that appropriate accountabilities have been set, and that the required competencies are in place. These requirements should be dealt with by managers.

For their part, operators, maintainers and maintenance management systems need to focus much more on ancillary equipment – items such as fuel gas filters, lube oil filters, separator level control valves, level control instruments, instrument air driers, seal gas system equipment etc. – to ensure that the inputs to the compressor are kept clean. It is important to ensure that the lube oil is clean and regularly tested for contamination and physical properties. A crucial area for centrifugal compressors is dry gas seals, wet seals and their supporting systems. The seals need to be fed with clean and dry seal gas at the correct (differential) pressure while the compressor is pressurized and it is important to ensure protection from lube oil contamination from the bearings by ensuring that barrier gas separating the seals from the bearings , typically nitrogen gas, is always on before the lube oil system is started.

The following three examples show how companies can successfully address this problem:

- One operator suffered from compressor trips due to vibration, and noticed solid deposits on the impellers which were probably caused by liquid carryover. The vibration trips were eliminated by retrofitting new, high efficiency internals to selected slug catchers and separators and upgrading unreliable level control instruments.
- In another operator the biggest single cause of compressor trips was poor quality fuel gas supplied to the gas turbine prime mover. The gas was received from a sweetening plant, but this was not working properly and did not remove H2S, moisture and particles sufficiently. The operator set up a programme to upgrade the sweetening plant, and ensure it was maintained correctly in the future – in order to improve the reliability of the compressors.
- Finally, a company was experiencing problems with compressor trips caused by instrument damage resulting from poor quality instrument air and initiated a programme to improve its cleanliness through design changes and better maintenance.

8. Put real effort into ensuring top priority work is actually done

What is the paradox?

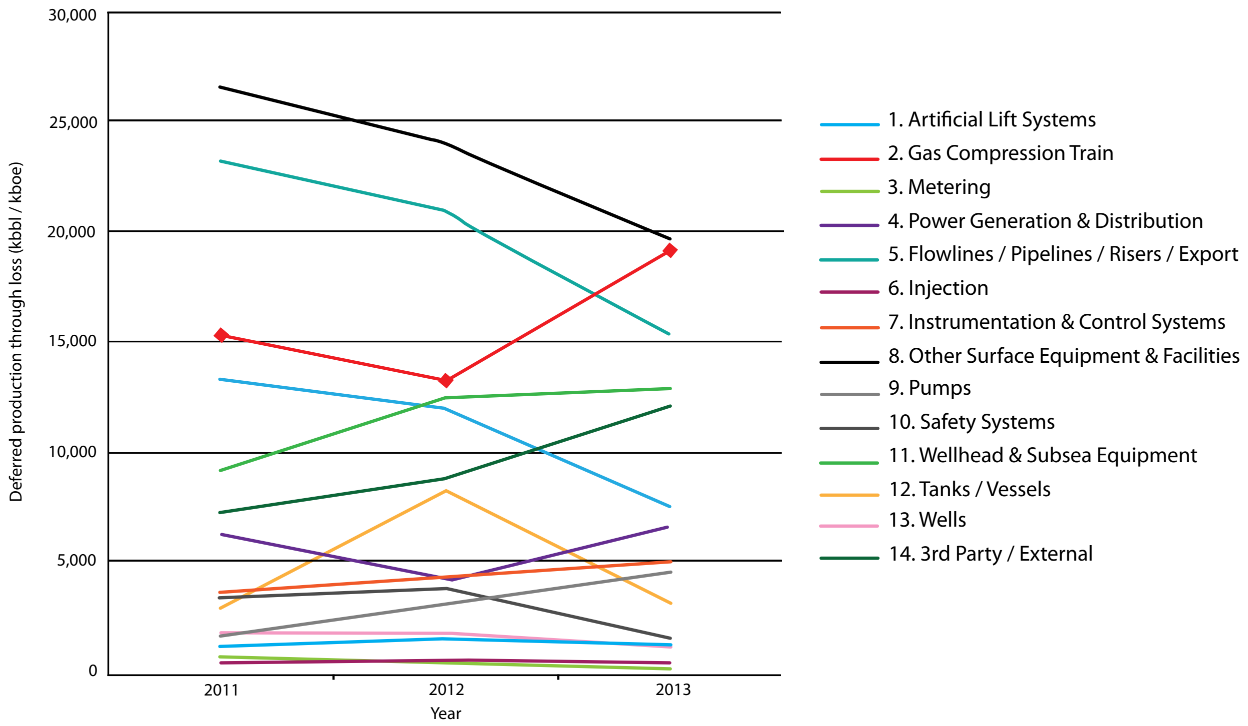
Operators often intend to do the necessary work to improve compression system performance, but then fail to implement (or implement late), so the anticipated improvements are not realized.

What are the issues?

It should go without saying that improvement initiatives will not deliver results if the recommendations are not implemented. However, many compression systems perform badly, and continue to do so, year after year, for just this reason.

The graph at the outset of this document demonstrated that, across UK North Sea operators who participated in the ULWG survey, compressors have consistently been bad performers and recently got worse.

EVOLUTION OF UNPLANNED LOSSES AMONG SEVERAL NORTH SEA OPERATORS FROM 2011 TO 2013



The reasons for lack of implementation are complex. Work to improve compressor performance has to take its place alongside a whole range of other activities on other equipment, many of which are safety critical. Resources (money, skilled personnel and time) are tight: there is limited space offshore for the installation of new equipment, limited bedspace, support vessels and helicopters, while there are limited resources onshore to support new projects. With old equipment, work often takes longer than anticipated because new and unexpected issues are uncovered.

Because everybody knows it is difficult to get work done, few people will admit that any job is not top priority because to do so would probably result in the work never getting done. The upshot is that all work is top priority, which means of course that nothing is. It also means that all initiatives move forward at the same (unsatisfactory) pace, regardless of merit.

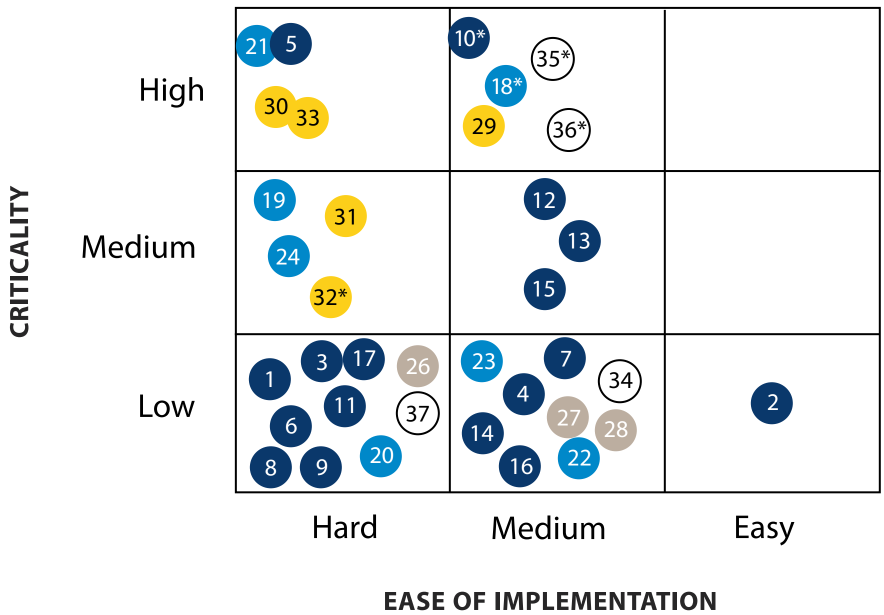
For example, in one operator, Engineers were implementing changes to a compressor with dubious business benefit (because the asset had a short remaining life and losses were low). However, they were unwilling to forgo the opportunity because it had taken a lot of time and effort to have the opportunity to do the work. However, if the project was shelved, it might have freed up resources to do other more beneficial work. Clearly, this point – like many others in this document – affects multiple equipment issues, not just compressors.

Considering all the points above, it is therefore not uncommon for planned compressor related work to be deferred or not carried out at all.

What should you do?

Part of the solution lies in appropriate prioritization, for compression systems and other equipment – as discussed in best practice 2. Prioritization should take into account the expected business benefit (safety, losses, costs etc) - which in turn is based on the frequency and consequence of events the work is intended to address - and the cost of implementing the solution. It therefore compares the cost of solving an issue with the cost of not solving it. An example of a typical prioritisation matrix is shown below. The key is not just to complete it, but to have it drive real prioritisation of actions and track that the most important are actually being delivered.

TYPICAL PRIORITISATION MATRIX



This should be done in good time to develop integrated, targeted plans of work, for which the correct spares are available (which can sometimes take years to procure), the correct people and skills are available in the correct time and the correct place, and the work fits in with other activities.

Planning needs to be carried out early – the system needs to identify and proactively fix gaps in the processes and systems to enable a long-term solution, minimizing overall production losses. Obsolescence needs to be taken into account.

Management can also assist this process by ensuring that management systems do not hold up beneficial activities. If an investment of $20m would yield a payback of $40m per year, should it be cancelled or delayed because the budget is not available this year? Should it have to wait while the wheels of the annual project approval process slowly turn? (And therefore miss the next summer shutdown "slot".) Or is it the role management to identify the work that would make a real difference, and ensure their own systems allow implementation with absolute priority? Alternatively, if money really is unavailable, can creative solutions (e.g., service contracts) be found to work within existing constraints?

9. Collaborate across companies

What is the paradox?

Compression systems are the largest single equipment-related problem in the UK North Sea, few operators are good at dealing with it, capabilities in the industry are limited, yet collaboration is minimal and restricted to technical discussions.

What are the issues?

Collaboration on compressor systems is happening at working level today in terms of gathering best practices – for example through the regular meetings of NSREuN (North Sea Rotating Equipment Users Network). This must be welcomed, the people responsible commended, and this initiative extended further. In addition, OEMs are sometimes called in to companies to share their thoughts on what it will take to improve compression systems in a particular company. Of course, the efficacy of this is dependent on the company really knowing what the problem is. In one example, a company called in compressor experts who spent time and barrels dismantling the compressor, when what they needed was a compression system expert who could have told them the problem was with the ancillaries.

At the same time, this is only a limited example of what the industry could achieve together. So, why has this topic not been an area for fruitful collaboration between individual operators and between operators and suppliers?

Firstly, before the Unplanned Losses Working Group's recent survey, it was not transparent to managers that most companies were in the same boat, with high compression systems losses. At the same time, this finding did not come as a surprise to them, so this cannot be the only reason not to act. Secondly, as highlighted above, many managers feel uncomfortable talking about the technical issues around compression systems to their own staff let alone with other companies. And finally, the insularity of oil and gas has led companies to want to solve all these problems themselves rather than with peers or suppliers. Sometimes, this approach is masked by the "excuse" of not wanting to share competitive advantages with peers. However, the results in the North Sea speak for themselves: few operators can claim to have a competitive advantage in this area, and most are experiencing real difficulties trying to fix the issue on their own. So, what are the real barriers to collaboration?

What should you do?

To achieve the full benefits of collaboration, managers need to get involved in this cross-company collaboration, not just technical experts. Whilst the opportunity here is as yet unproved (no one is fully realising it today, so we will have to test it to see what works), there are a number of avenues to explore, including:

- Sharing performance data and the results of improvement programmes to help managers set targets for improvements
- Sharing remote monitoring centres and technical experts across companies
- Cross-industry demands for the OEMs/ service companies to develop new business models/ approaches to solve the problems
- Sharing spares for the same type of compressors across companies, based on transparency of what compressors exist and a simple trading scheme

And as for technical experts, we recommend that some need to get better at sharing the insights from current cross-industry forums with managers, operators and maintainers in ways which lead to action within the company (e.g., what improvements are possible and what does it take?) rather than simply creating more and better binders for themselves.

How To Get Started

Obviously, the precise form of a compression system improvement programme depends on the problem and the strategy and capabilities of the company involved. That said, we see broad similarities in approach amongst those who have delivered improvements. And even amongst those who have been successful in this, we would argue that – often –the improvements could have been delivered a lot quicker (maybe twice as quickly) was there sufficient management focus.

The first step is to size the prize: to break through the technical questions with some simple numbers around the economics. What is the scale of the improvements that can be delivered? What is, broadly speaking, the problem? What could it cost to fix in terms of investments or changes to practices? Based on this management should make a go / no go decision to put some real effort into fixing it – and communicate that decision clearly. This would help companies break through the cycle of issues spinning round and never being fixed.

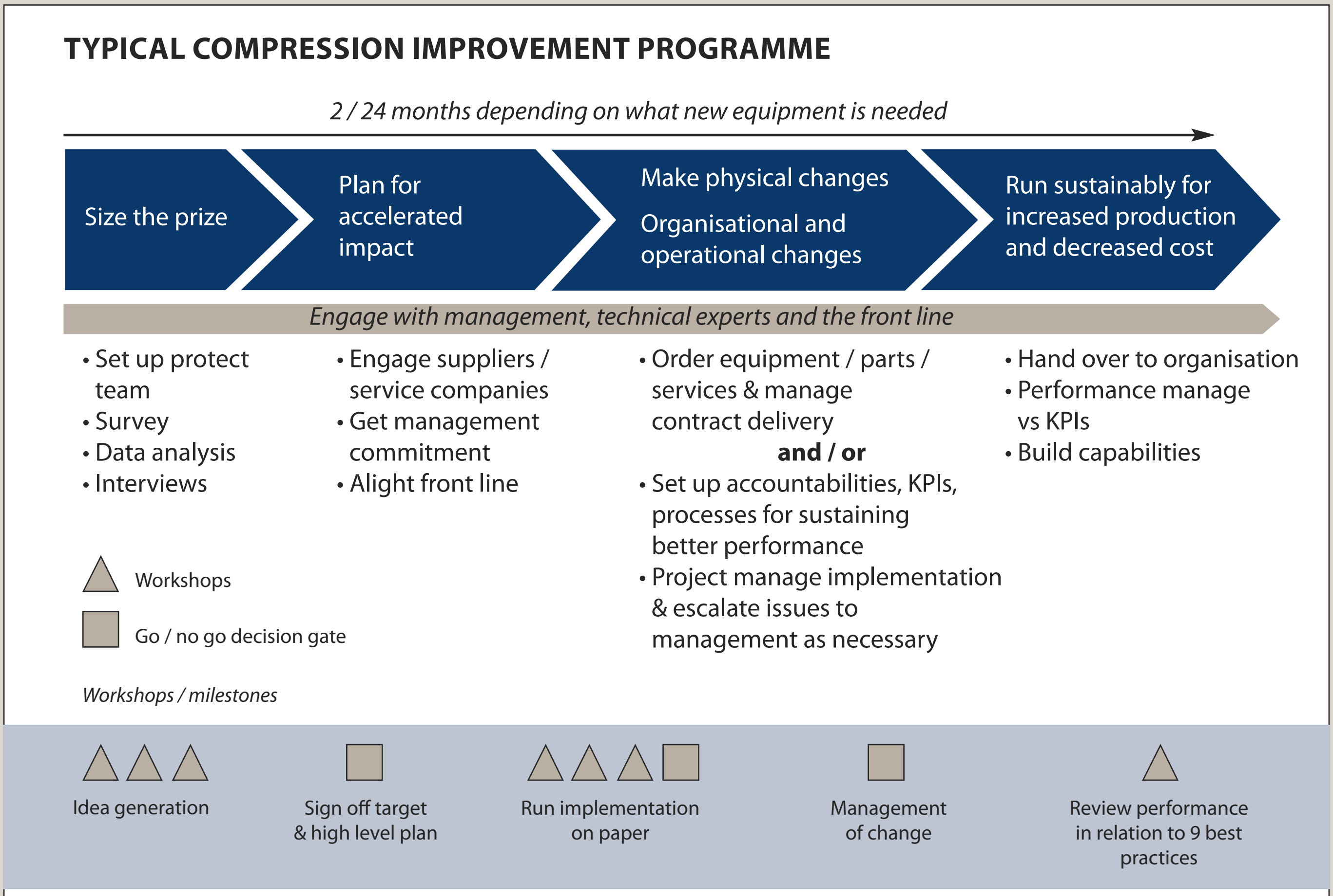
The second step is to demand an in-depth analysis of the issues, as laid out above, and a plan to deliver improvements as soon as possible. Technical experts, operators and maintainers need to clearly explain the recommendation (or even better options) in terms that management can understand (e.g. what value will be added). The role of managers is to challenge these solutions, especially around the time of delivery: e.g., what would it take to already have some impact in the next few months (through changes to operational practices) and to improve the economics of fixing the issue?; and if investment is required, will it really take 2-3 years to implement the solution – how could we do it in half the time?

The third step is to project manage the delivery of these improvements. As highlighted above real impact demands real effort. This can be in terms of managing a small engineering project to fix the issue. But equally it could be insisting on real management focus to ensure that ancilliaries are properly looked after and that maintenance regimes are changed. The latter may cost less (ideally it should save money) but the effort required to change the mindset of the organization is none-the-less considerable.

Finally, to avoid backsliding, the operator needs to create the management system, organizational responsibilities and skills to ensure that any improvement lasts – essentially to ensure that the 9 practices described above form part of the company's new DNA.

The exhibit below shows what a typical improvement programme might look like. The time to achieve results depends on the nature of the changes required, and could take anything from 2 months (for some training and procedural changes) to 24 months (if significant design changes are required).

If you would like to discuss this in more detail, please contact: compressor-systems@slb.com.



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