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The road to a fully integrated asset management strategy applied to rotating equipment

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Abstract

Today most companies around the world are very much aware of the benefits of improved plant reliability and the elements necessary to achieve this, such as the development and implementation of risk-based equipment maintenance strategies and spares parts optimisation. However, because these projects require a significant investment of time and effort, most companies either do not complete them or reduce their scope along the way.

The other important aspect of an integrated asset management strategy is that it integrates all the elements together and establishes systems and procedures to sustain and continuously improve them. This paper mainly focuses on how companies can overcome the challenges during the journey from development to implementation of a fully integrated asset management strategy.

Introduction

RasGas Company Limited is a producer of liquefied natural gas (LNG) located in Qatar. The company currently operates seven LNG trains with a total production capacity of 36.3 million tonnes per annum. The company also operates two sales gas trains which supply gas to local industries.

LNG is natural gas cooled to –256°F (–161°C), at which its main component, methane, liquefies. As a liquid LNG is reduced to around one six-hundredth of its volume as a gas, which makes it a very attractive option for shipping in large quantities across the globe. It is stored and transported at atmospheric pressure at boiling point. LNG is an odourless and colourless liquid. It burns more cleanly than oil and coal.

Integrated asset management model

In today's competitive world obtaining and maintaining the highest plant reliability is a must. The implementation of best practice in operations, maintenance and spare parts management is paramount.

The road to a fully integrated asset management strategy to ensure the reliability and availability of equipment will contain many road blocks and will take several years. The end result will be an integrated system between departments that positions a company for the future. Initially asset management strategies for the equipment may not be perfect, but will surely establish a platform to start the continuous improvement process, something not many companies have.

Reliability improvement starts with a strong management commitment not only to start reliability initiatives but all the way to execution and continuous improvement.

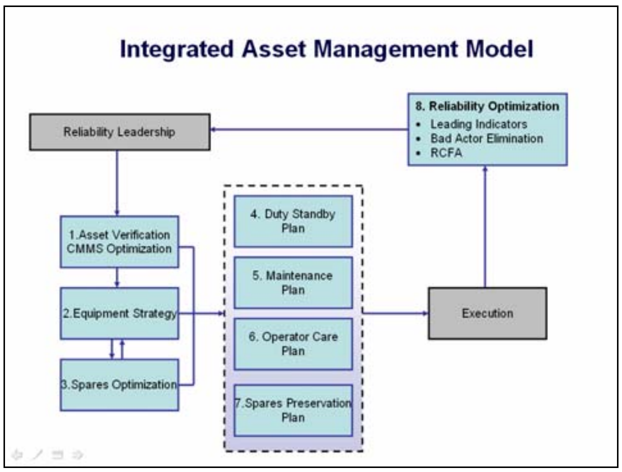

Figure 1: RasGas reliability optimisation model

Achieving a strong reliability performance is like building a house: one needs to start with the foundation. The foundation for high-reliability performance begins with having a computerised maintenance management system (CMMS) in place and correctly configured (Step 1 in Figure 1), such as a structured functional location hierarchy and consistent nomenclature. All equipment in the plant that requires maintenance or needs spare parts should be in the CMMS.

This first step is often skipped as it is labour-intensive and companies go with what is received from the initial project team. Most companies perform only minimum quality checks due to restrictions in resources to review the complete database received from the project team.

Step 2 is the building of the house and ensuring that the equipment maintenance strategies are in place. The objective is to have identified cost-justified maintenance and operator tasks for all equipment, to mitigate any risk of failure. In the process of developing equipment strategies assumptions are made on the availability of spare parts. It is important that these recommendations are taken into account in Step 3, spare parts optimisation. This step will determine minimum stock levels, re-order points and safety stock levels for all materials.

The outcome of these three steps needs to be translated into a duty-standby plan for spared equipment (Step 4), a maintenance plan (Step 5), an operator care plan (Step 6) and a spares preservation plan (Step 7), see Figure 1.

Just as a house needs continuous maintenance and improvements over time, so do the asset management strategies and plans. Systems and processes need to be in place and training should be provided to ensure correct execution and that any lessons learned are captured and implemented.

Step 8, reliability optimisation, the final step to an integrated asset management programme, integrates the various programmes into one system and starts the continuous improvement process. This is what differentiates the company from other companies.

This paper mainly focuses on how the company has overcome the challenges during this journey and the challenges still faced to implement a fully integrated asset management strategy. The main steps during this journey will be highlighted and explained in detail:

1. Asset verification and CMMS optimisation
2. Equipment maintenance strategies
3. Spare parts optimisation
4. Maintenance plan
5. Duty-standby plan
6. Operator care plan
7. Spares preservation plan
8. Reliability optimisation

For the purpose of explaining these steps the propane refrigerant compressor is selected as an example.

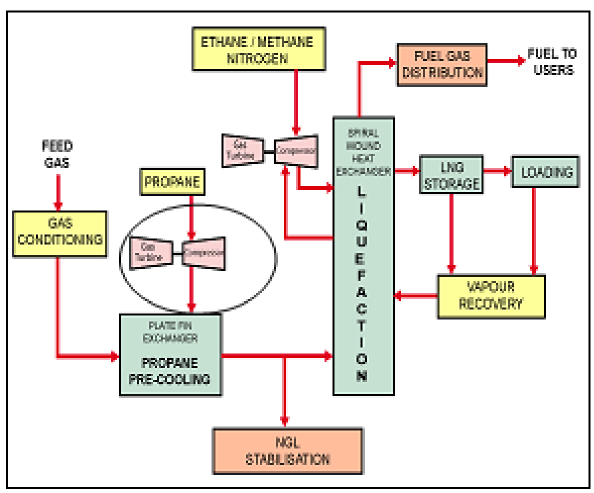

Figure 2: APCI Propane Pre-cooled and MR Refrigeration Cycle

Figure 3: View of Propane Compressor at Train-2

Feed gas chilling and liquefaction unit is at the heart of an LNG plant. The objective of the gas chilling, liquefaction and refrigeration unit is to produce LNG from which $C0_2$ and H_2S have been removed in units upstream. The company is using the APCI-patented propane pre-cooled mixed refrigerant (MR) process for Trains 1 to 5, where propane refrigeration provides the necessary pre-cooling of feed gas and cools it down to -31°F (-35°C) and then mixed refrigerants cool it down further to -256°F (-161°C) in the main cryogenic heat exchanger. This process is illustrated in Figure 2.

The propane system uses propane evaporation at three pressure levels to supply refrigeration to the feed gas and MR circuit. This is accomplished by flashing propane liquid at successively lower pressure levels in propane evaporators designated as HP, MP and LP evaporators. The propane compressor has two side loads at HP and MP levels see Figure 3. The compressor suction conditions are 1.5 PSI (0.1 barg) and -35°F (-37°C), while MP side load is at 33 PSI (2.3 barg) and 10°F (-12°C). The HP side load is 73 PSI (5.0 barg) and 32°F (0°C). Compressor discharge conditions are 258 PSI (17.8 barg) and 163°F (73°C).

The propane refrigerant compressor is an Elliott Make 88M7-5 single body, horizontal split casing compressor driven by GE Frame 7 gas turbine at a speed of 3500 rpm. The rated power consumption and flow for the compressor are respectively approximately 80460HP (60 MW) and 6144 $kNft^3/h$ (174 kNm^3/hr). Compressor nozzles are 60” (1.52m) and 30’’ (0.76m) respectively at inlet and discharge. The train is also equipped with a starting motor for compressor train start-up. The compressor rotor is made up of seven impellers in total: the first section has three, and the second and third sections have two each.

1. Asset verification and CMMS optimisation

Asset verification is the first step to a fully integrated asset management strategy. Basically, asset verification ensures that what is in the field and requires routine maintenance or spares is configured in a CMMS system. The ability to maintain equipment properly, and ensure that the correct spares are in stock at the right levels, depends on the quality and degree to which CMMS data is complete. The lack of a good maintenance programme and non-availability of spares will have a direct impact on the plant’s availability and safety.

General concerns at the company related to spare parts were:

- It was suspected that not all assets were recorded in the company CMMS.
- Inventory levels in the warehouse were not adequate to keep plant running at the uptime required. A high level of work orders were open, pending materials availability.
- The company bill of materials (BOM) concept was based on vendor recommended 2 year spare parts list (RSPL), rather than complete spare parts lists (CSPL).
- The BOM structure across the different plants (trains) was inconsistently applied. For example the BOM for identical pumps in Train 1 and 5 was often different.
- There was no standard method used to determine correct stock levels and replenishment. Stock level adjustments were manually calculated and uploaded. Typically individual stocking levels for stock keeping units (SKU) were only reviewed when field personnel requested a change.
- The total lead time (internal and external) for routine and non-routine materials was excessive in many cases.

Although CMMS optimisation is the first step in the integrated asset management model, at the company it was not started until after the equipment maintenance strategies project was in full swing. This generated extra work for the equipment strategy project team, since after asset verification 59,000 items of equipment were added to the CMMS system. It meant that the equipment strategy team needed to be reassembled on several occasions to go over the additional equipment. It would have been more efficient to have done the equipment maintenance strategies review only once.

Some companies delay starting their maintenance strategy optimisation programme until all the data in the CMMS is correct. The downside is that they operate for a prolonged period with ‘old’ maintenance strategies. For example, at the company asset verification was started in December 2008 and it is only recently that the first batch of asset verification data was uploaded in CMMS. The expected time frame to have everything uploaded is December 2010.

Methodology

In 2007 a project charter was developed and approved by senior management across the affected departments: Engineering, Maintenance & Supply (Procurement). This was essential, as CMMS optimisation and determination of correct stock levels involve different areas of expertise and stakeholders have different interests. For example, in the company, CMMS data (functional location, equipment data details, equipment strategy information) is controlled by the Maintenance Department. Material requirement planning (MRP) settings and the upkeep of the material master catalogue is controlled by the Supply Department.

The company also faces the same internal pressures as most organisations holding a large maintenance repair and operational (MRO) inventory. The Maintenance Department typically wants all spares immediately available and in stock. Finance and Supply Departments like to run with a lean inventory with a minimum of spares in stock. To find the right balance Reliability Engineering, part of the Operations Department, was assigned as the lead department.

The charter documented the objectives of the project, boundaries, team members, roles and responsibilities, project plan and schedule.

The main reason this project was delayed was due to its size, complexity, scope and resources. At the start of the asset verification project the company CMMS contained 270,000 equipment tags and 100,000 material masters.

One of the unknowns was how many items of new equipment would be found in the plant that would need to be configured in CMMS. To determine the exact scope of the project, a qualified consultant was invited to audit the Company CMMS system, work management and procurement processes.

After the audit it became easier to define the exact work scope. Nonetheless there were still several variables. A decision was made to tender with a fixed scope of work and include an additional ad-hoc portion based on price per item of equipment, to cover any additional scope that was not completely identified. This also created an incentive for the contractor to do a thorough job.

Some of the general concerns were confirmed and quantified in the audit. These included:

- Physical asset verification identified inconsistencies between plant and SAP.
- BOM structure was inconsistent. Parent equipments were not always clearly defined.
- Inconsistent processes for creating new functional locations, equipment and BOMs, resulting in different hierarchies across the plant.
- Inconsistencies in the nomenclature of existing material items.
- Duplicate materials.
- Delays in the current procurement process.
- The existing MRP (inventory management and control) process was not fully functional.

The preferred strategy was to award the contract to one company who could deliver all the objectives across all the phases. Due to the project nature, selected companies were invited to tender.

The project finally was divided into five phases:

1. Asset verification
2. BOM review & standardisation
3. Material data cleansing
4. Stock level optimisation
5. Spare parts philosophy

Phase 4, stock level optimisation, should follow a review of the maintenance strategies. The equipment maintenance strategy should drive the stocking level, and not the other way around.

Phase 5, spare parts philosophy, was written during the course of the project. Lessons learned, agreements between stakeholders, undocumented rules and other important information were documented and compiled in one document. This was sent for approval once the project was close to completion, just before the stock level optimisation exercise. It contains the information and agreements needed between different parties to start the exercise.

Asset Verification

The objective of this phase was to ensure that all physical assets in the plant were captured in CMMS, the data inside CMMS was complete and accurate, and the functional location hierarchy was consistently applied across all plants.

At the company the functional location hierarchy was in general based on ISO 14224, petroleum, petrochemical and natural gas industries – collection and exchange of reliability and maintenance data for equipment.

Using the propane compressor as an example, the propane compressor becomes the parent tag and the lubrication system, seal gas system and anti-surge controller become its children. Contrary to ISO 14224 the driver, in this case the gas turbine, will fall within the boundary definition of the propane compressor and become a child. The propane compressor boundary definition is shown in Figure 4.

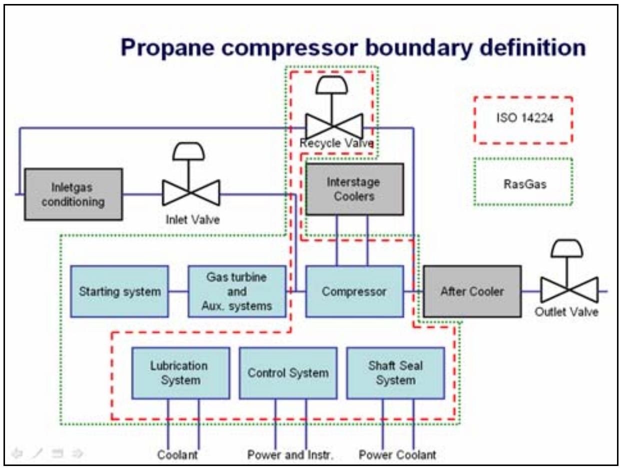

Fig 4: Propane compressor boundary definition

This phase was the most challenging and resource-intensive. A team of 20+ contractors were continuously working in the plant. In addition, the company provided a team of five multi-skilled technicians across all disciplines and a plant operator to facilitate the process. The contribution of this team to the project in terms of getting relevant permits to work (PTW), finding the maintenance personnel, assistance in preparing mandatory job safety analysis (JSA), assistance in getting the required documents and more specifically in QC, was key to the success of this phase of the project.

The methodology used is outlined as follows:

- P&IDs were used as a baseline. Field equipment name plate data was recorded and then compared with functional locations and equipment master data recorded in SAP.
- The data collected from name plates included tag number, original equipment manufacturer (OEM), OEM model number, serial number, physical location, height from ground, scaffolding requirements for potential future maintenance and various other information (e.g. material composition and sizes for valves).
- Management of change (MOC) documents that relate to design modifications, plant drawings or P&IDs, were captured at the physical verification stage to ensure these were updated and included in SAP data.

Upon completion it was found that that 90,000 items of equipment in the plant were not configured in CMMS. This included 25,000 valves, 9,900 junction boxes, 6,800 switches, 6,300 telecom and 5,500 gauges, as well as rotating equipment including 760 fin fans, 536 motors, 259 pumps, 46 gearboxes, 40 blowers and 29 compressors. As this equipment had not been configured in CMMS, it was likely that they had not been maintained in a structured way. It is probably also safe to assume that no spares or replacement parts were kept in stock for these assets.

Bill of materials review and standardisation

The objective of this phase of the project was to ensure that the existing BOMs in SAP are accurate and complete. Any spare part not included in the existing BOM or in the material catalogue was added.

Typical BOMs only included two years of operating spares as per recommended spare parts list (RSPL) and not complete spare part list (CSPL). As some of the company' trains are more than 10 years old, these older BOMs were often incomplete, which wasted time in searching for the correct part details in drawings and vendor documents. With this project the company moved to the concept of CSPL where, regardless of whether the material needs to be stocked or not, the item will show up in the BOM.

To make the BOMs more maintenance-centric and to reduce the number of material items per BOM, many new assembly BOMs were created. For example, in the case of the propane compressor, assemblies were created for bearing and seal arrangement thrust end, coupling assembly, compressor rotor assembly and dry gas seal assembly, journal end and special tools.

This activity was performed offsite at the contractor's home office. A team of about 30 engineers were engaged in reviewing a total of almost 17,000 unique BOMS. The BOM optimisation phase consisted of the following activities:

- Completeness of the existing BOMs in CMMS was reviewed and compared to sectional drawings in the equipment manuals. Checks were made to ensure that identical equipment had identical BOMs.
- Existing BOM structures were reviewed. All existing material masters were confirmed as belonging to the BOM.
- Extra attention in the review stage was paid to materials which were de-linked from the existing BOM.
- For BOMs with incomplete or missing data, the contractor used the Company RGDMS system, interviewed plant personnel and finally contacted the original equipment manufacturer (OEM), original construction manufacturer (OCM) or supplier.
- Some items identified in the Company spare part philosophy document do not require a complete BOM and only require a replacement component.
- Identification of part commonality between OCM and OEM part number.

Material data cleansing

The objective of this phase of the project was to ensure a consistent taxonomy and nomenclature throughout the existing material catalogue, that material descriptions were improved and that all duplicate material masters were eliminated.

This phase was performed simultaneously with BOM optimisation with the predominant activity occurring offsite. Material cleansing began as soon as the materials were confirmed in the BOMs. A total of 82,000 materials were identified to be cleansed. The following activities were performed:

- Material items were cleansed. Taxonomy was reviewed and where necessary standardised. Material descriptions and supplementary fields were reviewed.
- Maintenance-centric text was introduced in the material items. For example, simplified description, drawing numbers and technical reference numbers were added.
- The Company material master table was downloaded and an analysis was run in the contractors' software to identify potential duplicate SKUs.
- A review of material types was completed to ensure material masters were coded and assigned to the correct material type.

Lessons learned

Due to the nature and size of this project many lessons were learned. The most important lesson of all was to ensure that everything learned was captured in a document and that processes were documented and implemented to sustain and enable future improvements. Otherwise it would be necessary to repeat the exercise after a few years. Other major lessons learned include:

- Many equipment tags in the plant had missing name plate or name plates could not be read due to corrosion damage or other reasons. The total number of equipment tags with missing or corroded name plates, or names plates that were painted over or inaccessible, was 95,000.
- Accessing elevated equipment was a challenge. On average, scaffolding was erected for five or fewer items of equipment per week. To overcome this, a scaffolding team was set up under the Maintenance Department. It is recommended to organise a dedicated team at an early stage and to follow up progress frequently. It is also a costly exercise to erect scaffolding when it will be used for a very short period of time (5-10 minutes). It is recommended to investigate alternative means of accessing name plate details, such as a mobile crane. Scaffolding was erected in approximately 2,000 different locations.
- Hot weather in the Middle East is a challenge as summer temperatures can reach over 122 ºF (50 ºC). During summer, plant asset verification starts at 4am and finishes at 9am. After this time, the contractor engineers return to the office to record their results in the master database. The focus in the summer months was on equipment in shaded areas. In winter months, the focus shifted to outdoor equipment in open areas, such as the tank farm, jetties and the port.
- To verify equipment in critical packages, such as compressors and turbines, the complete unit needed to be shut down. It was not possible or sensible to shut down major equipment just for verification purposes. Nonetheless there was still some equipment that could not be verified because the shutdown schedule fell outside the project schedule. This activity will continue after the project concludes by the company personnel.
- The supporting document was not available in RGDMS for a significant number of cases. For some packages, spares exist in the BOM without any document references. Without equipment drawings and spare part lists, it is almost impossible to complete the BOM review and standardisation. To simplify the process in contacting vendors, the company provided the last PO number as a reference to contact the OEM or OCM. Further, a Pareto analysis was performed to focus on the main OEM/OCM only.
- During the course of the project, the Maintenance Department responsible for the review of the BOMs prior to uploading in SAP became overwhelmed with data provided by the contractor. Three independent engineers were contracted to review the completed BOMS. This requirement was overlooked at the initial stage of the project, resulting in some delay due to the time it took to hire these resources.
- About 25,000 or 30% of the existing material master records were "floating" in CMMS, or in other words were not attached to any BOM. It is most likely that the majority of these items will be attached to a BOM when the BOM review process is completed. The material masters who are not attached to any BOMs at the completion of this phase will be the first candidates to be reviewed for material obsolescence. It will, however, be difficult to completely rule these materials as obsolete if the BOM exception list is not narrowed down significantly.
- Parallel updating of the material master data by the Supply Department required the contractor to revisit the completed material items before final submission. This activity could have been avoided if an asset management system had been used with a direct linkage to SAP.

2. Equipment maintenance strategies

The second and the most important step in the process towards an integrated asset management strategy is to develop equipment maintenance strategies. This step is the foundation for long-term reliability of equipment and plant.

Prior to proceeding to Step 2, equipment maintenance strategies, it is essential to complete Step 1, asset verification and CMMS optimisation. This ensures that all rotating equipment and associated equipment are included in the equipment strategy project scope.

Part of asset verification and CMMS optimisation was to re-align the functional location hierarchy structure. A good functional location hierarchy makes it easy to identify which equipment belongs to a system. This is an advantage when determining equipment criticality or doing reliability centred maintenance (RCM).

Like many other companies the company did not complete the asset verification and CMMS optimisation before starting the equipment strategy project. This meant that the equipment maintenance strategies project team needed to be re-assembled to complete this additional equipment. It also caused inconvenience during the development and implementation of the equipment maintenance strategies project. For example, in the case of Fin-fan heat exchangers, several strategies were linked to one single functional location (the heat exchanger). This was because the functional locations for other components of the fin-fan heat exchangers, such as the motor and fans, were missing. These multiple strategies linked to one single functional location resulted in difficulties and extra work at the CMMS implementation stage.

Methodology

An equipment maintenance strategy can be as simple as “run to failure” and apply to many pieces of equipment. In other cases, it can contain a number of equipment degradation mechanisms for a single piece of equipment and comprise dozens of specialised maintenance tasks, executed by several different people.

The total project was divided into phases, according to the different asset categories. With so much equipment, it was essential to limit the number of strategies. The higher the number of strategies, the more difficult it would be to sustain the project results and initiate continuous improvement in the future. Therefore, before starting to generate strategies, it is essential to review all variables that will differentiate strategies: for example, for pumps, circulating lube oil vs. non-circulating vs. self-lubricating. This will help define generic equipment strategies and minimise the overall number of strategies.

An equipment strategy development team should be cross-functional, consisting of a facilitator, subject matter experts (technical and process), operations and maintenance representatives. The ideal group size is four to five people.

The company adopted a risk-based equipment maintenance approach, similar to failure mode effect analysis (FMEA). This methodology analysed individual equipment rather than systems, although there was some deviation in the case of rotating equipment. Key steps of process are as follows:

- Define unit performance objectives, operating plan and shutdown schedule.
- Identify equipment tags, define primary function, determine criticality for each equipment
- Review maintenance history, regulatory requirements, applicable guidelines and standards such as ASME and API
- Identify failure modes/equipment degradation mechanisms (EDD), consequences, probabilities and unmitigated risks
- Define cost-effective mitigation tasks and determine mitigated risks
- Gain management approval at the company.

The primary function of equipment and the scope or boundary of a strategy should be well documented to ensure that all accessories are analysed adequately to meet functional requirements.

As illustrated in Figure 2, the propane refrigerant compressor primary function is to provide pre-cooling to feed gas and cool it down to -31 ºF (–35 ^{0}C). It is important to document correctly to assess criticality and failure consequences.

Important auxiliary equipment, such as lube oil filters, inlet filter, seal gas filter and N2-filter to seal gas, are analysed with parent equipment.

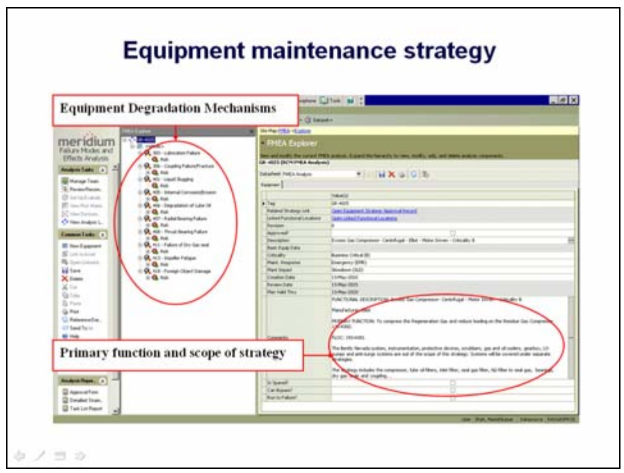

Figure 5: Equipment maintenance strategy

The financial and safety, health and environment (SHE) consequences of equipment failure are also well documented, which serves as a basis for any future strategy improvements.

The next step in the process is to identify all applicable equipment degradation mechanisms and analyse each for the unmitigated risk they pose. For our example of the excess gas compressor, all credible degradation mechanisms, such as lubrication failure, coupling failure, internal corrosion etc, were identified using a resource library and the past failure history of equipment, see Figure 5.

Once equipment degradation mechanisms are identified each degradation mechanism is analysed for possible failure scenarios. The risk of each failure scenario is mapped and the highest unmitigated risk is used for benefit-cost task evaluation.

Coupling failure EDD will be used to explain the methodology in more detail. The coupling failure scenario is determined as: failure resulting in parts penetrating coupling guard (parts uncontained), with potential for injury of personnel in surrounding area, and compressor trips on high vibration resulting in plant shutdown.

For this scenario total repair time was estimated to be one week, including replacement, alignment, start-up and shutdown time (assuming spare coupling is available), resulting in a financial consequence of category-I.

Once consequence is estimated, failure probability is estimated using past failure data and team experience. The combination of probability and consequence is mapped on a risk matrix to evaluate unmitigated risk. If risk is in a low risk area, as per the established risk matrix, then no mitigation tasks are proposed. In the case of the coupling failure, financial risk is estimated to be C-I, which requires mitigation while SHE risk of failure is estimated to be D-III, which does not require mitigation.

As a best practice all coupling parts with material numbers are listed in the strategy, and strategy evaluation of the spare coupling requirement will be used as an input in the minimum stock level determination exercise as a part of spares optimisation, see Figure 6. This integration ensures availability of necessary parts to mitigate the risks as identified in the equipment maintenance strategy.

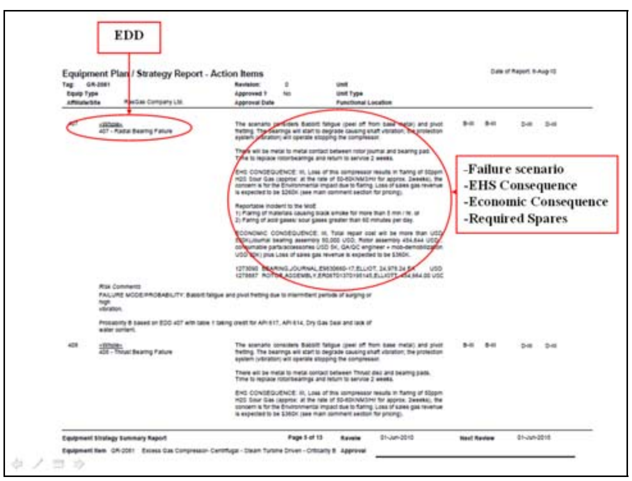

Figure 6: Equipment maintenance strategy report

The next logical step is to determine cost-justified tasks to mitigate the financial risks of coupling failure EDD. Team experience, industry best practices and the resource library is used to determine task, executing party and task frequency. In this case the team decided that detailed vibration analysis and trending can reduce probability of failure from C to D.

During task development all necessary details, such as detailed description of task, crew category, equipment status (i.e. on stream or off-stream) among others, are documented so that implementation of these tasks in CMMS is minimised.

Once all identified EDDs are analysed and mitigation tasks have been developed, the team reviews the complete strategy to make sure all unacceptable risks are either mitigated or, in cases where no maintenance tasks can be developed to mitigate risks, either design changes are recommended or residual risks are documented for management approval.

The final step is to have all strategies documented and approved by management. The approval team consisted of the maintenance, manufacturing and engineering managers, or their delegates.

Asset management system

Due to the huge size of the project, it was important to work with more sophisticated tools than standalone applications, developed in-house, running on MS Excel and MS Access. Initially MS Access was used to develop the equipment strategies and MS Excel to link them to specific equipment. However, once the project team size increased, there were several copies of the master file floating around. People could not access the data simultaneously and master files were split, making control of the files even harder.

During the course of the project it was decided to transfer all MS Excel and MS Access data files into an asset management system fully integrated with CMMS. There are numerous benefits to such a system, including the following:

- Enables the team to leverage existing work. The existing library can be used for new plants.
- Delivers synergy between applications, such as production loss events, bad actor elimination program.
- Provides business control, for example: programmed rules ensure a foolproof system or a system that records the history of changes.
- Ensures sustainability and enhancement through integrated reporting.

Business controls make sure that things are done the right way, for example:

- A strategy can only be applied to equipment if the strategy and equipment criticality are the same.
- The system does not accept duplication of strategy numbers.
- Strategies will have a revision history and are therefore auditable.

- Changes to strategies are tracked and old values can be recalled if required.

Lessons learned

As the company is a rapidly expanding organization, the project scope has been continuously increasing and various associated challenges were faced during each phase of project.

Although preparation was done thoroughly and management was fully supportive and championed the project, there were challenges too:

- Several other projects were initiated simultaneously. These initiatives had equal priority, resulting in limited resources being dedicated to equipment strategy development sessions.
- Traceability of documentation was also a challenge. Project deliverables, such as the equipment database and equipment criticality study, were in the process of being uploaded in CMMS. Also, electronic storage of documents such as datasheets, P&IDs and as-built drawings, was in full swing.
- Because of prevailing labour market conditions in 2006, it took considerable time to recruit staff with the required skill set for this project.
- With an increased team, multiple equipment strategy sessions were organised in parallel. Each sub-team focused on one area, such as electrical equipment. As multiple sub-teams were operating, the key was to maintain consistency across the teams. Weekly meetings were set up to discuss daily items and plan ahead.
- The MS Excel and MS Access applications that were developed in-house proved to be inadequate, causing problems such as capacity limitation, data quality enforcement issues and no record of revision history. As the applications were not integrated with CMMS, no current data was available. Applications were problematic in a multi-user environment. Also, in disaster recovery situations a far more robust solution was required than a standalone application. To overcome these application challenges, methodology and history were migrated to a single asset performance management system with the capability to handle a large amount of data and integrated with CMMS.
- To handle the large volume of incoming requests, a new module in the Company asset performance management system was created to store, track and manage these requests.
- Having completed nearly 100 per cent of the strategies, resources will be reassigned to other tasks. The challenge will be to keep the team intact and to move from 99 to 100 per cent completion. The remaining tags will be very difficult to close out. Problems have been encountered such as missing documentation, unrecognised tags or no available maintenance history.

3. Spare parts optimization

With the equipment maintenance strategy project nearing completion, the next project initiative in the integrated asset management strategy is spare parts optimisation. The objective of this phase is to “ensure the right spare parts are physically available in the right quantity and quality, complete with the correct technical information to ensure safe operation, plant reliability and smooth maintenance execution.”

As explained in the previous section, equipment maintenance strategies are developed to ensure equipment perform within their safety, environmental, regulatory, quality and reliability limits to guarantee long term sustainment of their function. The identification of spare parts is an integral of the equipment maintenance strategies process. For example, a particular equipment failure will have a lower consequence due to the fact that a spare part or replacement component is held in warehouse stock. If this part is to be removed, the impact of the equipment failure may have a higher impact due to the prolonged repair time and associated consequence.

Any review of spare parts and inventory levels should take into consideration the applicable equipment maintenance strategy which that spare part belongs to. This is particularly relevant if minimum stock levels or MRP settings are proposed to be reduced. In general, the equipment maintenance strategy should be the guiding principle behind whether a spare part is to be held in stock or not, and not the other way around.

Methodology

Before starting with this exercise, an overall company wide spare parts philosophy is required to be in place to guide the decision making process of personnel involved in recommending spare parts. This document describes the guiding principles, inventory management basics, the need for carrying inventory, the criteria for stocking or not stocking parts and defines the different types of inventory at the company and their subsequent treatment.

The objective of the spare parts philosophy is to drive quality stocking policies, processes and execution to:

- Prevent excessive purchase of materials
- Improve availability of materials
- Ensure the right spares are available when required
- Reduce the level of obsolescence and write offs.
- To save money through reduced unnecessary expenditure and improved plant reliability and availability through reduced downtime.

The stock level review process needs to ensure that all concerning parties are involved. At the company the following process was followed; see Figure 7. A list for all relevant material items, with maximum, minimum (reorder level) and safety stock level was compiled.

Wherever consumption history was not available, the MTBF approach was used.

The recommendation received through this specialised stock decision-making software tool was first reviewed by the Supply Department. The results were handed over to Maintenance and Engineering Department for review. Finally a cross-functional team was set up to review the recommendations and discrepancies. The team consists of a reliability engineer, who facilitates the meetings, a subject matter expert (SME), a Supply Department representative and a Maintenance Department representative. The review lists will be broken down by discipline to help with the review and to ensure the correct personnel are involved in the decision making process.

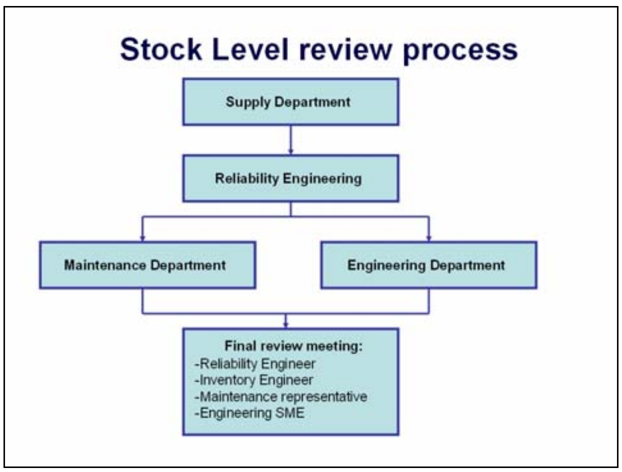

Figure 7: Stock level review process

Initially the company material criticality was entirely based on the type of commodity. Today, to arrive at a final material criticality both material classification (type of commodity) and the equipment criticality are considered. This material criticality matrix (see Figure 8) is an example of how the company has tried to overcome different interests between departments. Material criticality will be the main input to determine the service factor/level.

Existing Equipment Criticality	A	B	C	D
A	EC	EC	HC	MC
B	EC	HC	HC	MC
C	HC	HC	MC	LC
D	MC	MC	LC	LC
	Existing Material Classification			

Color Legend	Extreme Critical	High Critical	Medium Critical	Low Critical

Figure 8: Material criticality matrix

Generally, for materials to be in the most critical category, three elements must be present:

1. **Risk:** the failure scenario must fall within a consequence I or II of the risk matrix.
2. **Mitigation:** the spare part is required to mitigate the scenario.
3. **Availability:** the spare part is not routine, meaning that the material is not readily available off the shelf from the supplier.

Materials with the highest criticality rating must be reviewed and stewarded closely. Key performance indicators (KPI) should track the management performance of these parts, highlighting any specific issues (e.g. stock-outs). The monthly status of these critical spares should be shared with appropriate business lines (asset teams). Any gaps identified must be highlighted by Operations and given to the Supply Department for stewardship and resolution.

Other parameters used to determine required stock levels are, for example:

- Cost of the item
- Mean time between repair (MTBR) in case of no usage
- Potential production loss associated with equipment failure
- Supplier delivery time (existing company data)
- Potential environmental and safety impacts
- Number of identical items in the plants (installed base)
- Repairability
- Previous consumption history
- The company's equipment maintenance strategy
- The company's sparing philosophy
- Parts commonality
- Shelf-life

The results of this exercise determine maximum, minimum (reorder) and safety stock levels.

Lesson learned

Without doubt, the major challenge faced in this phase of the project was data quality. Many different variables influenced the ultimate and final stock level figures. Obtaining key data or "suspect" critical data was time consuming and achieved mixed results. Lead times and price information were the two key fields that created the most issues.

Parameters with insufficient or erroneous data in SAP were:

- Lead times (internal and external)
- Price (typically no price or older than five years)
- Consumption patterns.
- Incorrect repairable data
- MTBF data
- Parts criticality

Another challenge was the resources required to review the recommendations proposed by the stock level decision-making software tools. Engineers and technicians had to spend a significant amount of time reviewing the results.

4. Duty – Standby Equipment Plan

The duty-standby philosophy is a direct deliverable from equipment maintenance strategy project, Step 2 in the integrated asset management model. It is important that this step is executed before Step 5, the creation of a maintenance plan.

If the duty-standby schedule is available at the time of developing maintenance plans, it will be easy to align the maintenance tasks that require shutdown of the duty equipment or start-up of the standby equipment with the duty-standby schedule. In The company's case this was not done, resulting in many maintenance exceptions and in lower preventive planned maintenance (PPM) compliance.

The important thing is not which philosophy a plant adopts, but that it executes and adheres to the philosophy it chooses.

The company has chosen to operate with dedicated standby equipment, rather than a 50-50 configuration where both pieces of equipment operate alternately. This choice ensures that serviceable equipment is available when in the event of equipment failure. It has the added advantage that equipment with wear-type modes of failure will not reach end of life at the same time. Operating with dedicated standby equipment will also ensure that duty equipment will be run at optimum operational settings, instead of running in parallel at a non-optimal partial loading.

Methodology

Starting a pump or compressor causes the most severe transient stresses that a piece of rotating equipment, its seal(s) and bearings are subjected to. The more frequently a piece of equipment is started, the lower its reliability – mean time between repair – becomes. To ensure that standby equipment has not degraded and is not in a failed state, it must be tested. However, there is a balance between increased confidence in standby equipment and damage or wear caused by testing. In other words, there will be an optimum point between testing and equipment preservation.

Equipment can be divided into two groups: duty and standby. Equipment used very infrequently should be considered standby equipment and should be maintained and tested accordingly

The company applies the following two definitions for its rotating equipment:

- Duty: equipment running more than 10% each year, including plant shutdown and maintenance.
- Standby: equipment running less than 10% each year.

Where equipment has been designated as standby but is operated at more than 10% per year the equipment maintenance strategy must be revised accordingly.

The general arrangement of duty-standby equipment at the company is illustrated in Figure 9.

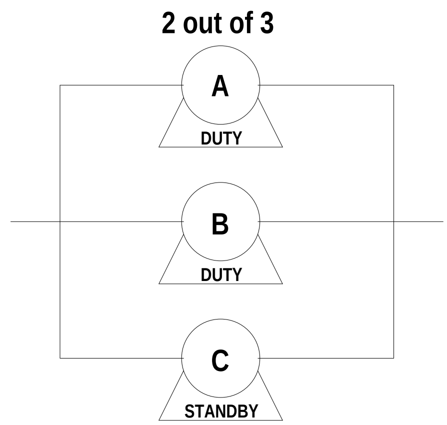

Figure 9: Duty-Standby arrangement

In a Duty-Standby configuration, the equipment with the last letter in alphabetical order will be considered as the Standby equipment. For example in a 2 out of 3 configuration, the C-equipment will be considered as the Standby equipment and is stopped, but available to take over from A or B.

In a duty-standby configuration, the equipment coming last in alphabetical order will be considered the standby equipment. For example in a 2 out of 3 configuration, the C-equipment will be considered the standby equipment and is stopped, but is available to take over from A or B.

Frequency of testing

In the equipment maintenance strategy, Step 2 in the integrated asset management model, criticality levels for all rotating equipment are established by a multidisciplinary team.

The criticality definitions are as follows:

- A-critical: loss of primary function results in SHE consequences, level I or II.
- B-critical: loss of primary function results in economic consequences, level I or II.
- C-critical: loss of primary function results in economic or SHE consequences, level III/ IV

The frequency of testing is based on the criticality of equipment is detailed in Table 1.

Table 1: Frequency of functionality testing, based on criticality

Criticality	Frequency of functionality testing
A	Every 1 or 2 weeks
B	Every 1 month
C (III)	Every 3 months
C (IV)	Every 1 year

None the less, there will be exceptions, such as in the case of the propane compressor as explained below.

The auxiliary lube oil pumps test run schedule is each 2 years, during the plant shutdown. The risk of the propane compressor shutting down during the pump test run cannot be ignored – the consequences are very high.

The same applies for the emergency DC lube oil pump. For this pump too, the test run schedule is every 2 years during plant shutdown. In addition, there is a standing instruction to test the emergency DC lube oil pump after every trip of the unit.

Exceptions are documented in the equipment maintenance strategy itself as well as in the duty-standby philosophy procedure

Duration of test run

Unless operational requirements do not permit, the duration of testing is as follows:

- Onshore standby equipment in general should be test-run for 48 hours to allow the Maintenance Department to conduct the necessary monitoring and performance activities on it. It also allows maintenance activities to be conducted on the stopped duty equipment.
- Offshore standby equipment is test-run for a period of 6–8 hours; the reduced window is for logistical reasons.
- Auxiliary equipment such as lube oil pumps, oil priming pumps, standby fans and coolant pumps should be test-run for a period of 4 hours. In this way, changeover can be executed by the same operator, who started the equipment.

Coordination of test runs

All test runs of standby equipment will be driven from a test-run schedule as agreed by Manufacturing and Maintenance Departments. An example schedule is shown in Figure 10.

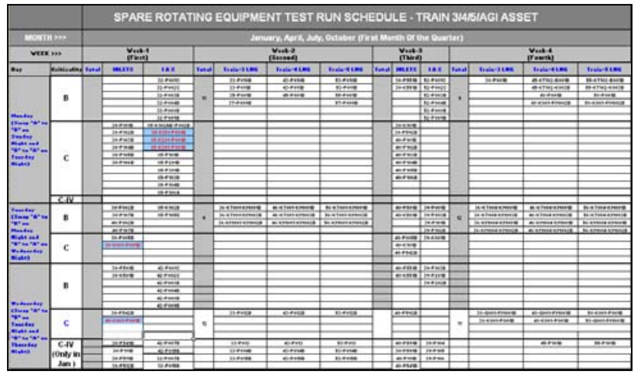

Figure 10: Test run schedule

When compiling the test run schedule, care must be taken as much as possible to perform equipment test runs on Mondays or Tuesdays to enable preparation for maintenance activities.

Normally, duty equipment should be stopped so that monitoring activities (vibration monitoring, performance monitoring etc) on standby equipment are not influenced by running equipment.

Maintenance on duty equipment that requires equipment to be shut down should be scheduled when standby equipment is being tested.

Lessons learned

The initial test-run coordination set up appeared not to be successful. The intention was to have all test runs of standby equipment configured in CMMS: the Maintenance Department would provide the Manufacturing Department with a monthly list of equipment to be tested; the Manufacturing and Maintenance Departments would meet in the monthly operations, maintenance and technical (OMT) meeting to align upcoming maintenance activities with the test-run schedule of standby equipment.

After a trial period it was decided to change the approach and compile an annual schedule in poster format, as outlined previously. This schedule is now posted in areas such as the Condition Monitoring Department, and the planning and control room.

Another challenge was compliance. Initial compliance was in the 20–50% range. Equipment could not be tested sometimes due to technical reasons, but more often due to poor performance of the staff responsible for testing.

By setting up a simple KPI, implementing duty-standby compliance and giving responsibility back to the asset teams, compliance shot up, and is now in the 80–100% range. When equipment cannot be tested now, it is mostly due to legitimate reasons, such as unavailability of spares.

5. Maintenance plan

Often equipment maintenance strategy projects do not deliver the intended results, or they are abandoned in the implementation stage because they appear too complex to implement. That's what this step in the integrated asset management strategy model is about: translating the output of Step 2 into executable work orders.

There are many steps in converting an equipment maintenance strategy into a work order with sufficient detail so that it can be flawlessly executed within the defined time bounds. The real challenge is getting all the developed equipment maintenance strategies implemented in CMMS.

Methodology

Equipment maintenance strategies implementation can be broken down into five phases. The list below is not complete, but highlights key items that must be taken into account for a successful implementation.

1. Verification
    - Checking the coherence of proposed tasks
    - Physical field verification
    - Determination at task level. Examples include;
        - Operating condition (running, not running, plant shutdown etc)
        - Task duration estimation
        - Practicality
        - Accessibility
        - Preparatory work requirement
        - Skills and man-hour requirements
        - Material (spares, consumables) requirements
        - Special tools and equipment needed
        - Permits, job safety analysis (JSA) and critical procedures
2. Grouping and data preparation
    - Combine multiple tasks on equipment
    - Prepare task lists, maintenance items with objects, maintenance plans, as outlined in Figure 11.
    - Determining multiplication factors on efforts and resources
    - Route optimisation
3. Plan initialisation
    - Synchronisation with last preventive maintenance performed
    - Segregate shut down plans
4. Test load and proving
    - As a general rule: anything that can go wrong will go wrong.
    - Use test database to validate everything. But a test database may not have all the production data, so do not assume a task will work perfectly in the production environment, simply because does so in the test database.
        - Load task lists and maintenance items with associated objects and maintenance plans
        - Set initial dates for plans and carry out schedule simulation
        - Reconfirm assumptions and constraints
5. Production activation
    - Load task lists and maintenance items with associated objects and maintenance plans in production environment
    - Schedule maintenance plans to generate call objects ensuring that sufficient planning time exists

Figure 11 is a representation of the mapping process in CMMS for the company.

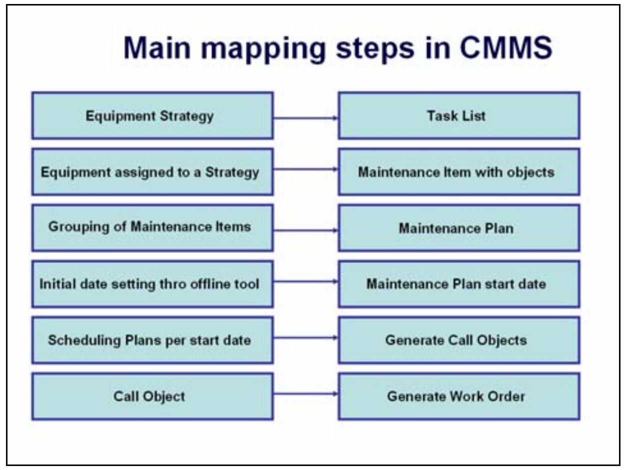

Figure 11: From equipment strategy to work order

A test client was created and populated with a copy of production data. Several simulations were carried out towards defining a final implementation approach. Upon completion, a master plan for implementation was presented to the project sponsors. Due to the nature of the work involved, the implementation activities were recommended to be managed as a sub-project, in the Maintenance Department, outsourcing labour-intensive work such as physical asset verification.

In order to define the dimensions of implementation, a pilot project was initiated. Representative samples from offshore and onshore facilities were selected, covering 10,000 items of equipment. Lessons learned from the pilot project helped to smooth the execution process. None the less, since initial implementation in 2008, more than 1,000 field requests have been received.

Within the company asset management system a module was developed to automate and control the request process. The system allows all incoming requests and feedback to be managed smoothly. Each field request receives a tracking number, description, date, request category and priority, and a solution leader is assigned. The system is accessible to everybody at the company and a field request's status can be tracked by its originator at any time.

The feedback has been classified in categories such as strategy clarification, re-linking of equipment to strategy, RCFA feedback and master data modifications – see Figure 12.

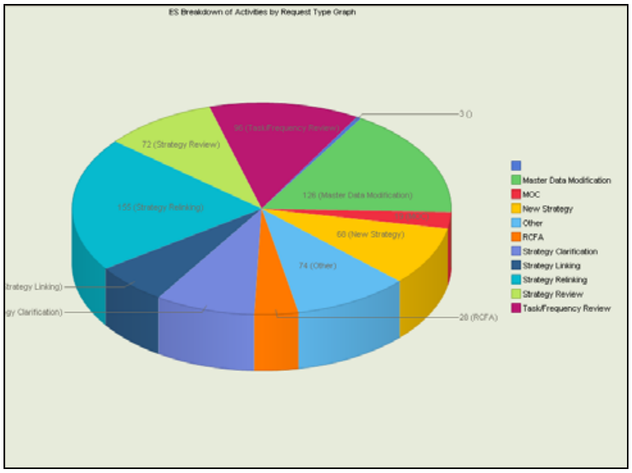

Figure 12: Equipment strategy feedback breakdown

The key to flawless execution is to minimise this type of discrepancy ensuring early adoption of new tasks by maintenance technicians. However, it is wishful thinking to believe that every discrepancy can be eliminated before implementation, so a system and process must be set up to deal with the expected feedback.

Within the company asset management system a separate module was developed to automate and control the request process. The system allows all incoming requests and feedback to be managed smoothly. Each field request receives a tracking number, description, date, request category and priority, and a solution leader is assigned.

The system is accessible to everybody at the company and a field request's status can be tracked by its originator at any time.

Lessons learned

The lessons learned helped the company in the final implementation. They included:

- Lessons learned related to the CMMS configuration, such as:
  - External number ranges for maintenance plans and maintenance items
  - Development and usage of mass change tools
- Since many activities such as asset verification are labour-intensive, an outside company with specialised knowledge was contracted to support the implementation team.
- During the equipment strategy development phase and the field verification phase, no attention was paid to determining plant shutdown requirements. This resulted in extra work during the risk-based work selection screening process for shutdown work.
- The development of a system and process to manage the significant amount of field feedback received from maintenance technicians.

6. Operator care plan

An operator care, or the operator-driven reliability programme is an integral and essential element of an integrated asset management strategy. The success of an equipment maintenance strategy depends to a great extent on flawless execution of maintenance, operator tasks and continuous feedback for improvement.

The benefits of a structured operator care programme are enormous. A successfully implemented operator care programme not only results in improved safety and reliability at reduced maintenance and operating cost, but also has long-lasting benefits such as increased ownership among operators and a reliability mindset at working level.

Most of the company will have some form of operator care program but the questions to be answered are:

- Are operator care tasks driven by risk-based equipment maintenance strategies?
- Do operators know why they are observing certain parameters and when they need to act?
- Are operator rounds structured for optimisation, and how is information recorded?
- Are the operating envelopes for equipment defined?
- Are operator tasks monitored and optimised for value addition?

Prior to development and roll-out of the structured operator care programme at the company, the answer to all those questions was no.

The operator care programme ensures that operators at consoles and in the field perform necessary monitoring and perform field tasks that ensure equipment is operated within its defined operating envelope and operated within critical parameters to ensure reliable performance.

Moreover, the operator care programme drives the accountability and ownership of operators. Deviations and abnormalities observed are translated into potential operating savings. In addition, operators are rewarded, based on the potential savings.

Methodology

Many good programmes fail due to lack of organised effort and teamwork. The operator care programme was very well thought through and a structured approach was adopted. In 2009 a multidisciplinary team, consisting of a field operator, a panel operator, a reliability engineer and subject matter experts (SME), was chartered to work on a pilot project for the Train 1and 2 asset team.

It was agreed to adopt a phased approach based on importance and the ease of implementation:

- Phase-1 was to develop and implement structured rounds for field and console operators, and to monitor execution and compliance.
- Phase-2 was to provide operators with basic maintenance skills to execute first-line maintenance, such as lube oil top-up and replacement, so that response time to deviations would be minimised. This phase also included the adoption of a portable data collector tool to automate the process.

The necessary steps in development and implementation of a structured operator care programme are:

- Set minimum standards for operator care tasks.
- Develop and select surveillance, data collection and operator tasks needs.
- Transfer knowledge to operators of how and when to perform operator care.
- Provide rationale and expectations for operator care to ensure ownership and accountability by operators.
- Provide the necessary execution steps to ensure that execution is done properly.
- Ensure that equipment returning to service is correctly commissioned.
- Provide a feedback loop to ensure that operator care is achieving the desired results.

The overall operator care process steps are outlined in Figure 13.

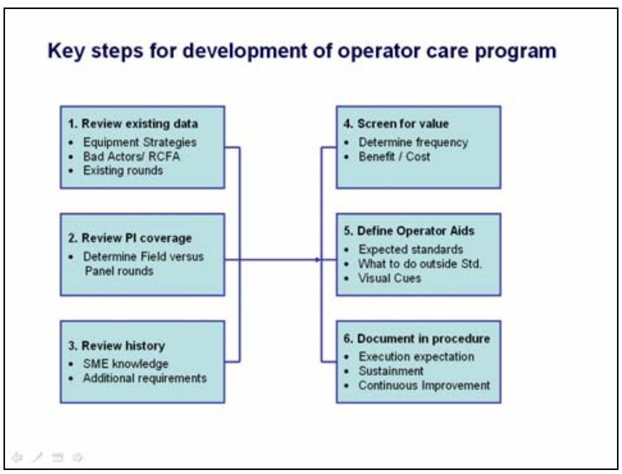

Figure 13: Key steps for development of the operator care program

The following example (the propane refrigerant compressor and driver gas turbine – GE Frame 7EA) demonstrates how different elements are integrated in a structured operator care programme.

Minimum standards

The minimum standards set the lower-level, non-specific activities that an operator is expected to perform, regardless of the specific tasks that could be set for that shift. Examples include a response to an unusual noise or smell while walking through the unit performing a data collection round.

Some of the minimum expectations for a field operator are:

- Walk through the unit at predetermined frequencies and investigate abnormalities.
- During the rounds gather information using all senses:
    - Smell (odour issues, overheating equipment)
    - Noise (unusual noises, leaks or faulty bearings)
    - Visual (emissions, flame patterns, housekeeping)
    - Feel (bearing temperatures, vibrations)
- Check for physical condition such as corrosion and loose or missing items.
- Ensure that minimum housekeeping standards are maintained within their area of responsibility.
- Perform line-up checks (for example, standby equipment).
- Take responsibility for the minimum safety and personal protective equipment compliance.
- Be responsible for ensuring all general use and protection safety equipment is functional and assessable.
- Check equipment handed over to operations from maintenance, construction or project staff.

The panel operator, as part of his monitoring activities, must:

- Review the alarm management at the start of the shift.
- Respond to DCS alarms and alerts, and investigate and correct abnormalities.
- Control equipment within operating envelopes.
- Optimise unit production and costs.
- "Walk through" DCS screens.

Structured rounds

The purpose of structured rounds is to provide a consistent, efficient and effective method for conducting operational activities and tasks. It integrates data from regulatory requirements, RCFA, the bad actor elimination programme and equipment maintenance strategies with operator knowledge on how to operate equipment safely and reliably to optimise plant reliability.

In a generic approach, single operator rounds include both observation and data collection rounds. At the company, in accordance with the risk-based approach, more frequent field surveillance rounds were separated from data collection rounds. Frequency of surveillance and data collection rounds were based on equipment criticality: more frequent rounds for critical equipment.

The structured rounds cover all propane compressor and gas turbine systems, such as the lube oil system, air intake filter, mist eliminators, fuel gas system, Exhaust stack, CO_2 system etc. The sequence is organised in the most efficient way, for example west, south, east, north.

- The primary focus of **Operational observation or surveillance rounds** is to ensure (a) that equipment and systems are operating within the specified operating envelope and (b) early detection of deviations and abnormalities. A surveillance round for a compressor includes activities such as lube oil return flow, DP across mist eliminator, visual or infrared temperature gun inspection for hotspots on the driver exhaust systems, CO_2 tank level and pressure, and bearing drain temperatures. Each activity was screened for value addition and frequencies were set accordingly. Operator aids, including visual cues, were developed to clearly define minimum expected standards and actions in case of deviations – see Table 2 and Figure 14.

Table 2: Field operator surveillance aid

Observation	**Expected standard**	**Action if outside of standard parameters**
CO_2 system	• No loose or missing covers	• Raise notification of any abnormalities
16-KT004-KM005A/B-K005A/B 16-KT004-KM006A/B-K006A/B	• CO_2 tank PSV is not popping / passing	• Ensure that tank pressure is within range and compressor is running normally and check the PSV setting
Refer to visual cues on page 27 for CO_2 tank pressure and level gauge	• CO_2 tank level should be > 70%	• Raise notification to make up CO2

Gauge #	Description	Normal Range	Troubleshooting Steps
1	CO2 Tank Level	Should be > 70 %	Raise notification to make up CO2
2	CO2 Tank Pressure	Should be 20 – 22 barg	- If pressure high, check to ensure the CO2 compressor working normal and no PSV popping / passing - If pressure low, ensure only one CO2 compressor is running

Figure 14: Visual cue CO_2 system field surveillance

- The primary focus of **field operator data collection rounds** is to collect operational information on pressure, temperature, flow, vibration speed etc that is not typically collected by facilities DCS. This enables a more complete operational picture for equipment surveillance. Data collection rounds for a compressor include recording parameter values and trending over time. A typical operator aid is illustrated in Table 3.

Table 3: Field operator data collection aid

Observation	Expected standard	Action if outside of standard parameters
Accessory compartment	Reservoir oil level should be 25% – "FULL" mark on the field gauge (every 3 months)	See actions in the field observation section
Lube oil system	Lube oil pump discharge pressure should be 7 – 9 barg (every first D/S and second N/S) Auxiliary Pump will automatically start at 4.8 barg	See actions in the field observation section
Oil cooling system	Flushing of standby oil cooler CW side should be done (every three cycles on first-N/S)as per RCFA recommendation	See actions in the field observation section

- The primary focus of **Console or panel operator rounds** for compressors is to determine parameters to monitor and to establish integrated operating envelopes. Operator aids were developed to clearly define minimum expected standards and actions for deviations - see Table 4.

Table 4: Console operator aid

Observation	Expected standard	Action if outside of standard parameters
Review DCS screen for the propane compressor	N_2 separation gas filter differential pressure (16PDI-693) should be < 0.1 bar	Ask operator to change over the strainer and raise notification for strainer replacement
Review DCS screen for the propane compressor	Axial / thrust position should be < 0.5 mm (ABS) displacement	Check for any surging indication and correct it, if surging can't be corrected, discuss with supervisor for further actions. Check axial / thrust position trending: if it has risen gradually consult with supervisor on further actions. If one out of two probes have failed, raise notification
Review DCS screen for the propane compressor	Compressor suction pressure (16PI-637A) should be 0–0.2 barg and first-stage deviation (16XI-652) should be positive (+)	If suction pressure is low, check whether any level upset in the LP propane evaporators 15-E004 and 16-E007 is causing less propane vaporisation Cross-check with 16PDI-632 to ensure no strainers are dirty (DP < 0.01 bar)

- **Integrated Operating Envelopes** are defined by integrating multiple operating envelopes to define the range of acceptable operating conditions for selected critical parameters (such as minimum and maximum flows, pressures, levels ,temperatures, speed and voltage) that can be manipulated from the console or locally. Operating envelopes are divided into three tiers;
    - Safe operating envelope- operating limit must not be exceeded. Immediate and defined actions to remain or return within target range should be taken. Exceeding safe operating limits will probably result in a consequence level I (> 10 Million USD) or II (>1 Million USD) incident. Action to be taken is to record, evaluate and investigate the deviation. This envelope is typically alarmed in distributed control system (DCS).
    - Reliability envelope - generally defines the best reliability range for equipment, where exceeding the limits will result in accelerated wear of equipment or process degradation that could lead to a consequence level III (>100k USD) or greater. Action to be taken is to record, evaluate and address repetitive or continuing deviations. This envelope may be alarmed in DCS.
    - Optimization envelope - deviations outside these limits will result in a quantifiable value loss either cost or volume. Deviations outside of these envelopes should be corrected on a value priority basis and defined actions to be taken to return within limits. If a return to within these limits is not possible, then the reason should be recorded. Optimization alternatives should be evaluated and operation envelope limits corrected. This envelope is normally not alarmed in the DCS.

  All operating envelopes will have a documented rationale covering why they are important and, in general terms, the expected actions to be taken to return to optimal operation.

Round evaluation and feed back

The execution measurement and feedback to shift personnel is extremely important for a successful operator care programme and for developing a reliability mindset. The company has developed and implemented shift handover guidelines to monitor execution of operator rounds.

The purpose of a structured shift handover is to ensure sufficient knowledge transfer from one responsible person/group to another and thereby limit operational and SHE exposure as result of lacking information. Measures to track operator execution – such as the number of rounds completed against those required, and actions taken against deviations etc – are built into shift handover.

Figure 15 shows the basic structure and systems of an operator care programme and its continuous improvement cycle.

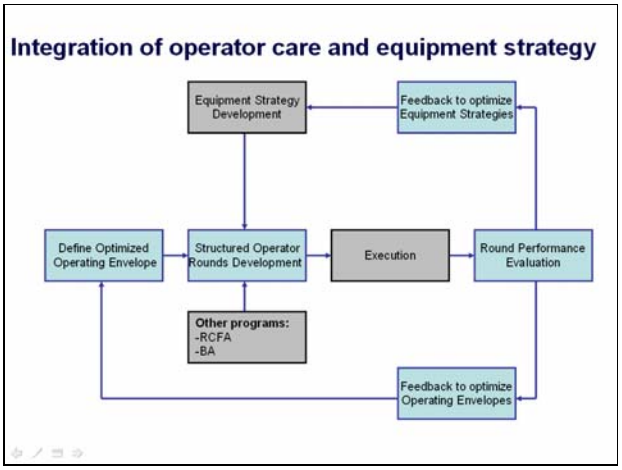

Figure 15: Integration of operator care and equipment strategies

Lessons learned

The initial approach to constructing operator rounds was based on the functional location hierarchy in CMMS. Unfortunately this didn't result in efficient routes, as pieces of equipment, even for single systems, were scattered across the plant. By using plot plans (equipment layout plans), physical locations of the equipment in the plant could be determined. Equipment was grouped according to its physical location rather than its functional system.

7. Spares preservation plan

Maintenance and management of materials is another key element in an integrated asset management strategy. This step can be done independently and therefore be executed in parallel with steps 4, 5, and 6 of the integrated asset management strategy model.

Most maintenance professionals have experienced equipment failures in the plant for which spare parts were not properly preserved. A spares preservation strategy is a must to sustain the reliability of spare parts. The strategy should focus not only on preservation tasks, but also on storage requirements.

Currently about 15 spares preservation strategies for rotating equipment are approved by management. They cover spares such as rotors, reciprocating machine spares, nozzles and diaphragms, blades, bearings and seals. Implementation of these strategies is in progress.

Methodology

The methodology followed is basically the same as that for the development of equipment maintenance strategies. A cross-functional team must be set up – in this case comprising a representative from the engineering, maintenance and warehouse areas.

First, degradation mechanisms and unmitigated risks are determined. For example, in the case of storing the propane compressor rotor, the degradation mechanisms will be rotor bow and atmospheric corrosion, as illustrated in Figure 16.

Risk Analysis

EDD No.	*Components* *EDD - Degradation Mechanism*	*Consequence Scenario*	*Unmitigated* *S/H/E*	*Unmitigated* *Econ*	*Mitigated* *S/H/E*	*Mitigated* *Econ*
102	<Whole> 102 - Rotor Bow	Horizontal orientation of rotor for prolonged period can cause bowing of rotor due to it's own weight.	NA	B-II	NA	D-II
	Risk Comments FAILURE MODE/PROBABILITY: Horizontal orientation of rotor for prolonged period can cause bowing of rotor due to it's own weight. Probability B EHS CONSEQUENCE: None ECONOMIC CONSEQUENCE: Replacement and production loss cost >$1M USD					
101	<Whole> 101 - Atmospheric Corrosion	External Atmospheric Corrosion occurs on equipment exposed to the surrounding environment. The intensity of atmospheric corrosion is influenced by the exposure to marine winds (airborne chlorides), temperature and humidity.	NA	B-II	NA	D-II
	Risk Comments FAILURE MODE/PROBABILITY: If spare rotor is not available at right time due to atmospheric corrosion, leads to a prolonged period of shutdown . Probability : B EHS CONSEQUENCE: None ECONOMIC CONSEQUENCE: Replacement and Production loss cost >$1M					

Figure 16: Risk analysis for a compressor rotor

The next question that needs to be answered is what tasks are required to mitigate the risk to a low risk area. To mitigate previous mentioned the degradations mechanisms mentioned previously, the following tasks are required:

- Inspection upon arrival to ensure rotor integrity and storage requirements are met
- Monitoring of nitrogen pressure
- Functionality test of the nitrogen gauge

Figure 17 shows part of the preservation task.

Tasks / Action Description	Start Date	Frequency	Responsibility
0002 - Check and monitor nitrogeon pressure		1 M	Warehouse
Complete the following steps to perform monthly inspection to monitor the nitrogen charging pressure of the preservation container. Note: This task is performed by the Supply Department. (Warehouse Preservation Inspector). 1. Check and record the nitrogen pressure of the preservation container: Range: 5 Psig (34.5 Kpa) - 2.5 Psig (17.2 Kpa) 2. Recharge the preservation container with nitrogen, if necessary. 3. Visually inspect the exterior condition of the preservation container. 4. Post a notification in the SAP for the corrective action, if required. Note: Maintenance Department (M&R Supervisor) shall be informed of any change or update of the material list and the inspection record shall be detained for references.			
0003 - Functionality test for N2 Pressure gauge.		1 Y	Warehouse
• Check the proper functioning of the nitrogen pressure gauge by testing with Test pressure gauge. The end connections to facilitate the test gauge to be modified wherever necessary. • Refill nitrogen to the required pressure as necessary. Note: If any repair/replacement of gauge required, warehouse Team will notify maintenance department via SAP			
0001 - Visual Inspection of Rotor		1 T	FM-ROTAT
This procedure applies to the new Compressor and Turbine rotors (Upon receival from manufacturer) as well as the the rotors which are stored and never been inspected before.			

Figure 17: Preservation tasks required

Similar to equipment maintenance strategies, the spares preservation strategies will not serve their purpose as long as they are not implemented or well executed. The company decided on an innovative approach to implement these preservation strategies through its current CMMS. The current CMMS does not support the raising of work orders against material items, therefore for each material item that needs to be maintained, an associated dummy functional location needs to be created in CMMS.

Preservation of spares is not a new phenomenon, but the way the programme is managed and stewarded is new. By embedding all spares preservation strategies in an asset management system and the associated tasks in a CMMS, integration is achieved and stewardship of the programme enabled.

Lessons learned

The major lessons learned relate to the delays encountered in approving the spares preservation strategies. For some people it required a change of mindset. It is not only the responsibility of maintenance staff or engineers to prescribe preservation strategies, nor is it only the responsibility of warehouse staff to execute these preservation tasks. It is a combined effort between different departments that will make the development, implementation and execution of preservation tasks successful.

8. Reliability optimisation

The final step to an integrated asset management programme is integrating and improving the individual programmes outlined in Steps 1 to 7.

For example, if the duty-standby interval is modified for particular item of equipment, this will immediately have an impact on the maintenance tasks scheduled during testing of this equipment. Programmes are not independent any more, but should be integrated, and modifications and improvements should take that into account.

To ensure that improvements in one programme don't have negative impacts on another programme, all programmes must be linked and embedded in an overall system. There are three areas to focus on:

- The equipment maintenance strategy is the starting point for improvements as per the integrated asset management model. All improvements should be reflected in the equipment maintenance strategy and from there modifications should be made to programmes and plans. This risk-based process ensures that maintenance and operator care tasks are cost-justified and mitigating any risks.
- Ensure that procedures and processes are in place and updated. Procedures should be aligned and should refer to the other procedures related to the integrated asset management strategy model. Business controls are essential to maintain strategies and plans evergreen, and to maintain the relationships between the steps of the model.
- Embed equipment and preservation strategies, work history, maintenance plans, materials stocking levels and programmes such as RCFA into a single asset management system. This will create synergy between applications and ensure that the interrelationship is maintained.

Experience shows that before starting with reliability optimisation, such as analyzing failures at component level, greater reliability improvement can be gained simply by ensuring the basics explained in Steps 1 to 7 are in place and properly executed.

Examples include:

- Ensuring that all equipment maintenance tasks are aligned and that only those that require a shutdown are scheduled during a shutdown.
- Aligning condition-monitoring tasks with the duty-standby schedule, and operations staff testing the equipment accordingly.
- Maintenance tasks and equipment are grouped such that maintenance plans are efficient.
- An RCFA and a bad actor elimination programme are in place and recommendations are implemented.

Only when all previous steps, as outlined in this paper, are implemented and executed properly will it be beneficial to start with reliability optimisation. The reliability improvement that can be achieved will be relatively small compared with the major reliability improvements that can be achieved by having key programmes implemented and properly executed.

Nonetheless, to achieve reliability excellence one needs to climb the reliability optimisation ladder. The reliability optimization model is shown in Figure 18.

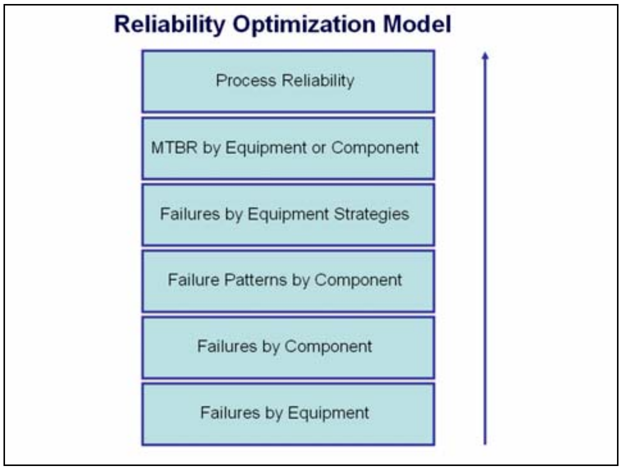

Figure 18: RasGas reliability optimisation ladder

Failures by Equipment

The roadmap to reliability excellence starts with reviewing failures at equipment level. Almost all companies will have a root cause failure analysis (RCFA) programme in place, where one looks to the past to improve the future. The next step is to become more proactive and to review potential equipment failures that could have a future impact on production. This is normally the objective of a bad actor elimination programme. It is important that equipment maintenance strategies are modified in accordance with with the lessons learned through these programmes.

Failures by Component

As high-quality data are not available, companies look at component level failures and failure patterns much less than they look at equipment-level failures.

Not only must data be entered correctly, but technical data should be entered in an asset management system. For example, to analyse data at bearing level, the bearing manufacturer and model details are necessary. In other words, to analyse failures at component level, both failure and component data should be available.

Failure Patterns by Component

The next logical step is to analyse failure patterns at component level. For example, once analysis concludes that all bearing failures are related to a certain model, the next step is to investigate the failure pattern. Are the failures random failures, wear-out failures or a result of infant mortality. This knowledge will help to determine whether failures are related to maintenance execution in a case of infant mortality, or improve bearing replacement intervals in a case of a wear-out failure.

Failures by Equipment Maintenance Strategy

More in-depth analysis can be done by analysing failures in equipment maintenance strategies and correlating them with failure modes or equipment degradation mechanisms. To achieve this, failure coding in CMMS must be linked to the failure modes or to equipment degradation mechanisms in the equipment maintenance strategy.

MTBR by Equipment or Component

To climb the ladder further up means benchmarking and comparing the mean time between repair (MTBR) for equipment or components with data from other companies, and identifying areas for improvement. People sometimes argue that for such exercise to be effective it must be done earlier in the reliability optimisation process, and that’s correct. On the other hand, it is critically important to improve the quality of data at component level and its linkage to equipment degradation mechanisms is a must. Only knowing that the MTBR for pumps is low, for example, is not enough. An asset management system should be in place, resulting in data that will provide answers to such questions as which manufacturer, which service, which equipment strategy, what components are failing, and what is the failure pattern.

Process Reliability

The final step is to change gear once equipment reliability has been optimised and equipment failures have been eliminated – efforts should now be focused on optimising process reliability. The question to be answered is this: what is holding the company back from producing at the highest achieved production rate on a daily basis?

Key success factors

If we look back on this journey, many lessons were learned and challenges faced. Currently spare parts optimization, the spares preservation plan and the operator care plan are in progress and still need to be completed.

To summarise, the key success factors that took the project from an idea to implementation are these:

- **Management support**: it is vital to have a high-level sponsor who, throughout the journey, emphasises its importance to all relevant people.
- **Phasing of steps**: this enabled small celebrations each time minor milestones were achieved and kept

the team and stakeholders happy and enthusiastic all the way.

- **Leveraging work using a single platform.** The switch to an asset management system tied in people, process and assets. It created many synergies between the different reliability plans and enabled the team to leverage existing work.
- **Complete started initiatives:** it is important to see initiatives through to completion. Often people get quickly distracted, management looses focus and an initiative can lose the visibility it had in the beginning.

The road to a fully integrated asset management strategy is long and will take several years. RasGas Company Ltd. started its journey in 2005 and several projects are still ongoing. Success sometimes seems distant, but by pursuing excellence end goals will come within reach, laying a strong foundation for the future.

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