Availability assessment of a raw gas re-injection plant for the production of oil and gas

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Abstract- Driven by the needs of highly competitive markets, the performance requirements of today's production systems are becoming increasingly demanding. High availability is one of the key requirements for new machines and industrial plants. The objective of the present study is the assessment of the availability of a Gas Re-injection Plant used for the production of oil and gas in the Kashagan field (Kazakhstan). In order to assess the availability performance of this complex system, a broad set of studies has been carried out to gather accurate information at the level of detail considered suitable to meet the availability analysis target. Following this preliminary work, the availability analysis was performed using a simulation approach. The RBD (Reliability Block Diagram) technique, in conjunction with Monte Carlo simulations, allowed many different elements to be evaluated simultaneously to determine the plant availability.

I. Introduction

The availability of a system is a non-linear function that depends on many parameters, including reliability, maintainability and logistics. Reliability is determined from an analysis of the expected life of components and the functional configuration of the system; maintainability can be estimated from the time to repair or restore failed equipment, and the frequency and duration of scheduled maintenance tasks; finally, logistics can be evaluated from the spare parts warehouse policy established to support the maintenance activities.

In order to assess the availability performance of a complex system such as a raw gas re-injection plant, a broad set of studies is needed to obtain the correct inputs to populate a model. These preliminary studies include, among others:

- Reliability Data Collection to gather reliability information at the failure mode level
- Maintainability Analysis, carried out at the failure mode level to identify the tasks and the associated time required to carry out corrective maintenance
- Failure Modes and Effects Analysis (FMEA) coupled with a Criticality Analysis (CA) following international standards applicable to the Oil & Gas industry. The FMEA and CA are supported by a variety of design and specification documents.

The availability analysis that followed the preliminary studies can be divided into three main phases.

In the first step, the Plant and Instrument Diagrams (P&IDs) and other relevant documentation were analyzed to identify those components whose failure could cause system unavailability. As a general approach, this analysis included every individual component included in the GE Oil & Gas scope of supply. For example, in the overall system availability evaluation, even the impact of small piping, flanges and manual valves was considered.

The second step was the construction of the plant Reliability Block Diagram (RBD), which represents a reliability model of the system. It was constructed by connecting the different blocks representing the components evaluated in the firs step. Since some redundant components have different reliability configurations, depending on the failure mode considered, the RBD structure could include simultaneous series-parallel connections.

Finally, in the last step, simulations based on the Monte Carlo method were run. This methodology is one of the most frequently used techniques for the simulation of complex systems because it allows taking into account the non-linear effects of reliability, maintainability and logistics in the assessment of the system reliability and availability performance. Simulations were performed by simultaneously considering two different operating stages of the plant: normal operation and start up.

II. Problem Statement

Today, the Caspian Sea is one of the areas of greatest interest for oil and gas companies in spite of the high concentration of contaminants found in these oil fields. In order to exploit in full the oil reservoirs located in the northeast area of the Caspian Sea within the Kazakh Republic, it is necessary to safely handle the associated gas that contains high percentages of H2S. This gas cannot be released into the atmosphere because it is lethal. The only way to recover this crude oil is to process the natural gas and re-inject the sour gas into the reservoirs at high pressure. Sour gas (H2S), often found in oil fields, imposes environmental and safety problems proportional to the type of contaminants and their concentration. The only compressor manufacturer that has accrued experience in the re-injection of sour gas at the pressures required by Caspian Sea fields is GE Oil & Gas.

The Raw Gas Re-injection Plant sited in Kashagan, (Kazakhstan) is the most advanced project in the field because of both the high re-injection pressure involved, 11,022 psi (760 bar), and the amount of H2S contained in the gas, 18%. The high pressure level required the development of a new compressor model to assure meeting the re-injection pressure at the third compression stage.

The GE Oil & Gas scope of supply is the RGI Offshore Plant, which consists of two identical barges. Each barge includes:

- Turbo-group containing an MS5200D Gas Turbine equipped with a Dry Low NOx emission system and three barrel type Centrifugal Compressors
- Two Motor-compressors (each consisting of an electric motor driving a Reciprocating Compressor) to provide the proper pressure for the Centrifugal Compressor Seal Gas
- Balance of Plant (BoP) including all the utilities external to the machines, such as Process Gas, Fuel Gas, Seal Gas, Electrical and Control System, etc.

GE Oil & Gas was also asked to carry out an Operation and Maintenance (O&M) project for the above scope of supply.

Considering the attention to safety issues mirrored by the dedicated safety studies carried out outside the project itself, the O&M project included a variety of analyses, including an Availability Analysis (AA) addressing production capability. The final goal of the study was the evaluation of the plant availability and the determination of the critical weak points to identify potential improvements in the maintenance policies. The Availability estimate and the prediction of the performance in terms of production are based on the system design (components, failure modes and frequencies, repair/restoration times, and system architecture) but also on the Operation and Maintenance policies foreseen (maintenance strategies, mission profile, logistics, etc.).

As a consequence of the unique and critical nature of this technical application, the level of detail of the analysis was set at the item level and the criticality of the associated FMs (Failure Modes) was assessed. The solution, adopted to provide maintenance feedback at the component level and suited to the design documents used to support the analysis, required a major effort including about 2500 blocks to set up the RBD model based on about 4700 plant items that were analyzed in the project.

A simulation approach was selected to perform the availability analysis. In this case it is based on the Monte Carlo simulation method that generates random failure times from each component's failure distribution. The results, which are difficult to solve analytically, can be obtained through the simulation. On the other hand, simulation methods also have certain drawbacks, not the least of which is that they can be time consuming. Furthermore, the results depend on the number of simulations, which implies a lack of experimental repeatability, even though Monte Carlo simulation is one of the most reliable prediction tools.

III. Previous Analyses

The modelling of the system required that several analyses be carried out to provide the necessary data and/or information in support of the different phases.

The most important input steps in support of the availability model are the following: the setting up of the Reliability Block Diagram with the reliability links between the numerous items composing the plant modelled, the reliability input data, the corrective maintenance input data, and the preventive maintenance input data. A brief description of all the preliminary activities carried out in support of this objective follows.

A. Equipment breakdown structure

All the items belonging to the boundary limits were structured hierarchically. Each item to be

potentially inserted in the RBD was registered and identified with a unique TAG, and for each TAG, all the necessary information for the subsequent phases such as reference drawings, P&IDs, specifications, datasheets, O&M manuals, reference manufacturers and suppliers, and complete identification of the TAG reliability characteristics were collected.

B. Reliability data collection

The TAG reliability characteristics determine the appropriate reliability data for each item. The data sources are:
- Dedicated analysis of similar equipment from internal GE Oil & Gas fleet monitoring tools
- Data from manufacturers
- Commercial databases such as OREDA or NPRD95 [1], [2], [3].

These data are collected at a failure mode level when available. Otherwise a global value is assigned to the component failure rate.

C. Corrective maintenance data collection

Maintainability was a key consideration in the design of the RGI plant. Special analyses, such as 3-D modelling, were conducted to optimize the layout of the barges to provide safe and rapid access for both corrective and planned maintenance activities.

For the availability analysis, a dedicated study was performed for identifying the Corrective Maintenance Time, that is the time necessary to restore an item back to service after a failure. It includes several contributing factors:

$$Tcm_{j,i} = t_{FLDT,j,i} + t_{TOST,j,i} + t_{ART,j,i} + t_{BIST,j,i} - t_{AOT,j,i} \qquad (1)$$

where

$Tcm_{j,i}$ = corrective maintenance time associated with the *j-th* failure mode of the component *i*

t_{FLDT} = time necessary for fault location and diagnosis

t_{TOST} = time necessary for getting the item out of service,

t_{ART} = active repair time

t_{BIST} = time for getting the item in service again after the repair

t_{AOT} = overlap time for activities conducted in parallel.

All these data are collected recognizing that each failure mode of each item requires a unique maintenance time, depending on the accessibility and on the barge/plant safety procedure to be followed.

C. Failure Modes and Effects Analysis

The purpose of the Failure Modes and Effects Analysis is to analyze the failure modes of each item to be potentially inserted in the RBD in order to determine their effects on the process in terms of safety, production and the environment. The output of the FMEA can be used as a good basis for deciding if an item should be inserted into the RBD. The FMEA results were integrated with other general project documentation such as "Cause and Effect Diagrams", "Functional Descriptions", Component Specifications" and "Component Datasheets".

D. Maintenance Plan

The Maintenance Plan defines the preventive and on-condition activities to be carried out on each TAG within the scope of supply and collects all the relevant information on activities, skills, durations, tools and spare parts. By the proper filtering and analysis of these data it is possible to define the maintenance plan to be modelled in the RBD.

IV. Modelling Approach

In order to estimate the production availability, the entire RGI plant was modelled using a complex Reliability Block Diagram. More than 18,000 failure modes for the elementary components along with their potential effects were analyzed in order to evaluate whether they should have been included in the reliability model.

The goal of the study was to predict the production availability during two operational modes: Start-up and Production, without taking into account the potential degradation of production in the event of "non-critical" or incipient failures. Other specialized analyses, such as Quantitative Risk Assessment, were performed for evaluating the probability of having critical safety problems. This implies that only those items, which could impact either the ability to start the plant or production, were included in the RBD. Details of the decision rules for selecting the failure modes, the associated failure rates, and their corrective maintenance times are presented, while the planned maintenance intervals and durations are identified in the Maintenance Plan study.

A. Identification of the Critical Failure Modes

Working with all the available engineering documents and customer guidelines, the potential failure modes of each component were analyzed to determine which of them actually could have an impact on the global availability of the system.

Each block of the RBD represented a single system component whose failure rate was computed as follows:

- A global failure rate that is the sum of the failure rates of the associated critical failure modes is considered:

$$\lambda_i = \sum_{j=1}^{n} \lambda_{j,i} \qquad (2)$$

where

λ_i = failure rate associated with the component i and

$j=1,..,n$ = component failure modes that influence the system availability

- The corrective maintenance time used for each block of the RBD (representing one plant item) is calculated using the results of the Maintenance Plan by weighting the corrective maintenance time of each critical failure mode based on its probability of occurrence as follows:

$$T_{cm,i} = \frac{\lambda_{j,i} \cdot T_{cm,j,i}}{\sum_{j=1}^{n} \lambda_{j,i}} \qquad (3)$$

where

Tcm,i = global corrective maintenance time associated with the i-th component

- The preventive maintenance activities were modelled as blocks periodically failing at every planned maintenance cycle, whose restoration time is equal to the maintenance duration.

B. General assumptions

In the RBD for the availability assessment, the preventive and corrective maintenance intervals as well as the associated durations are carried out in accordance with the appropriate O&M manuals, procedures and applicable documents. In particular, due to the toxicity of the process gas, safety rules do not permit personnel to work on a barge while it is running. Therefore, corrective maintenance activities can be performed only when the barge is shut down, depressurized and purged. These operating procedures produce important consequences in the RBD and ultimately, in the availability estimate results. In fact, since even in the case of redundant configurations (like k out-of n and stand-by) it is not possible to repair failed units in the presence of hazardous fluids, both the failure rate and the corrective maintenance times of all redundant configurations have been calculated separately using individual RBDs, because maintenance will be performed only when all the redundant items have failed (except for some safety critical failure modes).

Moreover, the assumption that all the maintenance operations restore the component to an as-good-as-new condition was made. The human factor was not assessed, i.e., human reliability was considered equal to 100%. External factors such as natural events, dropping of objects and impact with external bodies were not considered in the availability analysis, which had indeed the aim of estimating the inherent availability of the GE Oil & Gas scope of supply. Some other factors, which could cause unavailability, are neglected, including incorrect design relating to sizing and materials, errors in installation and/or manufacturing, and incorrect documentation such as procedures, specifications, drawings, and reports. Nor have the spare parts strategy and logistic aspects been considered.

Since the analysis was carried out during the design phase, we assumed that the plant is operated in compliance with the specifications and design conditions.

C. Specific assumptions

There are some important considerations regarding leaks. All components and items that are associated with the process gas, fuel gas and leak gas piping are considered as potential sources of leaks. This appraisal is not prompted by the possibility of production loss but rather, primarily by the danger represented by fluids that could be lethal to operators. Therefore if there is any leakage, the production system is turned off to stop the release of fluids. Hence, leakage from actuated valves and other equipment has been considered and modelled within the boundary limits of the component that the leakage derives from. This approach has been applied both to leakage from the component body and leakage from flanges of piping carrying hazardous fluids. For flange couplings in particular, the parts count methodology was applied: the total leak rate is estimated by counting the number of flanges in the hazardous fluids piping and then multiplying by the flange leakage frequency. Both the leakage frequencies for the flange couplings and for the instruments were evaluated in the QRA study (Quantitative Risk Assessment) [4] and the same data were used in the RBD. We paid particular attention to the leakage failure mode of items within the parallel branches. The contribution of leakage to the overall plant unavailability is not negligible considering that all the critical leaks are in a series configuration in the global RBD, even if the leakage is from items redundant from a functional standpoint.

For those parallel configurations in which the number of items running at a given time depends on external environmental conditions, for instance the process gas cooling system, a specific representation was developed to determine an equivalent reliability redundancy, considering the average annual ambient conditions.

D. RBD Architecture

The breakdown structure of the whole RBD model is set up in four different levels and is briefly described as follows:
- 1st level: overall RBD for the whole system
- 2nd level: clearly identified RBDs for each rotating machine and BoP section (gas turbine, centrifugal compressor, process gas, fuel gas, seal gas, leak gas systems etc.) to be assembled into an overall RBD of the whole scope of supply
- 3rd level: clearly identified RBDs at subsystem level. Each subsystem is a machine or BoP auxiliary system and appears on a single sheet of the relevant P&ID whenever possible. These hierarchical level RBDs are set up by the elementary blocks (TAG level) and are put together in modelling the 2nd level RBDs
- 4th level: each elementary Block in the RBDs represents one single component and contains all the information relating to the selected critical FMs.

V. Results

In order to allow the high-level evaluation of the whole barge from the availability standpoint (which was estimated for start-up and normal operation), the entire re-injection barge was divided into four main subsystems as detailed in Table 1.

Table 1. High-level system definition

System	Description
RGI Line-up	- Gas Turbine - Centrifugal Compressors (machines themselves and auxiliary systems)
Seal Gas	- Process seal gas - Reciprocating compressors (machines themselves and auxiliary systems)
Electrical and Control	- Electrical single line diagram - Control and protection barge architecture
Balance of Plant	All other plant systems

Moreover, since the offshore Kashagan project will be expanded, thereby increasing the re-injection requirements, two different availability assessments were provided in accordance with the following scenario:

- CASE 1 – one barge is running and providing 100% of the production required, while the other barge is ready to start (in stand-by state)
- CASE 2 – (two out of two barge configuration) each barge provides 50% of the required production. In other words, both of the barges are required for nominal production.

The failure of a single barge is considered to be an event that causes an immediate and complete loss of its capability to provide the required output. So the single barge is considered available when it is "in a state in which it is capable of providing its service, whether or not it is actually in service, regardless of the capacity level that can be provided", in accordance with ISO3977-9, Gas Turbines, Procurement, Part 9: Reliability, availability, maintainability and safety [5]. The single barge is considered unavailable when it is in Emergency Shut Down, Pressurized Shut Down or Compressor Unloaded condition.

The Availability for CASE 1 and CASE 2 refers directly to the production that the two barges can provide. This means that in CASE 2 the global availability will also include events causing the shut down of one barge with the other running normally so that the group provides about the 50% of the required production.

From this standpoint the Global Availability (GA) is defined as the percentage of production in the reference period, in accordance with the definitions of failure and single barge availability provided above. The formula used for the Global Availability calculation is:

$$GA = \left(\frac{PH - OH}{PH} \right) \qquad (4)$$

where:

PH Period Hours – cumulative monitoring calendar hours. The PH is usually one or more whole system maintenance cycles, in this case the period in which both the gas turbines on the two barges have had all the preventive maintenance activities carried out per the O&M manual.

OH Outage Hours – number of production loss equivalent hours. The OH is calculated as follow.

CASE 1: OH = LPH, where:

LPH Loss Production Hours – the number of hours in which the two barges are simultaneously down for corrective or preventive maintenance.

CASE 2: OH = 0.5 * LPH1 + LPH2, where:

LPH1 Loss Production Hours 1 – the number of hours in which only one barge is running and the other is down for corrective or preventive maintenance

LPH2 Loss Production Hours 2 – the number of hours in which the two barges are simultaneously shut down for corrective or preventive maintenance

In order to allow the full analysis of the RAM performance of the plant, the Reliability of the systems described in Table 1 was also calculated for each barge, where the Reliability is defined as follows:

$$R = \frac{(PH - FOH)}{PH} \qquad (5)$$

where

PH Period Hours, that is, the simulation time

FOH Forced Outage Hours of the single system.

Upper and lower limits considering a confidence level of 90% have been evaluated for each Reliability figure. Actually, these confidence limits refer only to the results of the simulations using the Monte Carlo methodology and are not related to the variability of the RBD input data.

Ten thousand Monte Carlo simulations were run covering a complete maintenance cycle of the GE Oil & Gas scope of supply.

As for the Availability results for the whole plant, for Case 1 it must be highlighted that planned maintenance does not have any impact on the global availability of the overall plant, since optimization of the intervals and the activities permits avoidance of periods with no production at all except for the failure of a barge during the planned shutdown of the other, thanks to the fact that the Monte Carlo approach allowed the choice of the planned maintenance intervals to be verified through simulation.

Considering the confidential nature of the results of this study, the details of the values cannot be presented in this article.

VI. Conclusions and Development

This study focused mainly on the estimation of the availability of the specific plant described in this paper under the stated assumptions. It was based completely on the RBD technique combined with Monte Carlo simulation, which is considered at the moment to be the best process available for handling the different elements simultaneously acting in a non-linear way to determine plant availability. When all the information related to the real feedstock is finalized, the result can be further detailed by modelling the actual feedstock so as to also include the impact of logistic delays on the availability. The present analysis was carried out on a new installation prior to entering into production; when actual field data become available, the model can be enhanced based on the actual site conditions.

Updating the model would provide the customer/operator with a powerful and more precise instrument for carrying out all the relevant sensitivity analyses, such as evaluating the impact of any future changes that the user might consider for the plant, including changing the configuration (for possible plant expansions or changes in operation and maintenance procedures), equipment type, maintainability or feedstock.

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