Proceedings of
ASME TURBO EXPO 2002
June 3-6, 2002, Amsterdam, The Netherlands

GT-2002-30023

PERFORMANCE MONITORING ON THE ÅSGARD "A" FPSO AS PART OF AN INTEGRATED MONITORING STRATEGY

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ABSTRACT

An integrated machine condition monitoring system was developed, installed, tested, commissioned and successfully operated on a floating production, storage and offloading vessel (FPSO) in the North Sea. This system combines an existing vibration and process monitoring system with focused performance monitoring capability that has been implemented with the cooperation of the oil company end-user, a thermodynamics specialist consultant and a monitoring system supplier. Implementation of this integrated monitoring system strategy with advanced performance monitoring is partly based on the end-user's requirements to optimize their operation and maintenance functions to improve competitiveness.

The system has already been in use for one year and has demonstrated the ability to detect faults at an early stage of development, such as the compressor degradation and gas turbine fouling described in this paper. The same system has also been implemented in other oil & gas and power applications around the world with similar, positive results.

INTRODUCTION

In today's competitive oil & gas market place, effective asset management is highly dependent on an effective maintenance strategy. Knowing the condition of your machines and how well they are performing is a vital part of this strategy for optimizing safety, minimizing environmental impact, optimizing plant availability and reliability, and minimizing maintenance costs.

This was the justification for expanding the monitoring system ordered for the Åsgard "A" floating production, storage and offloading vessel (FPSO). Advanced performance monitoring capability was added to the existing vibration and process monitoring systems. This involved a close cooperation between the end-user, a thermodynamics consultant, and the condition monitoring system supplier both in the requirement specifications phase as well as the system implementation.

One of the important objectives in this project was for the monitoring system to be an integrated one with a single database, user interface and alarm handling method for all the monitoring techniques used. This method provides the "big" picture approach on the condition of the gas turbines, compressors, pumps, etc., which is not offered by separate stand-alone systems. The integrated monitoring system strategy also makes it easier to correlate the results of different monitoring techniques in order to corroborate fault detection and diagnosis, thus making it more reliable.

The performance-monitoring portion of the plant-wide integrated monitoring system imports process data from the distributed control system (DCS) for calculating performance parameters. In addition to this, data for each machine monitored (i.e., design losses, on-site performance reference data, part load operation curves, etc.) is used in the calculations together with a well developed gas properties modeling technique. The fine-tuned performance monitoring capability of the system was invaluable in diagnosing numerous machine faults in the early stages of development system, thus improving maintenance and operation decisions for more effective planning. This resulted in increased machine uptime with more stable production, and reduced maintenance costs. The same system is now used in several performance monitoring and diagnostics applications with other oil & gas customers.

ÅSGARD "A" FPSO

Fig 1 Åsgard "A" production ship

The 278m long Åsgard "A" is the world's largest oil production ship at the time this paper was written. It is operating over the Halten Bank seabed (290 m depth) in the Norwegian Sea about 200 km from mid-Norway. It is permanently moored to the most extensive subsea production facilities in world, with a total of 57 wells distributed between 17 seabed templates. Not far from the Åsgard "A" FPSO is the world's largest floating semi-submersible gas platform, Åsgard "B", and the storage tanker Åsgard "C".

The 184 300 ton Åsgard "A" production ship has a storage capacity for approximately 907,000 barrels of oil and is capable of producing up to 200,000 barrels of oil and 94,000 barrels of condensate per day. Oil production, which began on 19 May 1999, is transferred via a loading system to shuttle tankers for transport to customers or terminals. Associated gas from Åsgard "A" is reinjected into the oil producing fields. Gas and natural gas liquids produced by Åsgard "B" as well as from other platforms in the area are transported via a gas trunkline to the gas treatment facilities at Kårstø, which in return ties in this part of the Norwegian continental shelf to continental Europe.

Bringing Åsgard's large and complex production facilities on stream has presented the oil company owner and operator with major challenges. But this has contributed to the development and application of specialized technology. Although oil production has initially been lower than planned because the wells produced more gas than expected, all delivery commitments for oil and gas have been fulfilled. It also incorporated important experience of cooperating with other oil companies and numerous suppliers [1].

Åsgard "A" is owned and operated by the state-owned Norwegian oil company Statoil, which is operating on the relatively mature Norwegian continental shelf in the North Sea.

The commitment to place technological focus on operation and maintenance was one of the guiding concepts for implementing an integrated monitoring solution on Åsgard "A" [1].

INTEGRATED PERFORMANCE MONITORING PROJECT

Before a performance monitoring solution was considered, the Åsgard "A" project team had already selected a vibration monitoring solution for the topside process machinery early in the project phase so the same monitoring system could be used for commissioning these machines. The decision to implement performance-monitoring capability as a part of an integrated monitoring solution came later. The primary reasons for implementing a performance monitoring solution were to:

- **Improve the reliability of diagnosing faults** – Relevant information is needed for making better operation and maintenance decisions. The expected result of this is to increase overall production output, make production more stable and reduce maintenance costs
- **Monitor machine efficiency and emissions** – This gives an indication on how effective the process is running

The Åsgard project team, responsible for the integrated monitoring solution throughout the entire project, operates on Statoil's task team principle. This is based on a multi-skilled group with a systematic vision of the processes to which they are connected. The team is led by a facilitator to stimulate and guide the group. Teams are autonomous and committed to the results of the company and business unit.

Machine train	Qty	Driver	Vibr. mon.	Perf. mon.
Recompressor (2-Stage)	2	Motor	X	X
Recompressor (1-stage)	1	Motor	X	X
Excess gas compressor	1	Motor	X	X
Reinjection compressor	2	LM2500 GT	X	X
Turbo-generators	2	LM6000 GT	X	X
ESS diesel generator	2	Diesel	X	
Thrusters	5	Motor	X	
Sea water lift pump	3	Motor	X	
Centrifuges	6	Motor	X	
Air compressors	3	Motor	X	

Table 1 Machines monitored on Åsgard "A"

Performance Monitoring System Requirements

There were several performance monitoring systems on the market, but the selection was limited as a result of the following primary requirements:

- **Accuracy** – A thermodynamic model was needed that was more accurate than that provided by typical compressor and turbine supervisory and control systems
- **Flexibility** – Performance monitoring capability was needed for various types of gas turbines and compressors
- **Interface** – Process data for the thermodynamic calculations had to be imported from the DCS and the weather station
- **Database "snapshot"** - A user-defined database download that includes most process data during startups, shutdowns, inadvertent trips and manual requests
- **Integration** – The performance and process monitoring capability had to be functionally integrated to the existing vibration monitoring system

- **Open system** – All thermodynamic calculations had to be 100% transparent with no "black box" curve smoothing or conditioning.
- **At-a-glance view** – All relevant measured values and corresponding alarm status for each specific machine had to be readily visible
- **Standard product** – The system had to meet all the supplier's requirements for quality and service, but still could be fine-tuned to the application
- **Alarm strategy** – An effective means for alerting monitoring personnel of an alarm situation for any point with various levels of urgency

The Åsgard project team looked at several systems but basically only the vibration system supplier offered a system that complied with all of the project team's requirements. As one of the requirements was to fine-tune the system to the end-user's application, many special considerations were needed to implement the system as described in the next section.

Project Cooperation

Implementing the performance monitoring system, especially fine tuning the system to Statoil's application, required a three-way cooperation:

- End-user - Statoil Åsgard "A" project team
- Specialist in thermodynamic formulation and modeling - KEMA
- Monitoring system supplier - Büel & Kjær Vibro (BKV)

This cooperation, which continued up through the completion of the project, was necessary for several important reasons:

Process Data - Close cooperation was needed with Statoil in using their proprietary data interface program for importing data from their DCS to the performance monitoring system. This requires importing the relevant process data at sufficient frequency without loading the DCS. This also required cooperation with the DCS supplier.

Machine information - As one of the performance monitoring requirements was for accurate thermodynamic modelling, it was important to include machine losses into the calculations as well as machine baseline performance information. Statoil as an end-user has access to machine manufacturer's data.

Thermodynamic Calculations - Although the Åsgard "A" project team had performance monitoring specialists, the services of KEMA were still needed to create the thermodynamic model, fine tune the equations and acquire the necessary property tables for gases.

Testing - The system was tested and/or reviewed during different phases of the project, so BKV had developed a method for making fast review models that could be quickly evaluated by Statoil. The final system was then tested at the BKV factory, followed up by a site test. This required complete cooperation between Statoil, KEMA and BKV.

PERFORMANCE MONITORING SOLUTION IMPLEMENTED

The performance monitoring system Compass [5] was integrated with the existing vibration monitoring system about a year ago and has already been fully tested. Although there was much work involved in importing data using Statoil's existing interface program, the process for importing data has since been streamlined and readily implemented at other petrochemical plants [2].

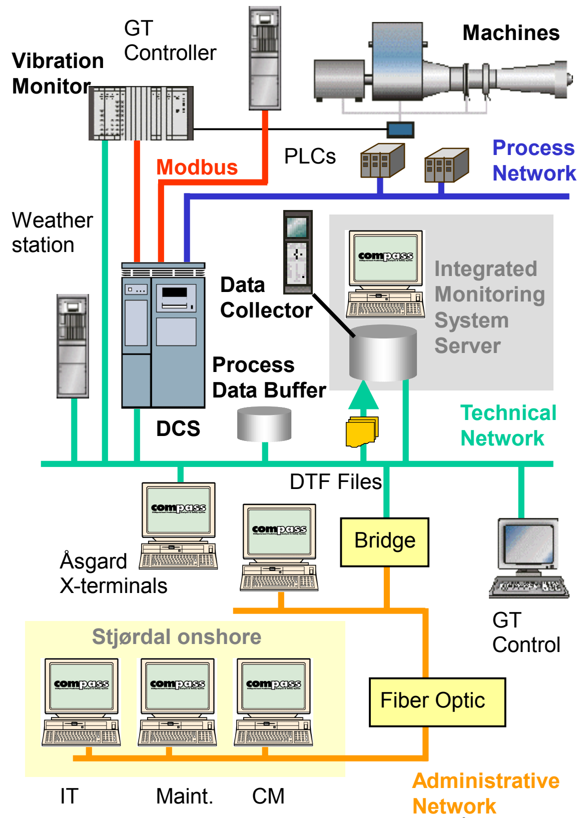


Fig 2 Monitoring system configuration on Åsgard "A"

Configuration

The installed monitoring system configuration is shown in Fig 2. The performance monitoring portion of the system is software based, meaning all process data used in the thermodynamic calculations is imported from the DCS. The imported data consists of DTF (data transfer files) text files that are imported using FTP (file transfer protocol) commands over a LAN network. This simple method is very effective for the rate at which data is imported for the performance monitoring calculations, and does not jeopardize the DCS control and safety function. Monitoring system hardware is used only for the vibration monitoring portion of the system, but both the vibration and performance monitoring portions of the system use the same database, alarm handling concept and graphical user interface.

The performance monitoring system is used only for predictive monitoring purposes and in no way replaces the control and anti-surge safety systems supplied with the machines. For this reason thermodynamic monitoring calculations are not done in real time but at one-hour intervals, partly because there are a lot of thermodynamic calculations being done specifically for predictive maintenance purposes, and partly because there are no expected dramatic changes within this user-defined time frame. Process data is imported into the monitoring system database at ½ hour intervals, and a database buffer stores around ½ hour of "first in, first out" imported process data at one-minute intervals for more detailed resolution diagnostics in case of a planned or unplanned trip, startup or a manual request.

The main users of the system are indicated in Figure 2.

Thermodynamic Calculations

Thermodynamic performance parameters are calculated using current, imported process data from the DCS. The Schultz method [4] of polytropic analysis is used to calculate the performance parameters to ensure accuracy. Machine design data and losses supplied by the manufacturer are also used in the calculations, and are updated to on-site conditions during machine testing to establish the "new, clean" baselines to which the corrected performance parameters are compared to, for detecting faults and trending wear.

The thermodynamic calculations are based on the assumptions that the natural gas components (including organic gases ranging from CH_4 to C_8H_{18}) are considered non-ideal, and their behaviour described by the Lee-Kesler method [3]. The gas properties that are used in the calculations are updated as the composition of the gas being processed change.

The thermodynamic formulas, with a syntax similar to that found in popular spreadsheet programs, are completely open for editing, which is necessary for the fine-tuning. There are no "hidden" or proprietary signal conditioning routines.

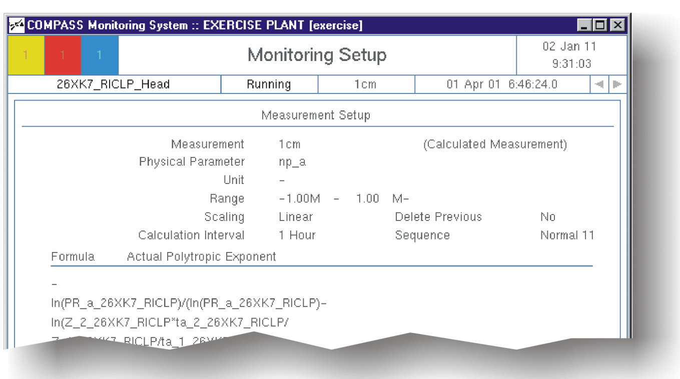


Fig. 3 Example of a performance parameter calculation

Alarm Limit Strategy

The Compass monitoring system allows the user to set up user-defined alarm limits - both upper and lower - which will activate an alarm if any of these limits are exceeded by an incoming measured, imported or calculated measurement [5]. There are three types of alarm severity:

- **Alert 1** (Yellow alarm) - Indicates changes just outside of normal and gives early warning of a deteriorating situation
- **Alert 2** (Yellow alarm on a separate channel for the same parameter) - Indicates that maintenance now has to be planned
- **Danger** (Red alarm) - Serious situation requiring immediate attention

These alarm limits are redefined each time there any changes to the "as new" condition of the machine (e.g. design modifications, process parameter changes, etc.).

Typical Gas Turbine Performance Monitoring Strategy

On the Åsgard FPSO there are two types of gas turbines installed; a dry, low emissions type (DLE) for the re-injection compressors and a dual fuel type for power generation. The standard performance monitoring calculations used for these gas turbines types complies with the ISO 2314 standards.

The performance monitoring done on the gas turbines driving the re-injection compressor is described in this section.

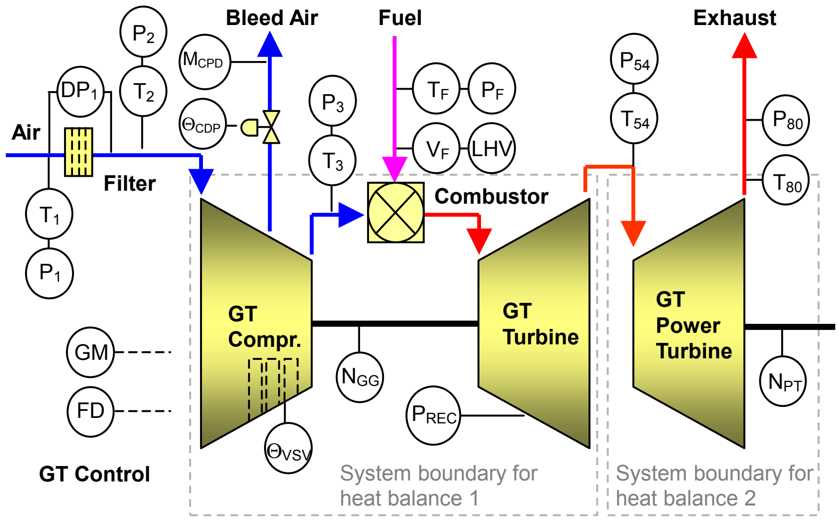
Machine correction and part load curve reference data is used from the machine manufacturer, such as the machine losses and machine reference data for making baselines (e.g. power vs. ambient temperature at baseload, etc.).

Type of parameter	Name/description of parameter
Actual conditions and corrected to ISO reference conditions	Base load shaft power
	Base and part load air flow
	Base and part load EGT
Actual conditions only	Pressure ratio
	Base and part load heat rate and thermal efficiency
	Isentropic turbine and compressor efficiencies
	Inlet filter pressure drop
	Rotor speeds

Table 2 Performance parameters monitored for the gas turbine

Type of plot	Name/description of plots
Deviation trend plots	EGT spread
	Heat rate vs. power
	Air flow vs. power
	EGT vs. power
	Compressor efficiency vs. flow
Performance map plots	Exhaust gas temperature spread plot
	Heat rate vs. power (part load)
	Air flow vs. power (part load)
	EGT vs. power (part load)

Table 3 Performance plots used for the gas turbine



Description of symbols	
DP	Pressure drop
FD	Fuel demand, Governor mode (for determining base or partial load)
GM	
LHV	Lower heating value of fuel
M	Flow
N	Rotor speed
P	Pressure
T	Temperature
Θ	Position

Description of subscripts	
CFD	Bleed air
F	Fuel
GG	Gas generator
PT	Power turbine
REC	Recuperating
VSV	Variable stator vane

Fig 4 Process data used for the re-injection compressors gas turbine

Typical Compressor Performance Monitoring Strategy

As indicated in Table 1 there are several different compressors monitored, but the monitoring strategy is basically the same. The standard performance monitoring solution for all the compressors complies with the VDI 2045 standards.

In this section the performance monitoring strategy is described for the 2-stage re-injection centrifugal compressor.

In order to implement baselines for the performance monitoring, machine performance curve reference data is used from the manufacturer, such as pressure ratio, efficiency and head vs. flow vs. speed. Data on the compressor design is also used. Different gas compositions are expected for this application, so this data is input for making accurate thermodynamic calculations.

Type of parameter	Name/description of parameter
Actual conditions and corrected to inlet reference conditions	Polytropic head
	Flow
	Rotor speed
	Pressure ratio
Actual conditions only	Polytropic efficiency
	Power consumption

Table 4Performance parameters monitored for the compressor

Type of plot	Name/description of plots
Deviation trend plots	Rotor speed
	Flow
	Polytropic head
	Pressure ratio
	Polytropic efficiency
Performance map plots	Pressure ratio vs. flow
	Efficiency vs. flow
	Head vs. flow

Table 5 Performance plots used for the compressor

Description of symbols	
DP	Pressure drop
M	Flow
N	Rotor speed
P	Pressure
T	Temperature

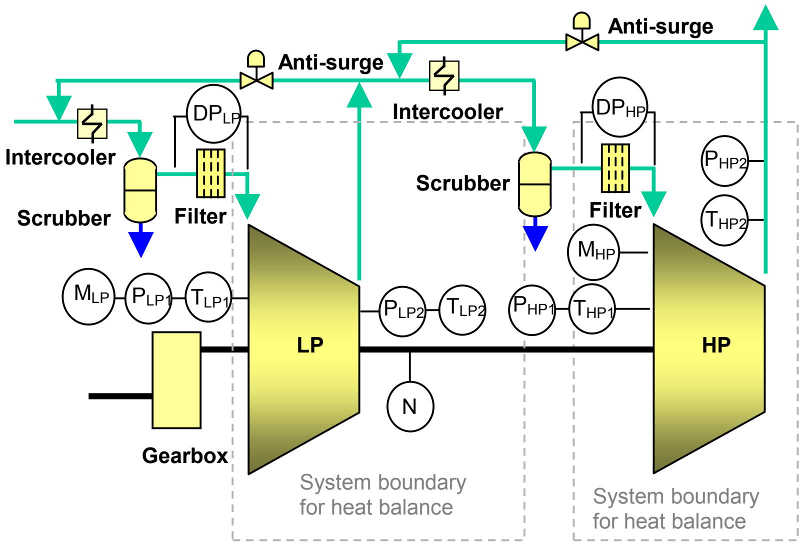


Fig 5 Process data monitored on the re-injection compressor

DEMONSTRATION OF CAPABILITIES

Compass has demonstrated its capabilities by providing condition parameters valuable for diagnostics and condition management of rotating machinery. The two cases described are taken from one of the re-injection compressors and its gas turbine:

- Gas turbine fouling
- Compressor fouling and erosion

Case 1: Gas turbine fouling

Monitoring gas turbine fouling is of vital importance for oil production capacity. Compass has demonstrated that its performance parameters may be used for tracking efficiency degradation and for defining the water wash intervals. Figure 6 shows some plots that may be used for trending isentropic efficiency degradation of the gas turbine compressor over time.

Fig 6 Efficiency plots showing a degradation trend between on-line compressor washes for the gas turbine

Case 2: Compressor fouling and corrosion/erosion

In the figures that follow, a re-injection compressor is diagnosed to experiencing both fouling and corrosion/erosion. In this case, the fouling is most likely caused by condensates in the gas stream (see Fig. 10), and erosion/corrosion primarily caused by water ingestion (see Fig. 9).

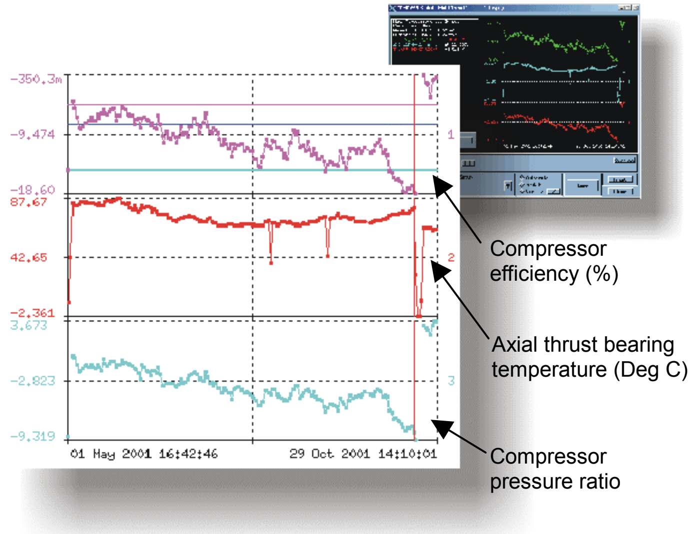


Fig 7 Multi-trend plot showing re-injection compressor drop in performance (rotor shifts its axial position as the degradation propagates, hence the corresponding thrust bearing temperature rise)

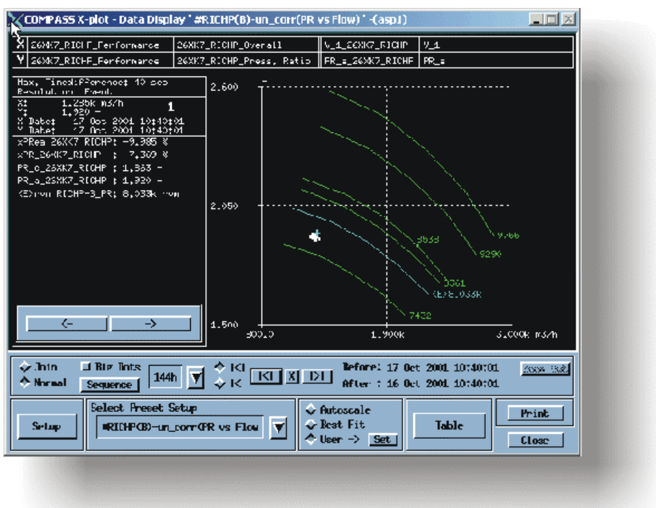


Fig 8 Pressure ratio vs. flow performance map showing 10% degradation of the re-injection compressor (operating point is below the expected operating line shown in blue)

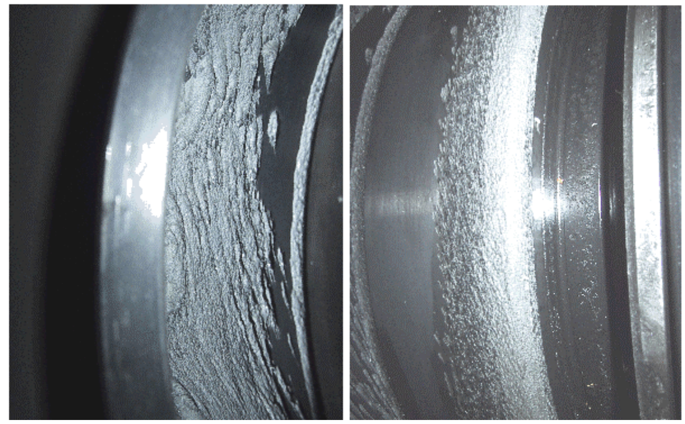


Fig 9 Disassembly of the of the re-injection compressor: Evidence of corrosion/erosion in the first stage impeller (photo taken from inlet side of the impeller)

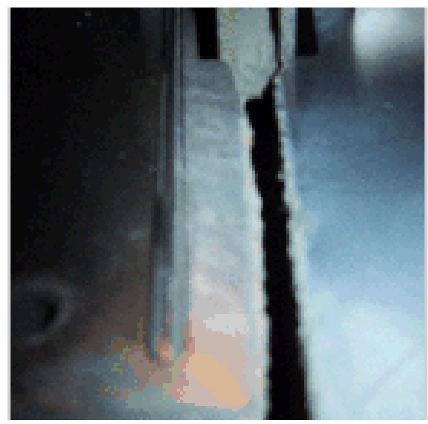


Fig 10 Fouling in the diffuser channel (at the 1st section outlet) of the re-injection compressor

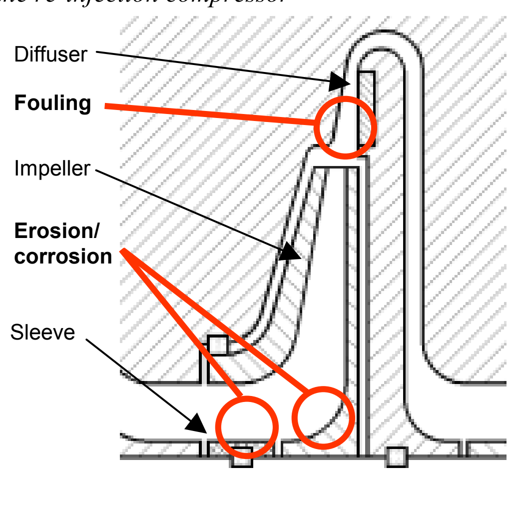


Fig 11 Location of fouling and erosion detected on the first stage impeller of the re-injection compressor

CONCLUSION

Reliable maintenance and operation decisions depend on timely, relevant information on the condition of the machines, and this originates for the most part from the diagnostic information and tools provided by the integrated monitoring system. The installed system has met this challenge and added considerable net value to the effectiveness of the diagnostics.

Performance monitoring is important in the overall monitoring strategy, since many incipient faults for turbomachinery are first identified by performance degradation before there are vibration changes detected. For example, for compressor blade deposit build-up, the efficiency will already have shown significant degradation long before deposit build-up is enough to indicate imbalance. Proper fine-tuning of the thermodynamic equations is one of the reasons for this early fault detection.

The performance-monitoring portion of the system has proven itself invaluable for accurately detecting corrosion/erosion and deposits on the inlet rings, impellers and diffuser plates at an early stage of development.

Although it is theoretically possible to only use process data as an indication of a developing fault, it is experienced that the diagnostic analysis work needed to do this is too much. Considerable time savings has been achieved using accurate, fine-tuned thermodynamic parameters provided by the monitoring system as indicators, together with an alarm system that warns of changes with varying degrees of severity.

But there are some drawbacks as well. Small process variations occur so often, so that performance parameters lend themselves only to long-term trends, not instantaneous values. All in all, however, the results of the performance portion of the system have more than justified its investment.

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