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NGGT FLEET RAM STUDY

RAM Study Report

National Grid PLC

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[redacted]

Abbreviations	
ART	Active Repair Time
CRT	Critical
CS	Compressor Station
DEG	Degraded
DLE	Dry Low Emission
EM	Electric Motor
EMD	Electric Motor Drive
ESD	Emergency Shutdown
ESDV	Emergency Shutdown Valve
GG	Gas Generator
GT	Gas Turbine
GTD	Gas Turbine Drive
LTSA	Long Term Service Agreement
MMscfd	Million standard cubic feet per day
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
NG	National Grid
NGGT	National Grid Gas Transmission
OREDA	Onshore & Offshore Reliability Database
PT	Power Turbine
PFD	Process Flow Diagram
PM	Planned Maintenance
RAM	Reliability, Availability and Maintainability
RBD	Reliability Block Diagram
VSD	Variable Speed Drive
[redacted]	[redacted]

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EXECUTIVE SUMMARY

NGGT are an operator of a wide range of compressor train machinery, with both electric and gas turbine driven systems used on the network. While their VSD fleet is relatively new, the GT fleet contains a range of equipment from different eras. The focus of this study is the VSD, Avon and SGT400 fleets. In the current price control, NGGT needs to better understand how the availability and reliability of their compressor train assets contribute to their network.

In support of their decision making, [redacted] has performed a RAM Study to forecast compressor train availability to provide necessary capacity during periods of demand. The output of this RAM study will be used to inform and outline potential investment options and their benefits for input into a cost benefit analysis for an emissions legislation compliance project.

As part of the RAM study, 3 base case models have been built for 3 generic compressor trains. NGGT intend to translate learning/output from the RAM study to specific sites.

1. Avon driven Gas Compressor Train with legacy design from 1990 or earlier
2. SGT400 driven Gas Compressor Train (year 2000 onwards)
3. VSD driven Gas Compressor Train (year 2005 onwards)

Analysis of ALERT data for the NGGT fleet for the past 5 full years (2016-2020) was used for the modelling of the different compressor trains.

Base Case

The key performance parameters obtained from the base case models are presented in the table below:

Performance Parameter	Unit	AVON	SGT400	VSD
Compressor Train Availability	%	**64.33**	**77.78**	**81.64**
P10	%	78.62	84.32	87.80
P90	%	47.10	69.24	75.34
Required Running Hours	hours	403	1062	2463
Achieved Running Hours	hours	259	826	2011

The following key conclusions can be made from the base case models' results:

- Out of the 3 compressor fleets, Avon is forecasted with the least number of running hours, averaging 403 running hours required per year in the next 4 years (2022-2025). The Avon fleet is also predicted to be the least reliable compressor train, achieving an availability of 64.33%, equivalent to 259 running hours achieved per year.
- The VSD fleet, on the other hand, is forecast with the highest running hours, averaging 2463 running hours required per year in the next 4 years (2022-2025). They are also the most reliable compressor train, predicted to achieve an 81.64% availability, equivalent to 2011 running hours achieved per year.
- The SGT400 fleet is Gas Turbine driven, similar to the Avon fleet. However, they are newer and are forecast with significantly higher running hours than the Avon fleet, averaging 1062 required running hours per year in the next 4 years (2022-2025). The SGT400 fleet is also predicted to be more reliable than the Avon fleet, achieving an availability of 77.78%, equivalent to 826 running hours achieved per year.

The table below shows the contribution of each sub-unit to the compressor train's availability losses. Note, the Power Supply and VSD sub-unit are unique to the VSD fleet.

Sub-Unit	Absolute Loss (%)		
	AVON	SGT400	VSD
Safety/Protection/ESD	7.30	4.43	6.83
Control System	4.95	0.77	2.37
Compressor	4.44	0.53	0.13
Miscellaneous	4.42	6.39	3.73
Starting Trips	4.32	1.80	2.33
Power Turbine	4.31	1.06	-
Lubrication	2.10	2.80	-
Fuel	1.87	2.33	-
Gas Generator	1.18	2.10	-
Seal & Bearing	0.77	-	-
Power Supply	-	-	0.68
VSD	-	-	2.28
Total	**35.67**	**22.22**	**18.36**

Below are some observations for the criticality ranking of each of the fleet.

<u>Avon – Base case</u>

- Failures of the Safety/Protection/ESD sub-unit are the largest contributor to the availability loss. They account for 7.30% absolute loss. Most of the losses attributed to this sub-unit are caused by major failures; with 5.26% of the Avon's absolute loss contributed to Safety/Protection/ESD major failures.
- The second largest loss-contributor to availability is trips and failures of the control system, predicted to cause up to 4.95% absolute loss. The majority of losses attributed to this sub-unit are caused by major failures with long lead-times.
- The third largest contributor to the availability loss is the compressor sub-unit; recording an absolute loss of 4.44%.
- Contributions from the Miscellaneous and Power Turbine sub-units are significant. They cause 4.42% and 4.31% absolute loss respectively. Like other sub-units, most of the losses are caused by major failures and minor failures when spare parts are not available.
- Starting trips are also predicted to cause considerable availability loss. The Avon compressor train is assumed to have an average grid-start duration of 27 hours – this value was calculated through analysis of ALERT data for the Avon compressor trains. The grid starts will be subject to a starting failure probability. Overall, start trips account for 4.32% absolute loss.

<u>SGT400 – Base case</u>

- The largest contributor to the availability loss is the Miscellaneous sub-unit – causing a 6.39% absolute loss. Most of the losses attributed to this sub-unit are caused by minor failures when spare parts are unavailable.
- The second largest contributor to the availability loss are trips and failures of the Safety/Protection/ESD system, predicted to cause 4.43% absolute loss. Most of the losses attributed to this sub-unit are caused by major failures with a long lead-time.

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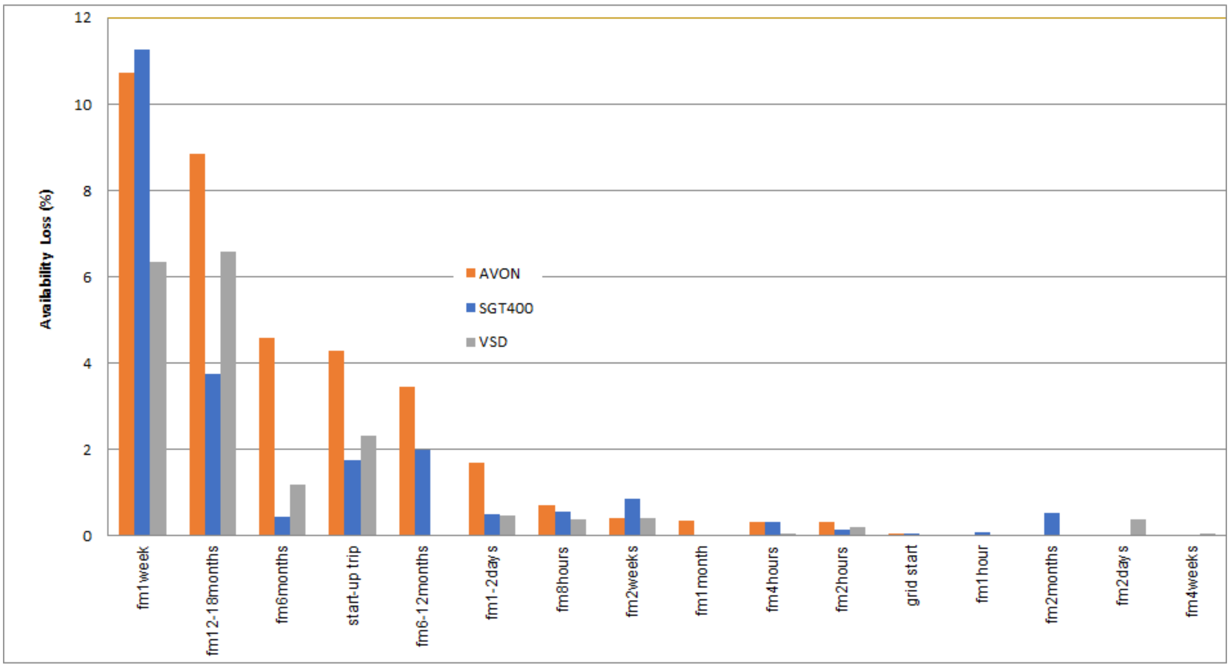
- Failures of the Lubrication sub-unit are the third largest contributor to the availability loss. They account for 2.80% absolute loss. Most of the losses attributed to this sub-unit are caused by minor failures when spare parts are not available.
- Contribution from the Fuel sub-unit is also significant, causing a 2.33% absolute loss. Similar to other sub-units, most of the losses are caused by minor failures, when spare parts are unavailable.
- Starting trips are also predicted to cause considerable availability loss. The SGT400 compressor train is assumed to have an average grid-start duration of 28 hours. The grid starts will be subject to starting failure probability. Overall, start trips account for 1.80% absolute loss.

VSD – Base case

- Failures and trips of the Safety/Protection/ESD sub-unit are the largest contributor to the availability loss. They account for 6.83% absolute loss. Most of the losses attributed to this sub-unit are caused by major failures with long lead-times.
- The second largest contributor to the availability loss is Miscellaneous failures, causing up to 3.73% absolute loss. Most of the losses are caused by minor failures - when spare parts are not available.
- The third largest contributor to the availability loss is failures of the control system, predicted to cause 2.37% absolute loss. Most of the losses attributed to this sub-unit are caused by minor failures when spare parts are not available.
- Contribution from the VSD sub-unit to the availability loss should also be considered significant, causing 2.28% absolute loss. Most of the losses from this sub-unit are caused by major failures with a long lead time.
- Starting trips are predicted to cause considerable availability loss. The VSD compressor train is assumed to have an average grid-start duration of 60 hours. The grid starts are subject to a starting failure probability. Overall, start trips account for 2.33% absolute loss.

The figure below shows the contribution of each failure mode (or failure associated with a specific repair time) to the availability loss for all fleets in comparisons.



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The following key observations are made from the distribution of availability loss by failure modes / repair times for all fleets from the base case models:

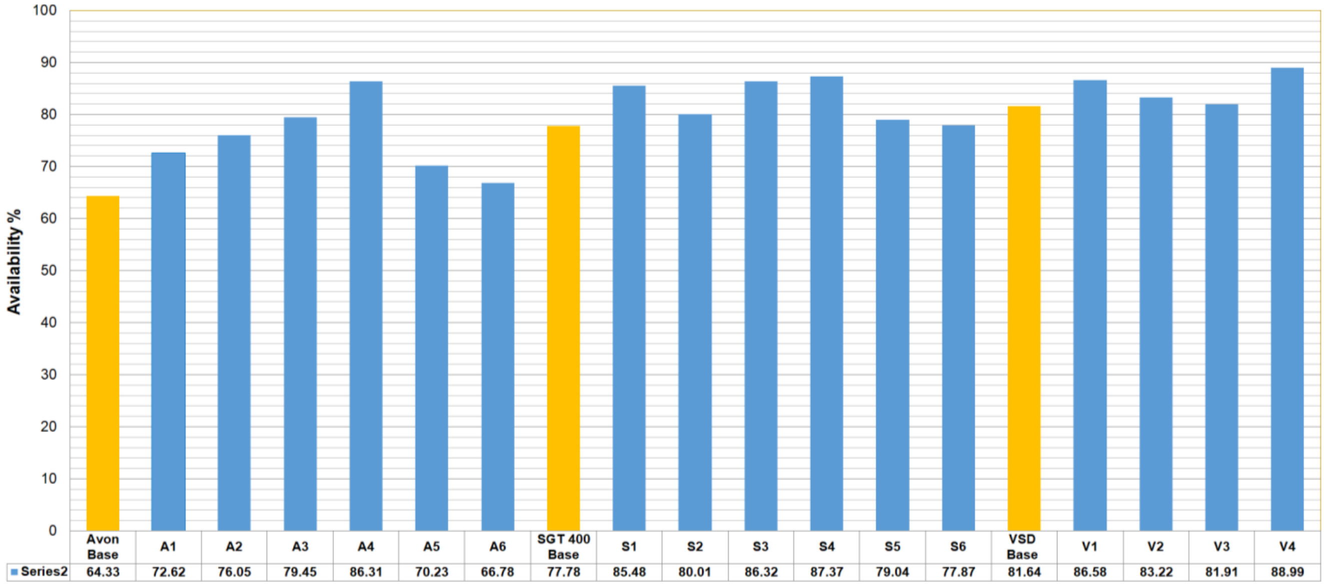
- The most critical failure mode (fm1week) will be minor failures, when spare parts are not available. For these failures, spare parts might not be available onsite or from warehouse in Didcot and would need to be ordered, leading to longer repair times (1 week).
- The second most critical failure mode (fm12-18months) will be major failures on the control and safety protection systems, where a long lead time for capital spare parts is expected. Note, the fm12-18months failure mode is the most critical for the VSD units.
- Other major failure modes (fm6months and fm6-12months) are also very critical, again due to the long lead time required.
- Starting trips are also critical and will contribute significantly to availability loss.
- Other failure modes, although occurring often, are less critical due to short repair times.

Sensitivity Cases

Following completion of the Base Case models and further discussion with the NGGT team; 16 sensitivity cases were chosen for analysis. Sensitivity cases have been considered to assess the performance impact of different operational strategies, equipment replacement at a sub-unit level and alterations to the running patterns of the compressor trains. The table below displays the definition of each of the sensitivity cases considered in this analysis.

Sensitivity Case	Compressor Unit	Investment
A1	Avon	Full replacement of the following sub-units: Control System, Safety/Protection/ESD, Lubrication & Fuel systems.
A2	Avon	Full replacement of the following sub-units: Control System, Safety/Protection/ESD, Lubrication, Fuel systems & Compressor.
A3	Avon	Full replacement of the following sub-units: Control System, Safety/Protection/ESD, Lubrication, Fuel systems, Compressor & Power Turbine
A4	Avon	Full replacement of all sub-units & Spares Holding for all sub-units
A5	Avon	Improved Spares holding
A6	Avon	Increased run-time for units
S1	SGT400	Implementation of Remote monitoring/LTSA
S2	SGT400	Control system & Safety/Protection/ESD overhaul/replacement
S3	SGT400	Control System Overhaul & Implementation of Remote monitoring/LTSA
S4	SGT400	Control System Overhaul, Implementation of Remote monitoring/LTSA, Fuel/Lubrication improvements & beneficial bulletins/site design improvements
S5	SGT400	Increased run-time for units
S6	SGT400	Compressor Overhaul
V1	VSD	Full replacement of the following sub-units: VSD, Control System, Safety/Protection/ESD, Miscellaneous
V2	VSD	Increased run-time for units
V3	VSD	Rewind VSD motor
V4	VSD	Remote Monitoring/LTSA + Spares for VSD/Control system/ Safety/Protection/ESD

A column chart outlining the achieved availability values for the base cases and each of the sensitivity cases has been displayed below.



Overall, the following observations are made for the sensitivity cases.

<u>Case A1</u>

Case A1 simulated a complete replacement of the: Control System, Safety/Protection/ESD, Lubrication & Fuel System sub-unit. This therefore increased the MTTF for the replaced sub-units, improved the starting failure probability and reduced the mean repair time for a major failure of the control and safety/protection/ESD systems.

Case A1 achieved 293 running hours, equivalent to an availability of 72.62%. This represents an 8.29% absolute improvement from the Avon base case.

<u>Case A2</u>

Case A2 built upon the investment made in case A1, plus Compressor sub-unit replacement. Case A2 achieved 307 running hours, equivalent to an availability of 76.05%. This represents an 11.72% absolute improvement from the Avon base case.

<u>Case A3</u>

Case A3 is built upon the investment made in case A2, plus Power Turbine sub-unit replacement. Case A3 achieved 320 running hours, equivalent to an availability of 79.45%. This represents a 15.12% absolute improvement from the Avon base case.

<u>Case A4</u>

Case A4 is built upon the investment made in case A3, plus improvements to the Gas Generator, Miscellaneous and Seal & Bearing sub-units, as well as increased spares holding for all sub-units. Case A4 achieved 348 running hours, equivalent to an availability of 86.31%. This represents a 21.98% absolute improvement from the Avon base case.

Case A5

Case A5 simulated an improved level of spares holding for the Avon compressor unit, this investment in spares reduced the MTTR for the minor failure without spare failure mode for all Avon sub-units. Case A5 achieved 283 running hours, equivalent to an availability of 70.23%. This represents a 5.90% absolute improvement from the Avon base case.

Case A6

Case A6 simulated a change to the running patterns for the Avon compressor train; the compressors were run continuously for the required 403 hours. Therefore, the model used only one grid-start for case A6. This is atypical for an NGGT compressor, generally compressor units are run in a discontinuous fashion based up on grid demand.

Case A6 achieved 269 running hours, equivalent to an availability of 66.78%. This represents a 2.45% absolute improvement from the Avon base case.

Case S1

Case S1 simulated the implementation of a remote monitoring system and use of a long-term service agreement for the SGT400 compressor train. The implementation of these systems reduced the MTTR for the minor failure without spare failure mode and substantially reduced the MTTR for a major failure.

Case S1 achieved 908 running hours, equivalent to an availability of 85.48%. This represents a 7.70% absolute improvement from the SGT400 base case.

Case S2

Case S2 simulated an overhaul to the Control System and the Safety/Protection/ESD sub-units. Case S2 achieved 850 running hours, and in turn an availability of 80.01%. This represents an absolute improvement of 2.22% from the SGT400 base case.

Case S3

Case S3 built upon the investment made in case S2, plus the implementation of a remote monitoring system and use of a long-term service agreement for the SGT400 compressor train. Case S3 achieved 917 running hours and in turn, an availability of 86.32%. This represents an absolute improvement of 8.54% from the SGT400 base case.

Case S4

Case S4 built upon the investment made in case S3, plus improvements to the fuel and lubrication sub-units and site design improvements to the SGT400 compressor station. Case S4 achieved 928 running hours and in turn, an availability of 87.37%. This represents an absolute improvement of 9.59% from the SGT400 base case.

Case S5

Case S5 simulated a change to the running patterns for the SGT400 compressor train; the compressors were run continuously for the required 1062 hours. Thus, the model used only one grid-start for case S5. This is atypical for an NGGT compressor, generally compressor units are run in a discontinuous fashion based upon grid demand.

Case S5 achieved 839 running hours, equivalent to an availability of 79.04%. This represents a 1.26% improvement from the SGT400 base case.

Case S6

Case S6 simulated an overhaul to the compressor sub-unit for the SGT400 unit. Case S6 achieved 826 running hours and in turn, an availability of 77.87%. This represents an improvement of 0.09% from the SGT400 base case.

Case V1

Case V1 simulated a complete replacement of the: Control System, Safety/Protection/ESD, VSD & Miscellaneous sub-unit. This therefore increased the MTTF for the replaced sub-units and reduced the mean repair time for a major failure of the control and safety/protection/ESD systems.

Case V1 achieved 2132 running hours, equivalent to an availability of 86.58%. This represents a 4.94% absolute improvement from the VSD base case.

Case V2

Case V2 simulated a change to the running patterns for the VSD compressor train; the compressors were run continuously for the 2463 required hours. Thus, the model used only one grid-start for case V2. This is atypical for an NGGT compressor, generally compressor units are run in a discontinuous fashion based upon grid demand.

Case V2 achieved 2463 running hours, equivalent to an availability of 83.22%. This represents a 1.58% absolute improvement from the VSD base case.

Case V3

Case V3 simulated the motor being rewound for the VSD compressor train; this resulted in an improvement to the MTTF value for the VSD (VSD Motor) sub-unit. Case V3 achieved 2017 running hours and in turn, an availability of 81.91%. This represents an improvement of 0.27% from the VSD base case.

Case V4

Case V4 simulated the implementation of a remote monitoring system, plus the use of a long-term service agreement for the VSD compressor train and increased spares holding for VSD, Control System and Safety/Protection/ESD sub-units. Case V4 achieved 2197 running hours and in turn, an availability of 88.99%. This represents an absolute improvement of 7.35% from the VSD base case.

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1 INTRODUCTION

NGGT are an operator of a wide range of compressor train machinery, with both electric and gas turbine driven systems present on the network. While their Electric Variable Speed Drive (VSD) fleet is relatively new, the Gas Turbine (GT) fleet contains a range of equipment from different eras. The focus of this study are the VSD, Avon and SGT400 compressor trains. Under their current price control, NGGT needs to better understand how the availability and reliability of their compressor train assets contribute to the gas transmission network.

In support of their decision making, NGGT has commissioned [redacted] to perform a Reliability, Availability and Maintainability (RAM) study to forecast compressor train availability to provide necessary capacity during periods of demand. The output of this RAM study will be used to inform and outline potential investment options and their benefits for input into a cost benefit analysis for an emissions legislation compliance project.

This document presents the results and findings of the study along with the scope of work and assumptions that have been used to develop the RAM models for the compressor fleets. [redacted] used its proprietary software, [redacted], to carry out the analysis.

This document consists of the following sections:

Section 1: Introduces backgrounds of the study

Section 2: Details modelling assumptions

Section 3: Presents the outcomes of the RAM models

1.1 Objectives of Analysis

The objectives of the RAM study are as follows.

- Forecast expected baseline **Availability** for each defined compressor train, based on current operation / condition / maintenance history:

  Availability = (Time all required equipment is available) / (Time)*100%

  The above KPIs will be forecast for the entire compressor train, excluding station and planned outages.

- Criticality Analysis - Identify main contributors ('bad actors') to unavailability and itemise individual sub-unit contributions.

- Identify potential areas of availability improvement in the operation and maintenance of the compressor train, through consideration of defined sensitivity cases. There are to be agreed with NGGT, but may include the following:

  - Component replacement
  - Component overhaul / refurbishment
  - Alternative maintenance strategy (e.g. response times, support contracts)
  - Spares holding strategy (reduced downtime)
  - Alternative operating modes (e.g. reduced stop / start frequency)

1.2 Study Boundaries

The RAM models have been built at sub-unit level (ISO 14224 level 7) and considered all components critical to the availability of the gas compression train. Note that impact of station and planned outages has been excluded.

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Critical sub-units include:

- Gas Generator
- Power Turbine
- VSD Motor
- Compressor, including impeller
- Anti-surge system
- Seal & Bearing system
- Lubrication system
- Supporting auxiliaries – Control System, Fuel Gas, Exhaust, Safety & Protection, Power System (HV supply in VSD model only)

System / component failures that are not immediately critical to compression train operation have been excluded from the RAM models.

1.3 Model Cases

Base Case models have been developed for 3 generic compressor trains (NGGT will translate learning/output to specific sites):

1. Avon driven Gas Compressor Train with legacy design from 1990 or earlier
2. SGT400 driven Gas Compressor Train (year 2000 onwards)
3. VSD driven Gas Compressor Train (year 2005 onwards)

The following sensitivity cases have been run following completion of the base case models:

Sensitivity Case	Compressor Unit	Investment
A1	Avon	Full replacement of the following sub-units: Control System, Safety/Protection/ESD, Lubrication & Fuel systems.
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A3	Avon	Full replacement of the following sub-units: Control System, Safety/Protection/ESD, Lubrication, Fuel systems, Compressor & Power Turbine
A4	Avon	Full replacement of all sub-units & Spares Holding for all sub-units
A5	Avon	Improved Spares holding
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S3	SGT400	Control System Overhaul & Implementation of Remote monitoring/LTSA
S4	SGT400	Control System Overhaul, Implementation of Remote monitoring/LTSA, Fuel/Lubrication improvements & beneficial bulletins/site design improvements
S5	SGT400	Increased run-time for units
S6	SGT400	Compressor Overhaul

[redacted]

Sensitivity Case	Compressor Unit	Investment
V1	VSD	Full replacement of the following sub-units: VSD, Control System, Safety/Protection/ESD, Miscellaneous
V2	VSD	Increased run-time for units
V3	VSD	Rewind VSD motor
V4	VSD	Remote Monitoring/LTSA + Spares for VSD/Control system/ Safety/Protection/ESD

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1.4 Performance Metrics

The following key performance metrics are used in this study:

1.4.1 Availability

Availability is defined as the ratio of time the facility is available to required running time:

Availability = (Time all required equipment is available) / (Time)*100%

It should be noted that the availability for the compressor train excludes impact of station and planned outages.

1.4.2 Criticality Analysis

Critical Analysis identifies system 'weak points' and ranks the sub-units by their contribution to unavailability. Criticality can be expressed in relative (relative loss) or absolute terms (absolute loss). Absolute loss is the actual availability loss. Relative loss, on the other hand, is the value relative to the overall availability loss.

The criticality for each sub-unit is made up of several components:

- Contribution from the mobilisation delays of maintenance resources necessary to address the failure from the time the failure is detected and diagnosed to the point when repairs can begin.
- Contribution from the active repair time necessary to return the failed equipment item to a working state from the time repairs begin to the point when the equipment item is ready to restart.
- Contribution from the restart delays from the time the equipment item is fully repaired to the point when equipment is up and running again.

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2 MODELLING ASSUMPTIONS

2.1 Running Hours and Starts

Due to the nature of NGGT operations, the demand running hours for each of the compressor fleets varies significantly. **Table 2-1** shows the average running hours in the last 8 years plus forecast running hours in the next 4 years (2022-2025) for each of the compressor fleets.

Table 2-1, Average Running Hours

Year	Running Hours		
	Avon	STG400	VSD
2014	764	693	753
2015	664	91	794
2016	470	194	1474
2017	737	1081	2938
2018	864	1443	2498
2019	330	626	2204
2020	179	88	2379
2021	582	780	2550
2022	419	910	2463
2023	415	1109	2463
2024	392	1113	2463
2025	387	1117	2463
Average	**517**	**770**	**2120**
Average (2022-2025)	**403**	**1062**	**2463**

The average running duration of each successful start on grid demand also varies as shown in **Table 2-2**

Table 2-2, Average Running Hours per Successful Start

Year	Average running hours per grid start		
	Avon	SGT400	VSD
2016	31.4	53.2	63.8
2017	26.7	30.1	54.1
2018	28.5	27.8	59.0
2019	14.9	7.9	62.0
2020	28.9	10.7	59.8
Average (2016 – 2020)	**27**	**28**	**60**

Each fleet model will be run for the respective average running time per year (2022-2025) as shown in **Table 2-1**. The number of successful start required for these running hours are presented below:

Table 2-3, Number of Successful Start Required

Avon	SGT400	VSD
14	37	41

2.2 Model Indenture Level

The fleet models have been built at sub-unit level, consistent with level 7 of ISO 14224 (see Figure 2-1). Note that the impact of station and planned outages has been excluded.

For each of the sub-unit, the model includes one or more failure modes (e.g., trips, minor or major failures) depending on the derived data from ALERT data base. Refer to Section 2.4 for the proposed reliability data for each sub-unit.

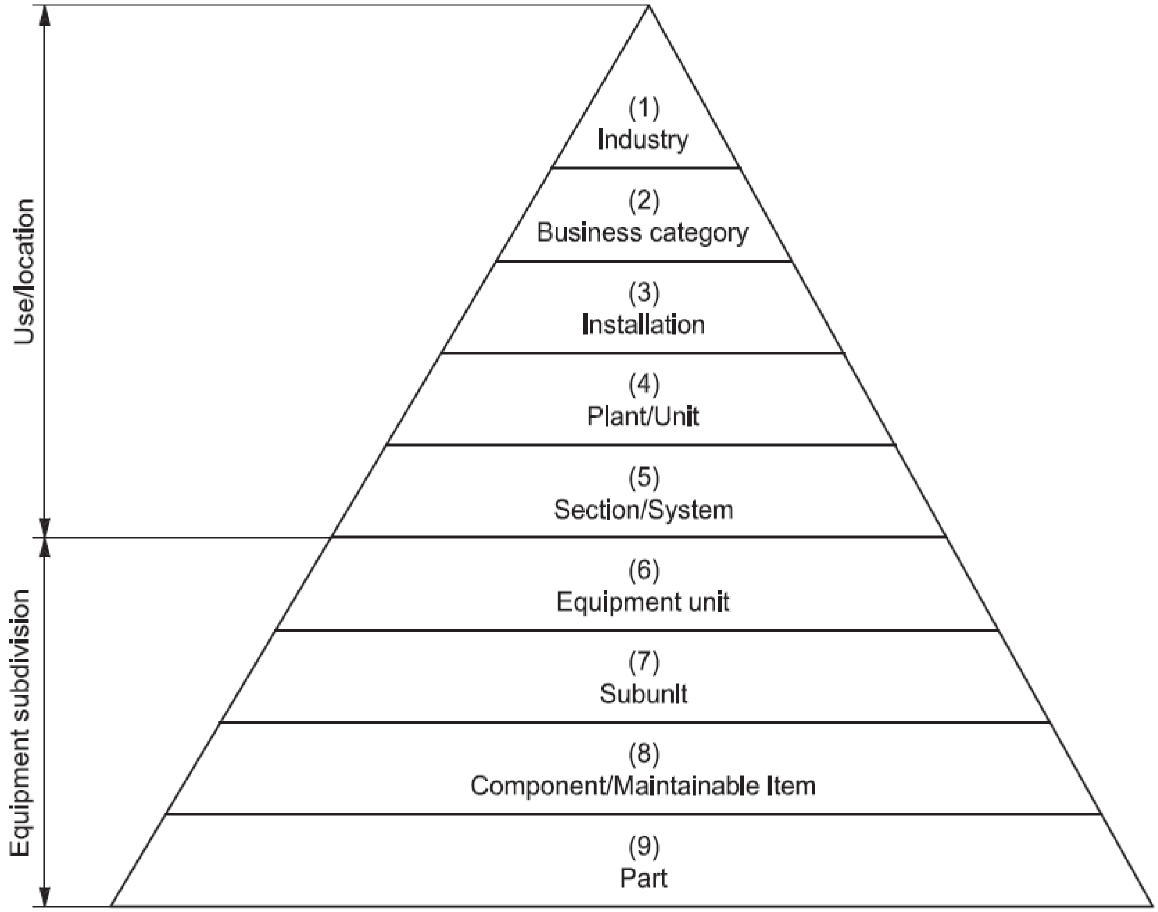


Figure 2-1, Level of Modelling

2.3 List of Sub-Units

This section lists the applicable sub-units for each of the compressor fleets. The list of sub-units is proposed based on the following:

- ISO 14224 / Oreda list of sub-units for compressors, electric motor and gas turbine
- Recent NGGT list of sub-systems obtained from ALERT

Table 2-4 below details the sub-units for each of the compressor fleets.

Table 2-4, List of Sub-Units

Avon	STG400	VSD
Gas Generator	Gas Generator	Power Supply
Power Turbine	Power Turbine	VSD
Exhaust	Exhaust	Motor
Compressor	Compressor	Compressor

Avon	STG400	VSD
Seal & Bearing	Seal & Bearing	Seal & Bearing
Control System	Control System	Control System
Safety/Protection/ESD	Safety/Protection/ESD	Safety/Protection/ESD
Anti-Surge	Anti-Surge	Anti-Surge
Lubrication	Lubrication	Lubrication
Fuel	Fuel	Miscellaneous
Miscellaneous	Miscellaneous	Unknown
Unknown	Unknown	

2.4 Reliability Data

2.4.1 Data Sources

The main source of reliability data for this study is from the following sources:

- ALERT data (for starting trip and running trip frequency)
- NGGT operational data (for repair times)
- Oreda data (for distribution of repair times)
- Engineering judgement

2.4.2 ALERT Data Analysis

Failure data recorded in ALERT has been analysed to obtain the following parameters for each of the fleet types:

- Running hours
- Running trips
- Number of starts from grid
- Number of starting trips

Due to the large number of data points and to reflect recent trends, it has been agreed that the study will only look at the ALERT data collected over the last 5 full years (2016-2020). For each of the fleets, the following units are selected. Note that all STG400 and VSD units are selected. However, for Avon, only compressor units that have at least 100 running hours per year over the time period were selected. Furthermore, the Avon units at Aylesbury were excluded from the model due to them being of a different construction. Additionally, the Mopico VSD units at Lockerley were not used due them being of a different construction to the other VSD models.

Table 2-5, List of Compressor Units Selected for Data Analysis

Avon	STG400	VSD
ALREWAS UnitA	Cambridge C	Churchover E
ALREWAS UnitB	Kings Lynn C	St Fergus 3B
CHELMSFORD UnitA	Kings Lynn B	St Fergus 3A
CHELMSFORD UnitB	Nether Kellet B	Wormington C
DISS UnitB	Nether Kellet A	
DISS UnitC		
HUNTINGDON UnitA		
HUNTINGDON UnitB		

Avon	STG400	VSD
HUNTINGDON UnitC		
KINGS LYNN UnitB		
KIRRIEMUIR UnitA		
KIRRIEMUIR UnitB		
PETERBOROUGH UnitA		
PETERBOROUGH UnitB		
PETERBOROUGH UnitC		
ST FERGUS Unit1A		
ST FERGUS Unit1B		
ST FERGUS Unit1C		
ST FERGUS Unit1D		
ST FERGUS Unit2B		
WISBECH UnitB		
WORMINGTON UnitA		

For each of the fleets, the starting failure probability, the running trip frequency, and subsequently MTTF, for each sub-unit have been calculated. Details of ALERT data analysis can be found in Appendix 1.

2.4.3 Repair Time (MTTR)

In addition to MTTF, in order to calculate the compressor train's availability, the repair times for running trips have been obtained through discussion and validation with NGGT experts. Note, the MTTR values are inclusive of mobilisation time, fault find, part delivery and repair time.

It should be understood that due to the lack of failure's description in ALERT, it is not possible to provide accurate repair time for each failure mode. Instead, a range of repair times have been provided based on the severity of failures and assumed spare parts' availability. The following repair times were provided by NGGT:

- Trip repair time: trip or simple component failure. This allows for operational paperwork e.g., work permit, fault finding activities and assumes repairability / spares held at site. Most of the cases, it only involves simple system resetting and should take less than 8 hours. The majority of the trips will fall to this category.
- Minor failure repair time: Based on simple failure, not associated with the safety systems with a 1-day investigation and 24hr turn around on parts. However, few spares are stored at sites or in Didcot. Hence, it is assumed that for up to 50% of minor failures, parts might not be available and would have to be ordered, leading to longer repair times. For these failures, an overall repair time of 1 week is assumed.
- Major failure repair time: equipment / component replacement is required with expected long lead times for capital spares and potentially vendor specialist. It is assumed that very few trips will fall into this category.

The assumed repair times for each failure mode and associated probability are listed in Appendix 1. The probability of each repair category below is based on Oreda data and validated by NGGT experts.

Table 2-6, Repair Time Distribution

failure category	% of failures	Repair time (hours)
Trips	63%	4-8
Minor failures	36%	24-48
Major failures	1.0%	120-240
Total	**100%**	

[redacted]

Based on this information, the repair times with associated probability for each sub-unit have been allocated. It is noted that the repair times provided in Section 2.4.4 are inclusive of maintenance and spare parts mobilisation delays.

2.4.4 Sub-Unit Reliability Data

The following sub-unit's reliability data is utilized in the Fleet RAM models.

Table 2-7, AVON Sub-Unit Reliability Data

Sub-Unit	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
Compressor	714	2 hours	63.0%	1134
		4 hours	18.0%	3968
		8 hours	1.3%	54137
		1-2 days	16.8%	4264
		6 months	0.9%	76761
Control System	Overall MTTF (hours)	MTTR (hours)	Probability	MTTF (hours)
	1978	8 hours	63.0%	3140
		1-2 days	18.0%	10989
		1 week	18.0%	10989
		12-18 months	1.0%	197807
Fuel	Overall MTTF (hours)	MTTR (hours)	Probability	MTTF (hours)
	3025	2 hours	18.5%	16327
		4 hours	5.3%	57144
		8 hours	44.5%	6803
		1-2 days	12.7%	23810
		1 week	18.0%	16807
		2 weeks	0.3%	1028594
		6-12 months	0.7%	428581
Gas Generator	Overall MTTF (hours)	MTTR (hours)	Probability	MTTF (hours)
	1905	2 hours	63.0%	3023
		4 hours	18.0%	10582
		1 week	18.4%	10348
		2 weeks	0.6%	321436
Lubrication	Overall MTTF (hours)	MTTR (hours)	Probability	MTTF (hours)
	1286	4 hours	63.0%	2041
		8 hours	1.8%	71430
		1-2 days	16.2%	7937
		1 week	18.1%	7113
		2 weeks	0.9%	138999
Miscellaneous	Overall MTTF (hours)	MTTR (hours)	Probability	MTTF (hours)
	651	1 hour	4.8%	13606
		2 hours	58.2%	1118
		4 hours	18.0%	3617
		1 week	18.1%	3602
		2 weeks	0.4%	160718
		1 month	0.3%	205719
		6 months	0.2%	321436
Power Turbine	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	1353	2 hours	14.9%	9070
		4 hours	4.3%	31747
		8 hours	48.1%	2815
		1-2 days	13.7%	9852
		1 week	18.0%	7519
		6 months	0.2%	571441
		6-12 months	0.8%	177344
Safety/Protection/ ESD	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	1319	4 hours	1.6%	81634
		8 hours	61.8%	2132
		1-2 days	17.5%	7519
		1 week	18.0%	7326
		1 month	0.0%	5142972
		12-18 months	1.0%	135341

[redacted]

	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
Seal & Bearing	3214	2 hours	43.3%	7421
		4 hours	32.1%	10025
		8 hours	5.6%	57144
		1 week	18.0%	17858
		2 weeks	0.3%	1028594
		1 month	0.7%	467543

Table 2-8, SGT400 Sub-Unit Reliability Data

	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
Compressor	7853	2 hours	63.0%	12466
		4 hours	18.0%	43630
		1-2 days	18.0%	43630
		6 months	1.0%	785345
Control System	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	15705	8 hours	63.0%	24932
		1-2 days	18.0%	87261
		1 week	18.0%	87261
		12-18 months	1.0%	1570689
Fuel	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	3141	2 hours	12.6%	24932
		4 hours	3.6%	87261
		8 hours	50.4%	6233
		1-2 days	14.4%	21815
		1 week	18.0%	17452
		2 weeks	0.2%	1570689
		6-12 months	0.8%	392672
Gas Generator	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	1309	2 hours	63.0%	2078
		4 hours	18.0%	7272
		1 week	18.2%	7205
		2 weeks	0.8%	157069
Lubrication	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	1047	4 hours	63.0%	1662
		8 hours	18.0%	5817
		1 week	18.0%	5817
		2 weeks	1.0%	104713
Miscellaneous	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	436	1 hour	45.5%	959
		2 hours	17.5%	2493
		4 hours	9.6%	4566
		8 hours	9.5%	4593
		1 week	17.0%	2562
		2 weeks	0.7%	60411
		2 months	0.2%	224384
Power Turbine	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	7853	8 hours	63.0%	12466
		1-2 days	18.0%	43630
		1 week	18.0%	43630
		6-12 months	1.0%	785345
Safety/Protection/ESD	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	2618	8 hours	63.0%	4155
		1-2 days	18.0%	14543
		1 week	18.0%	14543
		12-18 months	1.0%	261782

[redacted]

Table 2-9, VSD Sub-Unit Reliability Data

Sub-Unit	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
Compressor	9055	2 hours	63.0%	14373
		4 hours	18.0%	50306
		1-2 days	18.0%	50306
		4 weeks	1.0%	905502
Control System	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	5174	8 hours	63.0%	8213
		1-2 days	18.0%	28746
		1 week	18.0%	28746
		12-18 months	1.0%	517430
Miscellaneous	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	787	2 hours	63.0%	1250
		4 hours	9.0%	8749
		8 hours	9.0%	8749
		1 week	18.0%	4374
		2 weeks	1.0%	78739
Power Supply	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	5174	2 hours	63.0%	8213
		2 days	18.0%	28746
		1 week	18.0%	28746
		2 weeks	1.0%	517430
Safety/Protection/ESD	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	1725	2 hours	3.0%	57492
		4 hours	0.9%	201223
		8 hours	60.0%	2875
		1-2 days	17.1%	10061
		1 week	18.0%	9582
		2 weeks	0.05%	3622007
		12-18 months	0.95%	181100
VSD	Overall MTTF (hours)	MTTR	Probability	MTTF (hours)
	3018	2 hours	63.0%	4791
		2 days	18.0%	16769
		1 week	18.0%	16769
		6 months	1.0%	301834

Note (*): MTTF was calculated based on running time (not calendar time).

2.4.5 Starting Trip Data

The following starting trip data is utilized in the Fleet RAM model. Data was derived from ALERT database.

Table 2-10, AVON Sub-Unit Starting Trip Data

Compressor Unit	Starting Failure Probability	Average Time Between Start Attempts (hours)
Avon	0.094	14.6
SGT 400	0.086	5.9
VSD	0.062	22.1

2.5 Planned Maintenance

All Planned Maintenance activities are excluded from the Fleet RAM model.

2.6 Mobilisation and Spare Parts Delays

Maintenance crew and spare part mobilisation delays have been included in the repair time (MTTR).

[redacted]

2.7 Other Assumptions

The following assumptions have been discussed with the NGGT team and incorporated into the models for both the Base and Sensitivity cases.

- Any trips classed as an 'unknown' failure mode on the ALERT data have been re-distributed proportionally based upon the spread of the other sub-unit failure modes. This is shown in the tables within Appendix 1
- All MTTF and MTTR values have been modelled with an exponential probability distribution
- Planned maintenance trips have been excluded from the ALERT data used to produce the MTTR and MTTF values for the models
- Only the Compressor sub-units for the facilities have been modelled. Therefore, common site-based components such as inlet valves have not been considered
- Only the SGT400 trains have been modelled as part of the NGGT DLE (Dry Low Emission) fleet. This is due to the sites with SGT400 units being more prevalent to a RIIO-2 uncertainty mechanism, when compared to sites containing LM2500 units.
- It has been assumed that all NGGT maintenance teams have applied the same logic when assigning failure modes using ALERT and that any errors in assigning have been equally spread across all facilities
- The model's running time is continuous and the demand on the compressor units is constant throughout the simulation
- Units that are currently, or that will be under major repair/outage during the period 2022-2025 have still been considered when producing the MTTR and MTTF for the models from ALERT.

[redacted]

3 RESULTS

3.1 Avon

This section presents the key results obtained from base case model for Avon driven Gas Compressor Train.

3.1.1 Overall Performance

In order to obtain stable results, the model was run 10,000 lifecycles with each lifecycle representing one possible scenario of the performance of the facilities over the 100-year period (equivalent to 403x100 running hours). Table 3-1 presents the key performance indicators of the facilities.

Table 3-1, Avon - Key Performance Indicators

Performance Parameter	Unit	AVON
Compressor Train Availability	%	**64.33**
P10	%	78.62
P90	%	47.10
Required Running Hours	hours	403
Achieved Running Hours	hours	259

Review of the results shows the following:

- The Avon driven Gas Compressor Train Availability is predicted to be 64.33%. Note that this result is the mean availability over 10,000 lifecycles. The availability varies from one lifecycle simulation to another. In order to give an indication of the uncertainty in the achieved availability, the following observations can be made:
  - There is a 90% probability that the achieved Availability is greater than 47.10% (P90)
  - There is a 10% probability that the achieved Availability is greater than 78.62% (P10).
- The results indicate that the compression train can achieve an averaged 259 running hours out of the required 403 running hours per year.

3.1.2 Outage Distribution

Total outages of the compressor train are found to be very frequent, averaging approximately 2 outages over 1 year period (or 403 running hours). Figure 3-1 below presents the frequency and duration of the compressor total outages.

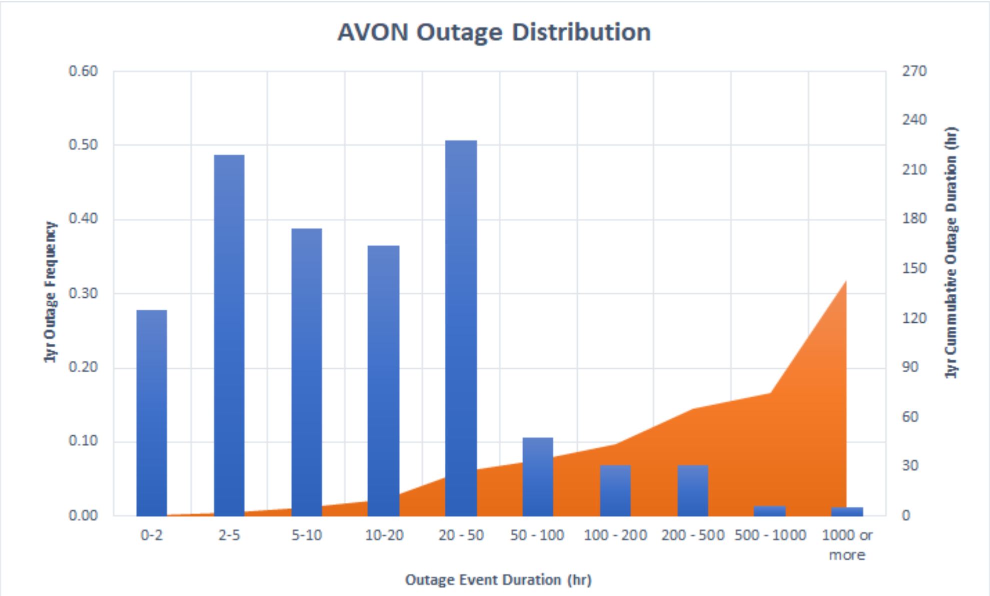


Figure 3-1, Avon - Outage Distribution

[redacted]

The following observations can be made from the outage distribution:

- Over the period of 1 year or 403 running hours, the average number of compressor total outages is predicted to be 2.3 times. The duration of the total outage events can range from a few hours, up to a few weeks / months, depending on the duration of repairs.
- The majority of the outages (50%) are less than 10 hours, i.e., mostly short compressor trips.
- Approximately 43% of outages have duration ranging from 10-100 hours. These outages are mostly minor failures with spare parts available and turnaround in 1-2 days.
- Approximately 6% of outages have duration ranging from 100-500 hours. These outages are mostly minor failures without spare parts available. For these failures, spare parts might not be available from warehouse in Didcot and would need to be ordered, leading to longer repair times (1 week).
- Approximately 1% of outages have duration longer than 500 hours. These outages are caused by major failures with overall repair time, including mobilisation of spare parts, in order of months.

3.1.3 Criticality

The contributors to compressor train's unavailability are given at sub-system and failure mode level. Table 3-2 and Figure 3-2 present the contribution of each sub-unit to the unavailability of the compressor train.

Table 3-2, Avon - Sub-Unit Contributors

Sub-Unit	Absolute Loss (%)	Relative Loss (%)
Safety/Protection/ESD	7.30	20.5
Control System	4.95	13.9
Compressor	4.44	12.4
Miscellaneous	4.42	12.4
Starting Trips	4.32	12.1
Power Turbine	4.31	12.1
Lubrication	2.10	5.9
Fuel	1.87	5.2
Gas Generator	1.18	3.3
Seal & Bearing	0.77	2.2
Total	**35.67**	**100.0**

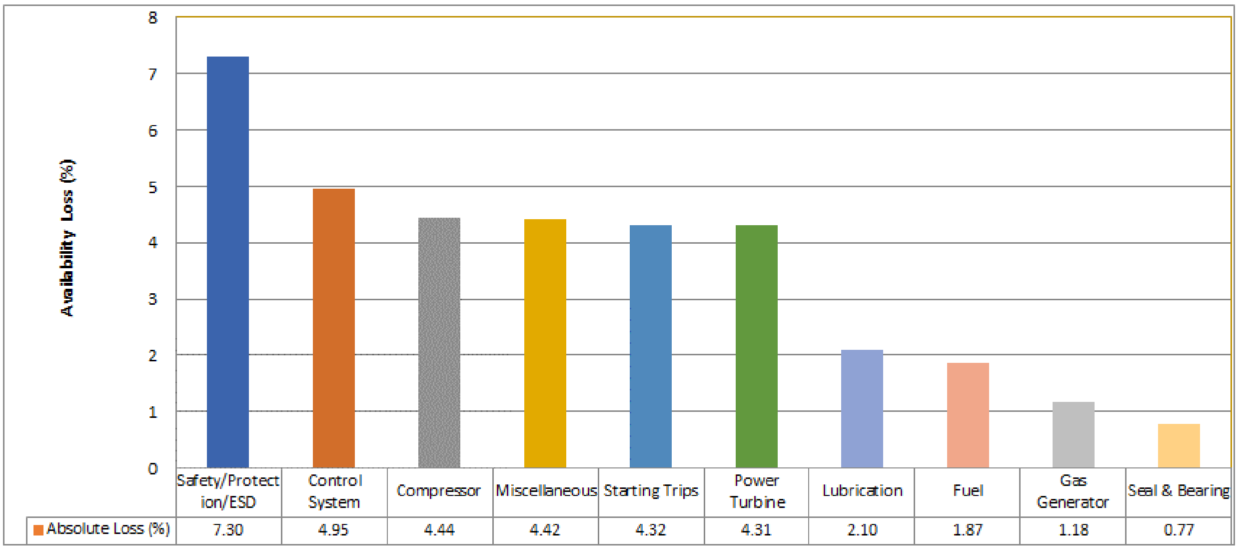


Figure 3-2, Avon – Sub-Unit Contributors

The following observations can be made from the sub-unit contributor results:

- Failures of the Safety/Protection/ESD sub-unit are the largest contributor to availability loss. They account for 7.30% absolute loss. Most of the losses attributed to this sub-unit are caused by major failures; with 5.26% of the Avon's absolute loss contributed to Safety/Protection/ESD major failures. See Table 3-3 for details of each failure category's contribution to sub-unit's availability loss.
- The second largest loss-contributor to availability is trips and failures of the control system, predicted to cause up to 4.95% absolute loss. The majority of losses attributed to this sub-unit are caused by major failures with long lead-times.
- The third largest contributor to the availability loss is the compressor sub-unit; recording an absolute loss of 4.44%.
- Contributions from the Miscellaneous and Power Turbine sub-units are significant. They cause 4.42% and 4.31% absolute loss respectively. Like other sub-units, most of the losses are caused by major failures and minor failures when spare parts are not available.
- Starting trips are also predicted to cause considerable availability loss. The Avon compressor train is assumed to have an average grid-start duration of 27 hours – this value was calculated through analysis of ALERT data for the Avon compressor trains. The grid starts will be subject to a starting failure probability. Overall, start trips account for 4.32% absolute loss.

Table 3-3 shows failure categories' contribution to the availability loss for each sub-unit.

Table 3-3, Avon – Failure Category Contributors

Failure Category	Absolute Loss (%)	Relative Loss (%)
Safety/Protection/ESD		
Major Failures	5.26	14.7
Minor Failures (Spare Not Available)	1.49	4.2
Minor Failures (Spare Available)	0.31	0.9
Trips	0.24	0.7
Control System		
Major Failures	3.59	10.1
Minor Failures (Spare Not Available)	0.98	2.7
Minor Failures (Spare Available)	0.21	0.6
Trips	0.16	0.5
Compressor		
Major Failures	3.70	10.4
Minor Failures (Spare Available)	0.55	1.5
Trips	0.19	0.5
Miscellaneous		
Minor Failures (Spare Not Available)	3.13	8.8
Major Failures	1.10	3.1
Trips	0.19	0.5
Starting Trips		
start-up trip	4.28	12.0
grid start	0.04	0.1
Power Turbine		
Major Failures	2.44	6.8
Minor Failures (Spare Not Available)	1.44	4.0
Minor Failures (Spare Available)	0.23	0.6

[redacted]

Failure Category	Absolute Loss (%)	Relative Loss (%)
Trips	0.21	0.6
Lubrication		0.0
Minor Failures (Spare Not Available)	1.67	4.7
Minor Failures (Spare Available)	0.29	0.8
Trips	0.13	0.4
Fuel		
Major Failures	1.00	2.8
Minor Failures (Spare Not Available)	0.68	1.9
Minor Failures (Spare Available)	0.10	0.3
Trips	0.09	0.2
Gas Generator		
Minor Failures (Spare Not Available)	1.12	3.1
Trips	0.07	0.2
Seal & Bearing		
Minor Failures (Spare Not Available)	0.62	1.7
Major Failures	0.10	0.3
Trips	0.05	0.1
Total	**35.67**	**100.0**

Figure 3-3 shows contribution of each failure mode (or failure associated with a specific repair time) to the availability loss.

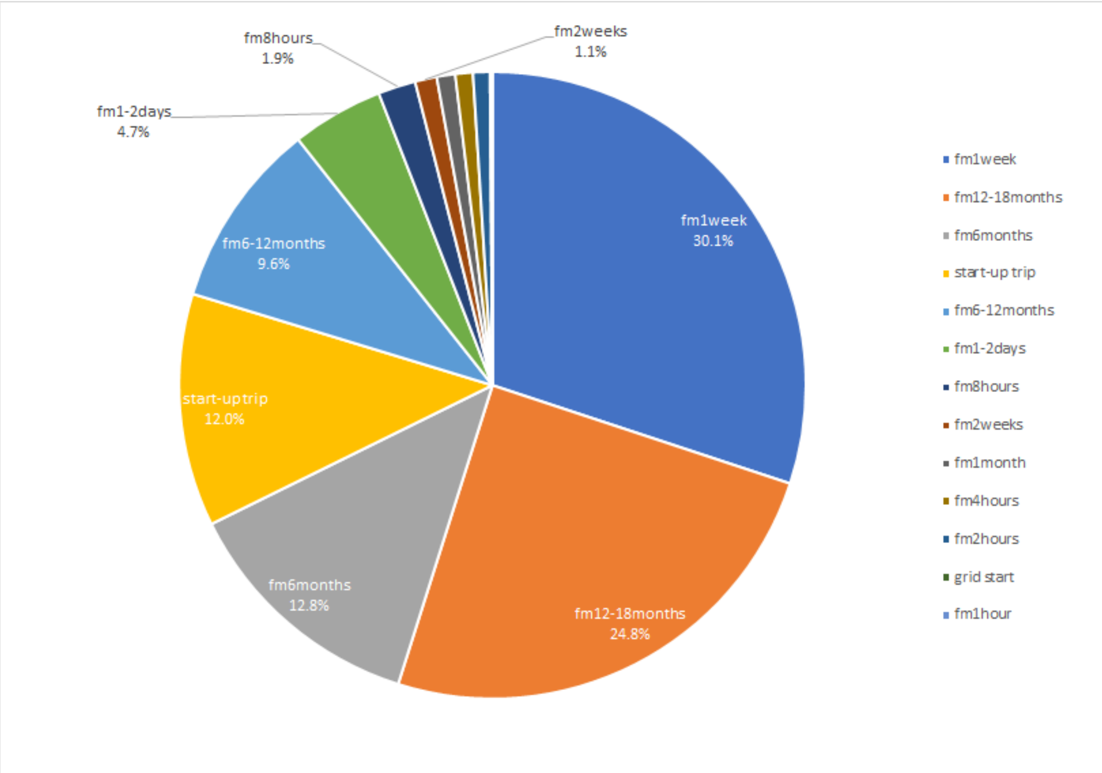


Figure 3-3, Avon – Failure Mode/Repair Time Contributors

The following observations can be made from the failure mode contributors:

- The most critical failure mode (fm1week) will be minor failures, when spare parts are not available. For these failures, spare parts might not be available onsite or from the warehouse in Didcot and would need to be ordered, leading to longer repair times (1 week).

- The second most critical failure mode (fm12-18months) will be major failures on control and safety protection systems, where long lead time for capital spare parts is expected. Other major failure modes (fm6months and fm6-12months) are also very critical, again due to the long lead time required.
- Starting trips are also critical. Starting success probability for Avon is 90.6%, however Avon compressor train is associated with frequent starts, averaging a successful start is required for every 27 running hours.
- Other failure modes, although occurring much more often, are less critical due to short repair times.

[redacted]

3.2 SGT400

This section presents the key results obtained from base case model for SGT400 driven Gas Compressor Train.

3.2.1 Overall Performance

In order to obtain stable results, the model was run 10,000 lifecycles with each lifecycle representing one possible scenario of the performance of the facilities over the 100-year period (equivalent to 1062x100 running hours). Table 3-4 presents the key performance indicators of the facilities.

Table 3-4, SGT400 - Key Performance Indicators

Performance Parameter	Unit	SGT400
Compressor Train Availability	%	**77.78**
P10	%	84.32
P90	%	69.24
Required Running Hours	hours	1062
Achieved Running Hours	hours	826

Review of the results shows the following:

- The SGT driven Gas Compressor Train Availability is predicted to be 77.8%. Note that this result is the mean availability over 10,000 lifecycles. The availability varies from one lifecycle simulation to another. In order to give an indication of the uncertainty in the achieved availability, the following observations can be made:
  - There is a 90% probability that the achieved Availability is greater than 69.2% (P90)
  - There is a 10% probability that the achieved Availability is greater than 84.3% (P10).
- The results indicate that the compression train can achieve an average of 826 running hours out of the required 1062 running hours per year.

3.2.2 Outage Distribution

Total outages of the compressor train are found to be very frequent, averaging approximately 5 outages over 1 year period (or 1062 running hours). Figure 3-4 below presents the frequency and duration of the compressor total outages.

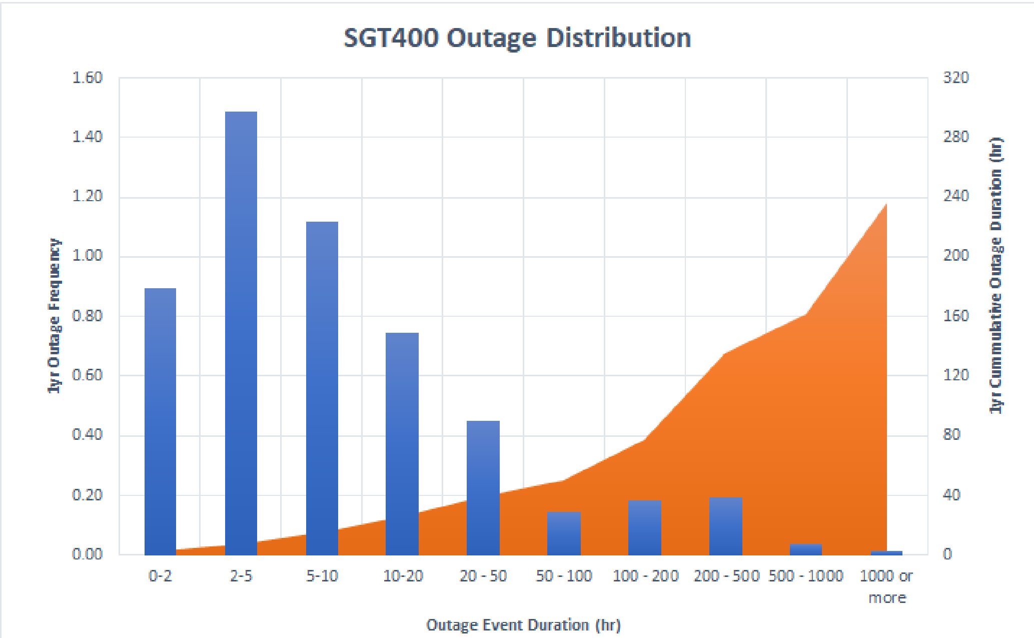


Figure 3-4, SGT400 - Outage Distribution

The following observations can be made from the outage distribution:

- Over the period of 1 year's running time or 1062 running hours, the average number of compressor total outages is predicted to be 5.3 times. The duration of the total outage events can range from a few hours, up to a few weeks / months, depending on the duration of repairs.
- The majority of the outages (67%) are less than 10 hours, i.e., mostly short compressor trips.
- Approximately 25% of outages have duration ranging from 10-100 hours. These outages are mostly minor failures with spare parts available and turnaround in 1-2 days.
- Approximately 7% of outages have duration ranging from 100-500 hours. These outages are mostly minor failures without spare parts available. For these failures, spare parts might not be available from the warehouse in Didcot and would need to be ordered, leading to longer repair times (1 week).
- Approximately 1% of outages have duration longer than 500 hours. These outages are caused by major failures with overall repair time, including mobilisation of spare parts, in order of months.

3.2.3 Criticality

The contributors to compressor train's unavailability are given at sub-system and failure mode level. Table 3-5 and Figure 3-5 present the contribution of each sub-unit to the unavailability of the compressor train.

Table 3-5, SGT400 - Sub-Unit Contributors

Sub-Unit	Absolute Loss (%)	Relative Loss (%)
Miscellaneous	6.39	28.8
Safety/Protection/ESD	4.43	19.9
Lubrication	2.80	12.6
Fuel	2.33	10.5
Gas Generator	2.10	9.4
Starting Trips	1.80	8.1
Power Turbine	1.06	4.8
Control System	0.77	3.5
Compressor	0.53	2.4
Total	**22.22**	**100.0**

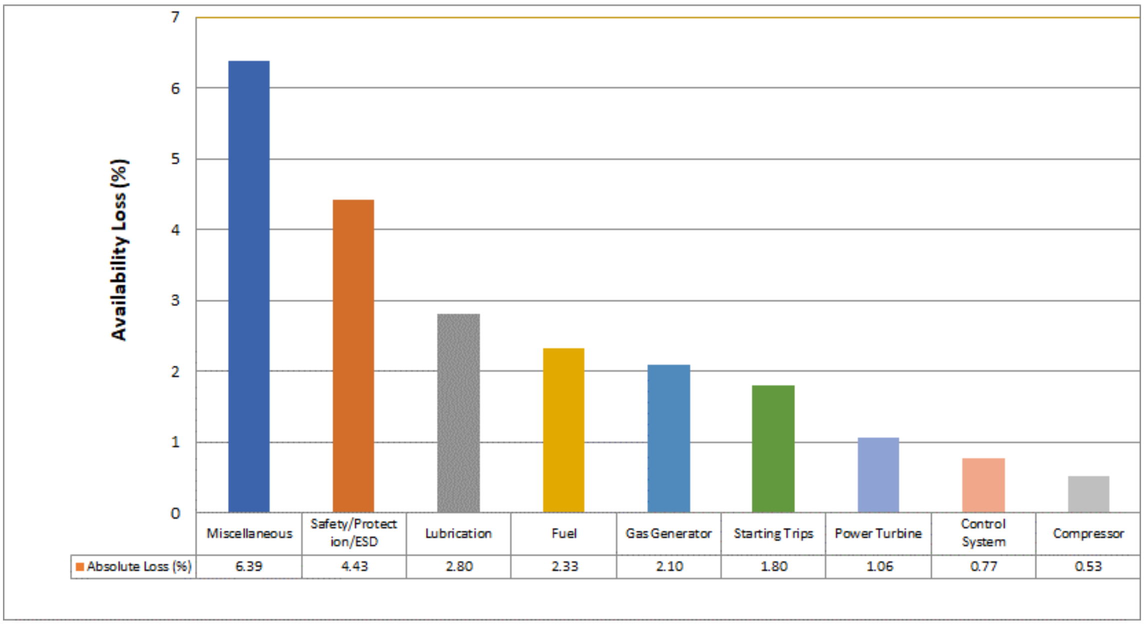


Figure 3-5, SGT400 – Sub-Unit Contributors

[redacted]

The following observations can be made from the sub-unit contributor results:

- The largest contributor to the availability loss is the Miscellaneous sub-unit – causing a 6.39% absolute loss. Most of the losses attributed to this sub-unit are caused by minor failures when spare parts are unavailable. See Table 3-6 for details of each failure category's contribution to sub-unit's availability loss.
- The second largest contributor to the availability loss are trips and failures of the Safety/Protection/ESD system, predicted to cause 4.43% absolute loss. Most of the losses attributed to this sub-unit are caused by major failures with a long lead time.
- Failures of the Lubrication sub-unit are the third largest contributor to the availability loss. They account for 2.80% absolute loss. Most of the losses attributed to this sub-unit are caused by minor failures when spare parts are not available.
- Contribution from the Fuel sub-unit is also significant, causing a 2.33% availability loss. Like other sub-units, most of the losses are caused by minor failures, when spare parts are unavailable.
- Starting trips are also predicted to cause considerable availability loss. The SGT400 compressor train is assumed to have an average grid-start duration of 28 hours. The grid starts will be subject to starting failure probability. Overall, start trips account for 1.80% absolute loss.

Table 3-6 shows failure categories' contribution to the availability loss for each sub-unit.

Table 3-6, SGT400 – Failure Category Contributors

Failure Category	Absolute Loss (%)	Relative Loss (%)
Miscellaneous		
Minor Failures (Spare Not Available)	5.53	24.9
Major Failures	0.51	2.3
Trips	0.35	1.6
Safety/Protection/ESD		
Major Failures	3.19	14.4
Minor Failures (Spare Not Available)	0.90	4.0
Minor Failures (Spare Available)	0.19	0.9
Trips	0.15	0.7
Lubrication		
Minor Failures (Spare Not Available)	2.51	11.3
Trips	0.29	1.3
Fuel		0.0
Major Failures	1.35	6.1
Minor Failures (Spare Not Available)	0.76	3.4
Minor Failures (Spare Available)	0.13	0.6
Trips	0.10	0.5
Gas Generator		
Minor Failures (Spare Not Available)	1.98	8.9
Trips	0.12	0.5
Starting Trips		0.0
start trip	1.76	7.9
grid start	0.05	0.2
Power Turbine		
Major Failures	0.65	2.9

[redacted]

Failure Category	Absolute Loss (%)	Relative Loss (%)
Minor Failures (Spare Not Available)	0.30	1.3
Minor Failures (Spare Available)	0.06	0.3
Trips	0.05	0.2
Control System		
Major Failures	0.56	2.5
Minor Failures (Spare Not Available)	0.15	0.7
Minor Failures (Spare Available)	0.03	0.1
Trips	0.02	0.1
Compressor		
Major Failures	0.45	2.0
Minor Failures (Spare Available)	0.06	0.3
Trips	0.02	0.1
Total	**22.22**	**100.0**

Figure 3-6 shows contribution of each failure mode (or failure associated with a specific repair time) to the availability loss.

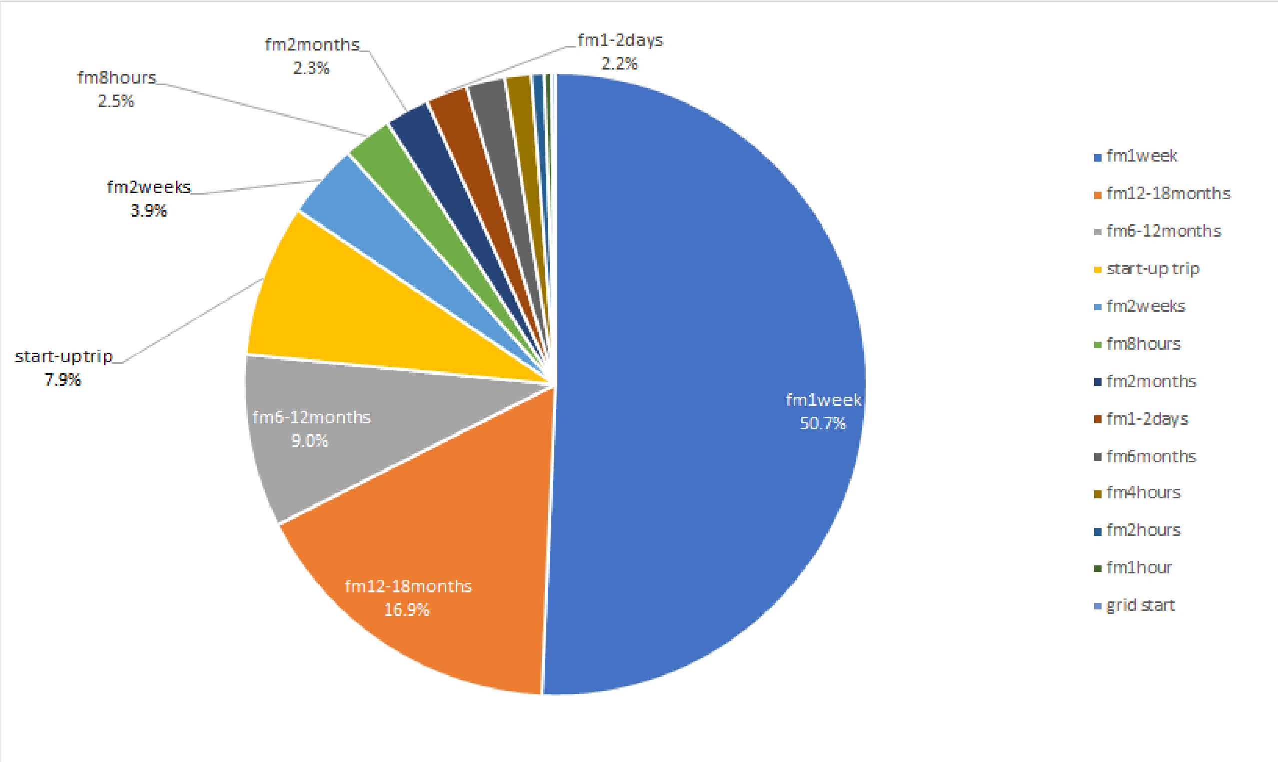


Figure 3-6, SGT400 – Failure Mode/Repair Time Contributors

The following observations can be made from the failure mode contributors:

- The most critical failure mode (fm1week) will be minor failures, when spare parts are not available. For these failures, spare parts might not be available onsite or from the warehouse in Didcot and would need to be ordered, leading to longer repair times (1 week).
- The second most critical failure mode (fm12-18months) will be major failures on control and safety protection systems, where long lead time for capital spare parts is expected. Other major failure modes (fm6-12months and fm2months) are also very critical, again due to the long lead time required.

- Starting trips are also a critical failure mode. Starting success probability for SGT400 (91.4%) is higher than that of Avon (90.6%). Though, the SGT400 is associated with a similar length of average grid start duration to the Avon units. The SGT400 having an average duration of 28 hours, compared to the Avon's 27 hours.
- Other failure modes, although occurring much more often, are less critical due to short repair times.

[redacted]

3.3 VSD

This section presents the key results obtained from base case model for VSD driven Gas Compressor Train.

3.3.1 Overall Performance

In order to obtain stable results, the model was run 10,000 lifecycles with each lifecycle representing one possible scenario of the performance of the facilities over the 100-year period (equivalent to 2463x100 running hours). Table 3-7 presents the key performance indicators of the facilities.

Table 3-7, VSD - Key Performance Indicators

Performance Parameter	Unit	VSD
Compressor Train Availability	%	81.64
P10	%	87.80
P90	%	75.34
Required Running Hours	hours	2463
Achieved Running Hours	hours	2011

Review of the results shows the following:

- The SGT driven Gas Compressor Train Availability is predicted to be 81.6%. Note that this result is the mean availability over 10,000 lifecycles. The availability varies from one lifecycle simulation to another. In order to give an indication of the uncertainty in the achieved availability, the following observations can be made:
    - There is a 90% probability that the achieved Availability is greater than 75.3% (P90)
    - There is a 10% probability that the achieved Gas Supply Availability is greater than 87.8% (P10).
- The results indicate that the compression train can achieve an averaged 2011 running hours out of the required 2463 running hours per year.

3.3.2 Outage Distribution

Total outages of the compressor train are found to be very frequent, averaging approximately 6 outages over 1 year period (or 2463 running hours). Figure 3-7 below presents the frequency and duration of the compressor total outages.

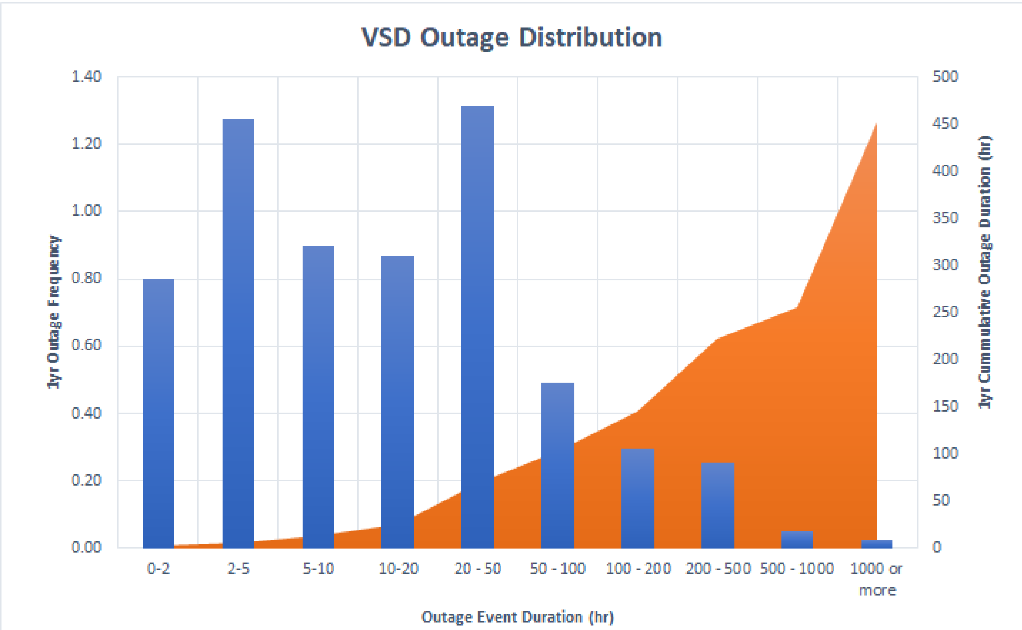


Figure 3-7, VSD - Outage Distribution

The following observations can be made from the outage distribution:

- Over the period of 1 year or 2463 running hours, the average number of compressor total outages is predicted to be 6.3 times. The duration of the total outage events can range from a few hours, up to a few weeks / months, depending on the duration of repairs.
- The majority of the outages (47%) are less than 10 hours, i.e., mostly short compressor trips.
- Approximately 43% of outages have duration ranging from 10-100 hours. These outages are mostly minor failures with spare parts available and turnaround in 1-2 days.
- Approximately 9% of outages have duration ranging from 100-500 hours. These outages are mostly minor failures without spare parts available. For these failures, spare parts might not be available from the warehouse in Didcot and would need to be ordered, leading to longer repair times (1 week).
- Approximately 1% of outages have duration longer than 500 hours. These outages are caused by major failures with overall repair time, including mobilisation of spare parts, in the order of months.

3.3.3 Criticality

The contributors to compressor train's unavailability are given at sub-system and failure mode level. Table 3-8 and Figure 3-8 present the contribution of each sub-unit to the unavailability of the compressor train.

Table 3-8, VSD - Sub-Unit Contributors

Sub-Unit	Absolute Loss (%)	Relative Loss (%)
Safety/Protection/ESD	6.83	37.2
Miscellaneous	3.73	20.3
Control System	2.37	12.9
Starting Trips	2.33	12.7
VSD	2.28	12.4
Power Supply	0.68	3.7
Compressor	0.13	0.7
Total	**18.36**	**100.0**

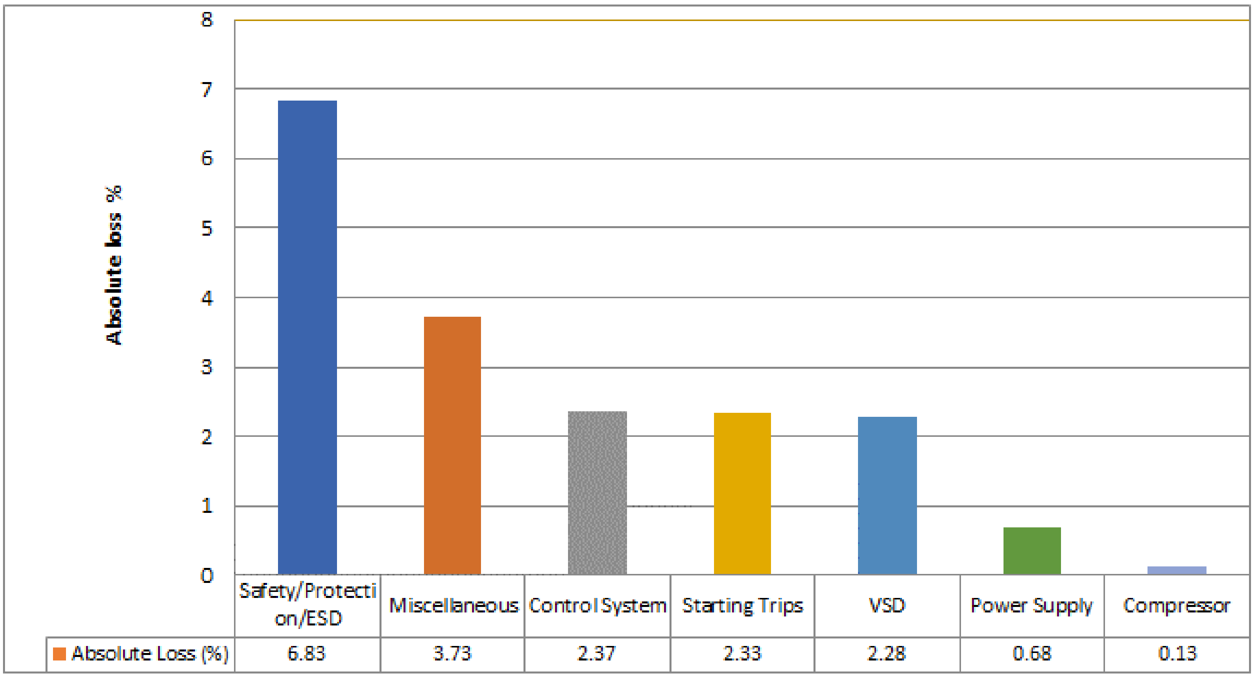


Figure 3-8, VSD – Sub-Unit Contributors

The following observations can be made from the sub-unit contributor results:

[redacted]

- Failures and trips of the Safety/Protection/ESD sub-unit are the largest contributor to the availability loss. They account for 6.83% absolute loss. Most of the losses attributed to this sub-unit are caused by major failures with long lead-times. See Table 3 9 for details of each failure category's contribution to sub-unit's availability loss.
- The second largest contributor to the availability loss are Miscellaneous failures, causing up to 3.73% absolute loss. Most of the losses are caused by minor failures; when spare parts are not available.
- The third largest contributor to the availability loss is failures of the control system, predicted to cause 2.38% absolute loss. Most of the losses attributed to this sub-unit are caused by minor failures when spare parts are not available.
- Contribution from the VSD sub-unit to the availability loss should also be considered significant, causing 2.28% absolute loss. Most of the losses from this sub-unit are caused by major failures with a long lead time.
- Starting trips are predicted to cause considerable availability loss. The VSD compressor train is assumed to have an average grid-start duration of 60 hours. The grid starts are be subject to a starting failure probability. Overall, start trips account for 2.33% absolute loss.

Table 3-9 shows failure categories' contribution to the availability loss for each sub-unit. Note, the Relative Loss value is the Absolute Loss value for each specific failure category, as a percentage of the total Absolute Loss (18.35%).

Table 3-9, VSD – Failure Category Contributors

Failure Category	Absolute Loss (%)	Relative Loss (%)
Safety/Protection/ESD		
Major Failures	4.87	26.5
Minor Failures (Spare Not Available)	1.44	7.9
fm1-2 days	0.29	1.6
Trips	0.23	1.2
Miscellaneous		
Minor Failures (Spare Not Available)	3.48	19.0
Trips	0.24	1.3
Control System		
Major Failures	1.71	9.3
Minor Failures (Spare Not Available)	0.48	2.6
Minor Failures (Spare Available)	0.10	0.6
Trips	0.08	0.4
Starting Trips		
starting trip	2.31	12.6
grid start	0.02	0.1
VSD		0.0
Major Failures	1.19	6.5
Minor Failures (Spare Not Available)	0.82	4.4
Minor Failures (Spare Available)	0.23	1.3
Trips	0.03	0.2
Power Supply		
Minor Failures (Spare Not Available)	0.53	2.9
Minor Failures (Spare Available)	0.14	0.7
Trips	0.02	0.1
Compressor		

Failure Category	Absolute Loss (%)	Relative Loss (%)
Major Failures	0.06	0.3
Minor Failures (Spare Available)	0.06	0.3
Trips	0.01	0.1
Total	**18.36**	**100.0**

Figure 3-9 shows contribution of each failure mode (or failure associated with specific repair time) to the availability loss.

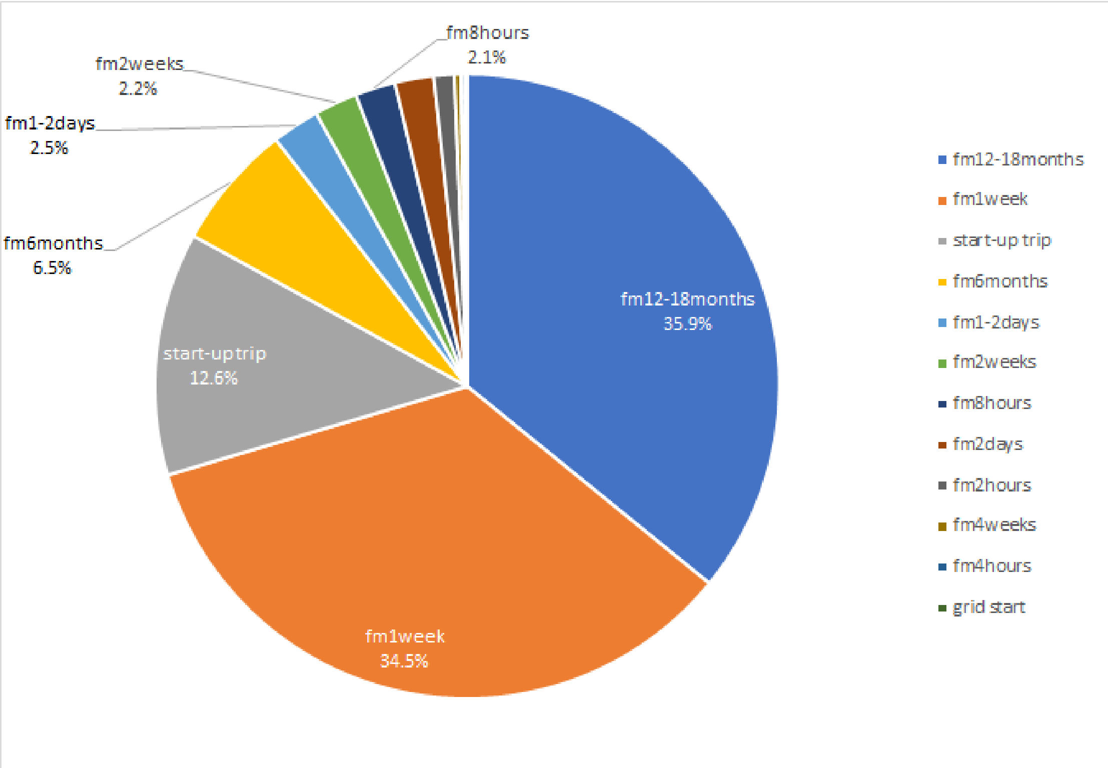


Figure 3-9, VSD – Failure Mode Contributors

The following observations can be made from the failure mode contributors:

- The most critical failure mode (fm12-18months) will be major failures on control and safety protection systems, where long lead time for capital spare parts is expected. Other major failure mode (fm6months) is also very critical, again due to the long lead time required.
- The second most critical failure mode (fm1week) will be minor failures, when spare parts are not available. For these failures might not be available onsite or from warehouse in Didcot and would need to be ordered, leading to longer repair times (1 week).
- Starting success probability for VSD is higher than that of Avon and SGT400, standing at is 93.8%. VSD also have the longest running time per successful start (60 hours) among the three fleets. However, the average duration between start attempts, following a failed start, is found to be longer with VSD fleet.

[redacted]

3.4 Sensitivity Case Results

Following completion of the Base Case models and further discussion with the NGGT team; 16 sensitivity cases were chosen for analysis. Sensitivity cases have been considered to assess the performance impact of different operational strategies, equipment replacement at a sub-unit level and alterations to the running patterns of the compressor trains.

3.4.1 Avon Sensitivity Cases

This section presents the key findings from the sensitivity cases completed for the Avon compressor trains. Displayed below is a table outlining the sensitivity case number, the planned investment from NGGT and the updated parameters for the model.

Table 3-10, Avon Sensitivity Case Definition

Sensitivity Case	Investment	Updated Parameters
A1	Full replacement of the following sub-units: Control System, Safety/Protection/ESD, Lubrication & Fuel systems + Capital spares	**Control System & Safety/Protection/ESD:** SGT400 MTTF values used for sub-units
		Lubrication & Fuel: 30% Improvement in MTTF values
		Starting Failure Probability: Improvement to match STG400 value (0.086)
		Control System & Safety/Protection/ESD: Major Failure MTTR = 6 Months
A2	Full replacement of the following sub-units: Control System, Safety/Protection/ESD, Lubrication, Fuel systems & Compressor + Capital spares	**All parameters updated as in Case A1**
		Compressor: SGT400 MTTF value used
A3	Full replacement of the following sub-units: Control System, Safety/Protection/ESD, Lubrication, Fuel systems, Compressor & Power Turbine + Capital spares	**All parameters updated as in Case A1**
		All parameters updated as in Case A2
		Power Turbine: SGT400 MTTF Value used
A4	Full replacement of all sub-units + spares holding for all sub-units	**All parameters updated as in Case A1**
		All parameters updated as in Case A2
		All parameters updated as in Case A3
		MTTF for all other sub-units improved to match SGT value or by a 20% improvement (whichever is larger)
		All minor failure without spares = 1-2 days MTTR
A5	Improved Spares holding	**All minor failure without spare:** 1-2 days MTTR
A6	Increased run-time for units	**1 start used per model run** (Starting Probability still applies)

As was the case with the base case models, in order to obtain stable results, the model was run 10,000 lifecycles with each lifecycle representing one possible scenario of the performance of the facilities over the 100-year period (equivalent to 403x100 running hours). Table 3-11 presents the key performance indicators of the Avon facilities for the base case and sensitivity cases outlined above.

Table 3-11, Avon Sensitivity Case Performance Indicators

Performance Parameter	Unit	Avon Base	A1	A2	A3	A4	A5	A6
Compressor Train Availability	%	**64.33**	**72.62**	**76.05**	**79.45**	**86.31**	**70.23**	**66.78**
Absolute loss	%	**35.67**	**27.38**	**23.95**	**20.55**	**13.69**	**29.77**	**33.22**
P10	%	78.62	82.65	84.06	85.85	91.66	86.58	82.13
P90	%	47.10	58.80	64.40	69.34	74.96	50.34	48.32
Required Running Hours	hours	403	403	403	403	403	403	403
Achieved Running Hours	hours	259	293	307	320	348	283	269

A criticality table has been displayed below showing the individual sub-unit contribution to absolute loss for the base case and the Avon sensitivity cases.

Table 3-12, Avon Sensitivity Case Criticality Table

Sub-Unit	Absolute Loss (%)						
Case	**Avon Base**	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**
Safety/Protection/ESD	7.30	2.41	2.46	2.53	1.95	6.63	7.54
Control System	4.95	0.41	0.44	0.44	0.36	4.78	5.09
Compressor	4.44	5.14	0.50	0.49	0.50	4.65	4.75
Miscellaneous	4.42	4.91	5.20	5.47	2.26	2.31	4.65
Starting Trips	4.32	4.32	4.39	4.53	4.86	4.71	0.70
Power Turbine	4.31	4.62	5.02	0.95	0.73	3.50	4.43
Lubrication	2.10	1.82	1.92	2.00	0.92	0.99	2.15
Fuel	1.87	1.54	1.71	1.70	1.36	1.46	1.89
Gas Generator	1.18	1.34	1.39	1.47	0.40	0.39	1.23
Seal & Bearing	0.77	0.87	0.92	0.96	0.34	0.34	0.80
Total	**35.67**	**27.38**	**23.95**	**20.55**	**13.69**	**29.77**	**33.22**

Each of the sensitivity cases completed on the Avon sub-units represented an improvement in terms of compressor train availability. Further analysis for each of the Avon sensitivity cases is presented below.

Case A1

This sensitivity case simulated a complete replacement of the: Control System, Safety/Protection/ESD, Lubrication & Fuel System sub-unit. This therefore increased the MTTF for the replaced sub-units, improved the starting failure probability and reduced the mean repair time for a major failure of the control and safety/protection/ESD systems by the values outlined in Table 3-10 above.

Case A1 achieved 293 running hours and in turn, an availability of 72.62%. This represents an 8.29% absolute improvement from the Avon base case.

Table 3-12 has been displayed above outlining the absolute loss for each of the sub-units modelled when compared to the Avon base case. It is evident that the sub-units with parameters altered have had the biggest change in absolute loss relative to the base case.

Case A2

This sensitivity case built upon the investment made in case A1 plus Compressor sub-unit replacement. Case A2 achieved 307 running hours and in turn, an availability of 76.05%. This represents an 11.72% absolute improvement from the Avon base case.

Case A3

This sensitivity case is built upon the investment made in case A2 plus Power Turbine sub-unit replacement. Case A3 achieved 320 running hours and in turn, an availability of 79.45%. This represents a 15.12% absolute improvement from the Avon base case.

Case A4

This sensitivity case is built upon the investment made in Case A3, plus a replacement or overhaul of all sub-units. This case additionally simulated spares holding for all sub-units.

[redacted]

Case A4 achieved 348 running hours and in turn, an availability of 86.31%. This represents a 21.98% absolute improvement from the Avon base case.

Case A5

Case A5 simulated an improved level of spares holding for the Avon compressor unit, this investment in spares reduced the MTTR for the minor failure without spare failure mode for all Avon sub-units. This is outlined in Table 3-10.

Case A5 achieved 283 running hours and in turn, an availability of 70.23%. This represents a 5.90% absolute improvement from the Avon base case.

Case A6

Case A6 simulated a change to the running patterns for the Avon compressor train; the compressors were run continuously for the required 403 hours. Therefore, the model used only one grid-start for case A6. This is atypical for an NGGT compressor, generally compressor units are run in a discontinuous fashion based up on grid demand. This is further outlined in Table 3-10.

Case A6 achieved 269 running hours and in turn, an availability of 66.78%. This represents a 2.45% absolute improvement from the Avon base case.

3.4.2 SGT400 Sensitivity Cases

This section presents the key findings from the sensitivity cases completed for the SGT compressor trains. Displayed below is a table outlining the sensitivity case number, the planned investment from NGGT and the updated parameters for the model.

Table 3-13, SGT400 Sensitivity Case Definition

Sensitivity Case Number	Investment / Change	Updated Parameters
S1	Implementation of remote monitoring & LTSA	**All minor failures without spare:** 3-4 days MTTR
		All major failures: MTTR improvement by 50%
S2	Control system overhaul/replacement	**Control system & Safety/Protection/ESD:** 20% improvement to MTTF value
		Control System & Safety/Protection/ESD: Major Failure MTTR = 6 Months
S3	Control System Overhaul & Implementation of Remote monitoring/LTSA	**All parameters updated as in Case S2**
		All minor failures without spare: 3-4 days MTTR
		All major failures: MTTR improvement by 50% (Aside from those outlined in S2)
S4	Control System Overhaul, Implementation of Remote monitoring/LTSA, Fuel/Lubrication improvements & beneficial bulletins/site design improvements	All parameters updated as in Case S3
		Fuel and Lubrication: 20% improvement to MTTF value
		Miscellaneous: 20% improvement to MTTF value
S5	Increased run-time for units	**1 start used per model run (**Starting Probability still applies)
S6	Compressor Overhaul	**Compressor:** 20% improvement to MTTF value

As was the case with the SGT base case model, in order to obtain stable results, the model was run 10,000 lifecycles with each lifecycle representing one possible scenario of the performance of the facilities over the 100-year period (equivalent to 1062x100 running hours). Table 3-14 presents the key performance indicators of the SGT400 base case and the sensitivity cases.

Table 3-14, SGT400 Sensitivity Case Performance Indicators

Performance Parameter	Unit	SGT 400 Base	S1	S2	S3	S4	S5	S6
Compressor Train Availability	%	**77.78**	**85.48**	**80.01**	**86.32**	**87.37**	**79.04**	**77.87**
Absolute loss	%	**22.22**	**14.52**	**19.99**	**13.68**	**12.63**	**20.96**	**22.13**
P10	%	84.32	89.23	84.74	89.64	90.59	85.84	84.37
P90	%	69.24	80.55	73.97	81.92	82.96	70.39	69.69
Required Running Hours	hours	1062	1062	1062	1062	1062	1062	1062
Achieved Running Hours	hours	826	908	850	917	928	839	827

A criticality table has been displayed below showing the individual sub-unit contribution to absolute loss for the SGT400 base case and sensitivity cases.

Table 3-15, SGT400 Sensitivity Case Criticality Table

Sub-Unit	Absolute Loss (%)						
Case	**SGT 400 Base**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Safety/Protection/ESD	4.43	2.65	2.16	1.95	1.99	4.59	4.49
Control System	0.77	0.45	0.36	0.39	0.40	0.79	0.76
Compressor	0.53	0.33	0.52	0.34	0.34	0.48	0.42
Miscellaneous	6.39	3.70	6.57	3.97	3.35	6.50	6.40
Starting Trips	1.80	1.98	1.85	2.00	1.99	0.22	1.80
Power Turbine	1.06	0.67	1.10	0.66	0.67	1.07	1.08
Lubrication	2.80	1.69	2.87	1.71	1.45	2.82	2.79
Fuel	2.33	1.80	2.40	1.44	1.20	2.36	2.28
Gas Generator	2.10	1.22	2.16	1.23	1.25	2.13	2.10
Total	**22.21**	**14.51**	**19.99**	**13.68**	**12.63**	**20.96**	**22.13**

Each of the sensitivity cases completed on the SGT400 sub-units represented an improvement in terms of compressor train availability. Further analysis for each of the SGT400 sensitivity cases is presented below.

Case S1

Case S1 simulated the implementation of a remote monitoring system and use of a long-term service agreement (LTSA) for the SGT400 compressor train. The implementation of these systems reduced the MTTR for the minor failure without spare failure mode and substantially reduced the MTTR for a major failure. The updated parameters used for the model have been displayed in Table 3-13.

Case S1 achieved 908 running hours and in turn, an availability of 85.48%. This represents a 7.70% absolute improvement from the SGT400 base case.

Refer to Table 3-15 for the absolute loss for each of the sub-units modelled, when compared to the SGT400 base case. It is evident that all sub-units have had a reduction in absolute loss due to the reduction in minor repair times and the 50% reduction major failure repair times – achieved through remote monitoring of the units and LTSA implementation.

Case S2

Case S2 simulated an overhaul or complete replacement of the control system and the Safety/Protection/ESD system. This improved the MTTF value for both sub-units and improved the MTTR for a major failure for both sub-units.

Case S2 achieved 850 running hours, and in turn an availability of 80.01%. This represents an absolute improvement of 2.22% from the SGT400 base case.

Case S3

This sensitivity case built upon the investment made in case S2, plus the implementation of a remote monitoring system and use of a long-term service agreement (LTSA). Case S3 achieved 917 running hours and in turn, an availability of 86.32%. This represents an absolute improvement of 8.54% from the SGT400 base case.

Case S4

This sensitivity case built upon the investment made in case S3, plus improvements to the fuel and lubrication sub-units and site design improvements for the SGT400 compressor station. Case S4 achieved 928 running hours and in turn, an availability of 87.37%. This represents an absolute improvement of 9.59% from the SGT400 base case.

Case S5

This sensitivity case simulated a change to the running patterns for the SGT400 compressor train; the compressors were run continuously for the required 1062 hours. Thus, the model used only one grid-start for case S5. This is atypical for an NGGT compressor, generally compressor units are run in a discontinuous fashion based upon grid demand.

Case S5 achieved 839 running hours and in turn, an availability of 79.04%. This represents a 1.26% absolute improvement from the SGT400 base case.

Case S6

This sensitivity case simulated an overhaul to the compressor sub-unit, this improved the MTTF value for the compressor sub-unit alone. Case S6 achieved 826 running hours and in turn, an availability of 77.87%. This represents an improvement of 0.09% from the SGT400 base case.

3.4.3 VSD Sensitivity Cases

This section presents the key findings from the sensitivity cases completed for the VSD compressor trains. Displayed below is a table outlining the sensitivity case number, the planned investment from NGGT and the updated parameters for the model.

Table 3-16, VSD Sensitivity Case Definition

Sensitivity Case Number	Investment /Change	Updated Parameters
V1	Full replacement of the following sub-units: VSD, Control System, Safety/Protection/ESD, Miscellaneous	**VSD, Control System, Safety/Protection/ESD, Miscellaneous:** MTBF Improved by 20%
		Control System & Safety/Protection/ESD: Major Failure MTTR = 6 Months
V2	Increased run-time for units	**1 start used per model run** (Starting Probability still applies)
V3	Rewind motor	**VSD:** 20% Improvement to MTTF Value
V4	Remote Monitoring/LTSA + Spares for VSD/Control system/ Safety/Protection/ESD	**VSD, Control System + Safety/Protection/ESD** (Minor failure without spare) = 1-2 days MTTR
		VSD: Major Failure = 2 Months MTTR
		All other sub-unit minor failures without spare: 3-4 days MTTR
		All major failures: MTTR improvement by 50%

As was the case with the base model, to obtain stable results, the model was run 10,000 lifecycles with each lifecycle representing one possible scenario of the performance of the facilities over the 100-year period (equivalent to 2463x100 running hours). Table 3-17 presents the key performance indicators of the facilities.

Table 3-17, VSD Sensitivity Case Performance Indicators

Performance Parameter	Unit	VSD Base	V1	V2	V3	V4
Compressor Train Availability	%	**81.64**	**86.58**	**83.22**	**81.91**	**88.99**
Absolute loss	%	**18.36**	**13.42**	**16.78**	**18.09**	**11.00**
P10	%	87.80	89.89	89.57	88.12	92.36
P90	%	75.34	82.50	76.60	75.56	85.49
Required Running Hours	hours	2463	2463	2463	2463	2463
Achieved Running Hours	hours	2011	2132	2050	2017	2192

A criticality table has been overleaf showing the individual sub-unit contribution to absolute loss for the SGT400 base case and sensitivity cases.

Table 3-18, VSD Sensitivity Case Criticality Table

Sub-Unit	Absolute Loss (%)				
Case	**VSD Base**	**V1**	**V2**	**V3**	**V4**
Safety/Protection/ESD	6.83	3.48	7.01	6.93	3.59
Control System	2.37	1.33	2.48	2.38	1.24
Compressor	0.13	0.14	0.14	0.14	0.12
Miscellaneous	3.73	3.29	3.80	3.72	2.16
Starting Trips	2.33	2.42	0.33	2.33	2.54
Power Supply	0.68	0.72	0.70	0.69	0.46
VSD	2.28	2.02	2.33	1.90	0.90
Total	**18.36**	**13.42**	**16.78**	**18.09**	**11.00**

Each of the sensitivity cases completed on the VSD sub-units represented an improvement in terms of compressor train availability. Further analysis for each of the VSD sensitivity cases is presented below.

Case V1

This VSD compressor train sensitivity case simulated a complete replacement of the: Control System, Safety/Protection/ESD, VSD & Miscellaneous sub-unit. This therefore increased the MTTF for the replaced sub-units and reduced the mean repair time for a major failure of the control and safety/protection/ESD systems. The updates to the modelling parameters have been displayed below in Table 3-16.

Case V1 achieved 2132 running hours and in turn, an availability of 86.58%. This represents a 4.94% absolute improvement from the VSD base case.

Table 3-18 has been displayed above outlining the absolute loss for each of the sub-units modelled, when compared to the VSD base case. It is evident that the sub-units with parameters altered have had the biggest change in absolute loss relative to the VSD base case.

Case V2

Case V2 simulated a change to the running patterns for the VSD compressor train; the compressors were run continuously for the 2463 required hours. Thus, the model used only one grid-start for case V2. This is atypical for an NGGT compressor, generally compressor units are run in a discontinuous fashion based upon grid demand.

Case V2 achieved 2050 running hours and in turn, an availability of 83.22%. This represents a 1.58% absolute improvement from the VSD base case.

Case V3

This sensitivity case simulated a rewind to the motor, this resulted in an improvement to the MTTF value for the VSD (VSD Motor) sub-unit.

Case V3 achieved 2017 running hours and in turn, an availability of 81.91%. This represents an improvement of 0.27% from the VSD base case.

Case V4

This sensitivity case simulated the implementation of a remote monitoring system, plus the use of a long-term service agreement (LTSA) for the SGT400 compressor train and spares holding for the VSD, Control System and the Safety/Protection/ESD sub-units.

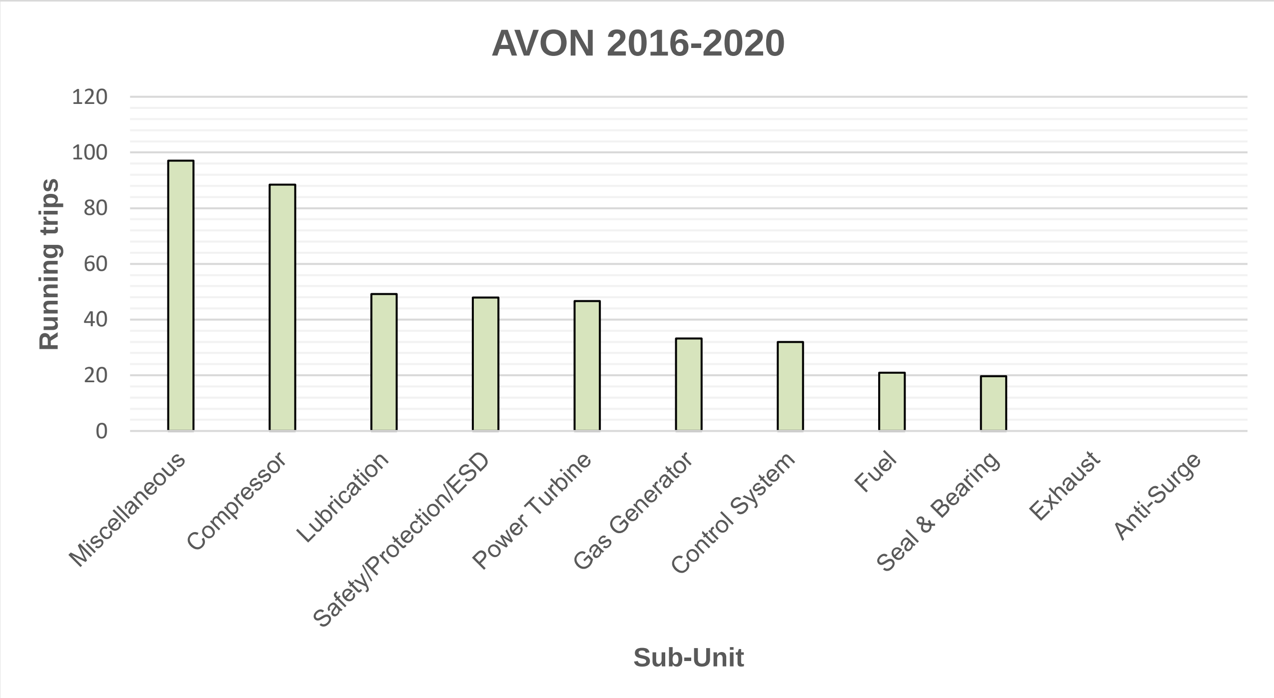
Case V4 achieved 2197 running hours and in turn, an availability of 88.99%. This represents an absolute improvement of 7.35% from the VSD base case.

Appendix 1: Summary of Compressors Trips Records (2016-2020)

AVON Compressor Units

Sub-Unit	Running Trips	Running trips (Unknowns distributed)	MTTF (hours)
Avon (2016-2020)			
Miscellaneous	79	97	651
Compressor	72	88	714
Lubrication	40	49	1286
Safety/Protection/ESD	39	48	1319
Power Turbine	38	47	1353
Gas Generator	27	33	1905
Control System	26	32	1978
Fuel	17	21	3025
Seal & Bearing	16	20	3214
Exhaust	0	0	1000000
Anti-Surge	0	0	1000000
Unknown	81		
Total	**435**	**435**	**145**

Appendix 1 - 1: Avon running trips by sub-unit



Appendix 1 - 2: Avon running trips by sub-unit

[redacted]

Appendix 1 - 3: Avon running trips by failure mode

Failure Mode	Sub-Unit	No. of Running Trips	Distributed Running Trips	MTTF (hours)
	Unknown	81	-	-
Control System	Control System	10	12.3	5143
ESD Other Station Failures	Safety/Protection/ESD	2	2.5	25715
Process Condition Other Station Failures	Miscellaneous	25	30.7	2057
Lube Oil System	Lubrication	36	44.2	1429
Fuel System Control System	Fuel	5	6.1	10286
Process/Safety System	Safety/Protection/ESD	5	6.1	10286
Ventilation Process/Safety System	Safety/Protection/ESD	2	2.5	25715
Gas Generator Other Temperature	Gas Generator	16	19.7	3214
Power Failure Other Station Failures	Miscellaneous	6	7.4	8572
Other Station Failures	Miscellaneous	25	30.7	2057
Fire Process/Safety System	Safety/Protection/ESD	9	11.1	5714
Power Turbine Vibration	Power Turbine	9	11.1	5714
ECU/GOV Failure Control System	Control System	3	3.7	17143
Gas Process/Safety System	Safety/Protection/ESD	8	9.8	6429
Flame Failure Control System	Control System	1	1.2	51430
PLC Control System	Control System	12	14.7	4286
Vibration	Miscellaneous	16	19.7	3214
Fire Other Station Failures	Safety/Protection/ESD	7	8.6	7347
Reason Unavailable	Miscellaneous	1	1.2	51430
Gas Compressor Vibration	Compressor	67	82.3	768
Gas Generator Vibration	Gas Generator	11	13.5	4675
Oil System	Lubrication	3	3.7	17143
Hydraulic Oil System	Lubrication	1	1.2	51430
ESD Process/Safety System	Safety/Protection/ESD	5	6.1	10286
Gas Compressor Other Temperature	Compressor	5	6.1	10286
Turbine Control System	Power Turbine	15	18.4	3429
Fuel System Turbine Control System	Fuel	12	14.7	4286
ECU/GOV Failure Turbine Control System	Power Turbine	9	11.1	5714
Wet Compressor Seal	Seal & Bearing	11	13.5	4675
Flame Failure Turbine Control System	Power Turbine	1	1.2	51430
Gas Compressor Bearing Temperature	Seal & Bearing	5	6.1	10286
Process Condition Vibration	Miscellaneous	6	7.4	8572
Ignition System Turbine Control System	Power Turbine	1	1.2	51430
PLC Turbine Control System	Power Turbine	3	3.7	17143
Gas leak on the regulator in the starter motor. Process/Safety System	Safety/Protection/ESD	1	1.2	51430

[redacted]

Appendix 1 - 4: Avon repair categories & associated MTTR

	Repair Category	MTTR	Probability (%)
Control System	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
ECU/GOV Failure Control System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
ECU/GOV Failure Turbine Control System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
ESD Other Station Failures	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
ESD Process/Safety System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
Fire Other Station Failures	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
Fire Process/Safety System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
Flame Failure Control System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
Flame Failure Turbine Control System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
Fuel System Control System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%

Fuel System Turbine Control System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	6-12 months	1%
Gas Compressor Bearing Temperature	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	4 hours	63%
	Minor Repair	8 hours	18%
	Minor Repair - Spare Not Available	1-2 days	18%
	Major Repair	2 weeks	1%
Gas Compressor Other Temperature	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	8 hours	18%
	Major Repair	8 hours	1%
Gas Compressor Vibration	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1-2 days	18%
	Major Repair	6 months	1%
Gas Generator Other Temperature	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
Gas Generator Vibration	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	1 week	1%
Gas leak on the regulator in the starter motor. Process/Safety System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	4 hours	63%
	Minor Repair	8 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	1 month	1%
Gas Process/Safety System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
Hydraulic Oil System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	4 hours	63%
	Minor Repair	8 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
Ignition System Turbine Control System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%

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Lube Oil System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	4 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
Oil System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	4 hours	63%
	Minor Repair	8 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	1 Week	1%
Other Station Failures	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	1 month	1%
PLC Control System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
PLC Turbine Control System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	6-12 months	1%
Power Failure Other Station Failures	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	1 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
Power Turbine Vibration	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	6 months	1%
Process Condition Other Station Failures	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 Weeks	1%
Process Condition Vibration	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	1 week	1%
Process/Safety System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%

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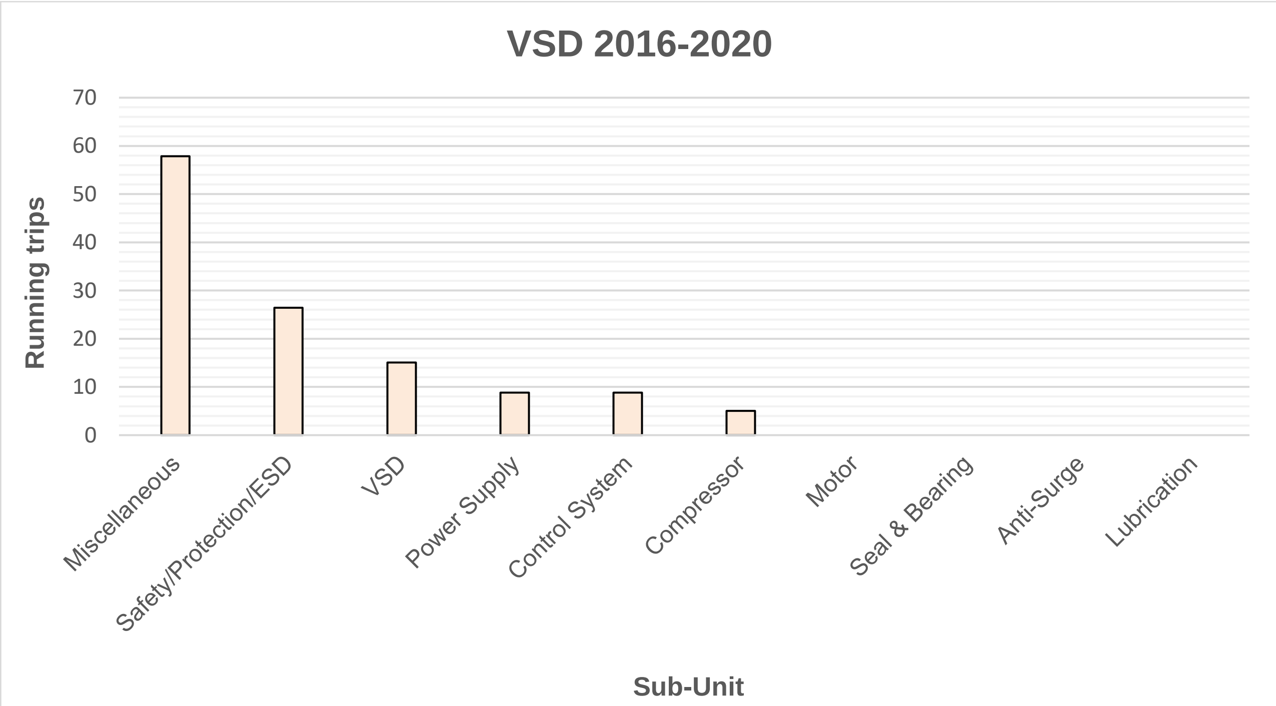
Reason Unavailable	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
Turbine Control System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
Ventilation Process/Safety System	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
Vibration	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	6 months	1%
Wet Compressor Seal	**Repair Category**	**MTTR**	**Probability (%)**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	1 month	1%

[redacted]

VSD Compressor Units

Sub-Unit	Running Trips	**Running trips** (Unknowns distributed)	MTTF (hours)
VSD (2016-2020)			
Miscellaneous	46	58	787
Safety/Protection/ESD	21	26	1725
VSD	12	15	3018
Power Supply	7	9	5174
Control System	7	9	5174
Compressor	4	5	9055
Motor	0	0	1000000
Seal & Bearing	0	0	1000000
Anti-Surge	0	0	1000000
Lubrication	0	0	1000000
Unknown	25		
Total	**122**	**122**	**373**

Appendix 1 - 5: VSD running trips by sub-unit



Appendix 1 - 6: VSD running trips by sub-unit

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Appendix 1 - 7: VSD running trips by failure mode

Failure Mode	Sub-Unit	No. of Running Trips	Distributed Running Trips	MTTF (hours)
MTTR Trip	Unknown	25		-
Control System	Control System	1	1.3	45555
ESD Other Station Failures	Safety/Protection/ESD	1	1.3	45555
Process Condition Other Station Failures	Miscellaneous	23	28.9	1981
Process/Safety System	Safety/Protection/ESD	14	17.6	3254
Ventilation Process/Safety System	Safety/Protection/ESD	1	1.3	45555
Power Failure Other Station Failures	Power Supply	7	8.8	6508
Other Station Failures	Miscellaneous	23	28.9	1981
PLC Control System	Control System	5	6.3	9111
Fire Other Station Failures	Safety/Protection/ESD	1	1.3	45555
ESD Process/Safety System	Safety/Protection/ESD	4	5.0	11389
Gas Compressor Other Temperature	Compressor	4	5.0	11389
VSD Other Temperature	VSD	12	15.1	3796
Turbine Control System	Control System	1	1.3	45555

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Appendix 1 - 8: VSD repair categories & associated MTTR

	Repair Category	MTTR	Probability (%)
Control System	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	2 weeks	18%
	Major Repair	12-18 months	1%
ESD Other Station Failures	**Repair Category**	**MTTR**	**Probability**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
ESD Process/Safety System	**Repair Category**	**MTTR**	**Probability**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
Fire Other Station Failures	**Repair Category**	**MTTR**	**Probability**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
Gas Compressor Other Temperature	**Repair Category**	**MTTR**	**Probability**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1-2 days	18%
	Major Repair	4 weeks	1%
Other Station Failures	**Repair Category**	**MTTR**	**Probability**
	Trips	2 hours	63%
	Minor Repair	8 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
PLC Control System	**Repair Category**	**MTTR**	**Probability**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
Power Failure Other Station Failures	**Repair Category**	**MTTR**	**Probability**
	Trips	2 hours	63%
	Minor Repair	2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
Process Condition Other Station Failures	**Repair Category**	**MTTR**	**Probability**
	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
Process/Safety System	**Repair Category**	**MTTR**	**Probability**
	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%

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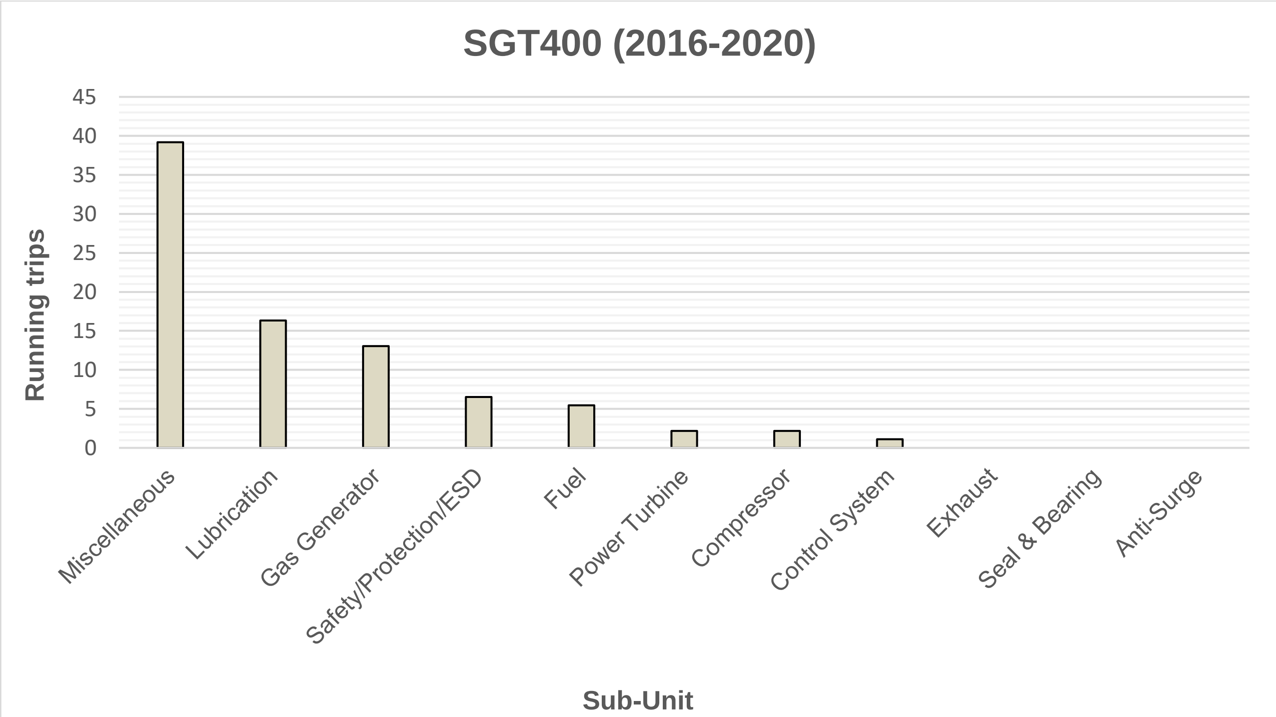
<table>
<tr><td rowspan="5">Turbine Control System</td><td>Repair Category</td><td>MTTR</td><td>Probability</td></tr>
<tr><td>Trips</td><td>8 hours</td><td>63%</td></tr>
<tr><td>Minor Repair</td><td>1-2 days</td><td>18%</td></tr>
<tr><td>Minor Repair - Spare Not Available</td><td>1 week</td><td>18%</td></tr>
<tr><td>Major Repair</td><td>12-18 months</td><td>1%</td></tr>
<tr><td rowspan="5">Ventilation Process/Safety System</td><td>Repair Category</td><td>MTTR</td><td>Probability</td></tr>
<tr><td>Trips</td><td>8 hours</td><td>63%</td></tr>
<tr><td>Minor Repair</td><td>1-2 days</td><td>18%</td></tr>
<tr><td>Minor Repair - Spare Not Available</td><td>1 week</td><td>18%</td></tr>
<tr><td>Major Repair</td><td>12-18 months</td><td>1%</td></tr>
<tr><td rowspan="5">VSD Other Temperature</td><td>Repair Category</td><td>MTTR</td><td>Probability</td></tr>
<tr><td>Trips</td><td>2 hours</td><td>63%</td></tr>
<tr><td>Minor Repair</td><td>2 days</td><td>18%</td></tr>
<tr><td>Minor Repair - Spare Not Available</td><td>1 week</td><td>18%</td></tr>
<tr><td>Major Repair</td><td>6 months</td><td>1%</td></tr>
</table>

SGT400 Compressor Units

Sub-Unit	Running Trips	**Running trips** (Unknowns distributed)	MTTF (hours)
SGT400 (2016-2020)			
Miscellaneous	36	39	436
Lubrication	15	16	1047
Gas Generator	12	13	1309
Safety/Protection/ESD	6	7	2618
Fuel	5	5	3141
Power Turbine	2	2	7853
Compressor	2	2	7853
Control System	1	1	15707
Exhaust	0	0	1000000
Seal & Bearing	0	0	1000000
Anti-Surge	0	0	1000000
Unknown	7		2443
Total	**86**	**86**	**199**

Appendix 1 - 9: SGT400 running trips by sub-unit



Appendix A - 10: SGT400 running trips by sub-unit

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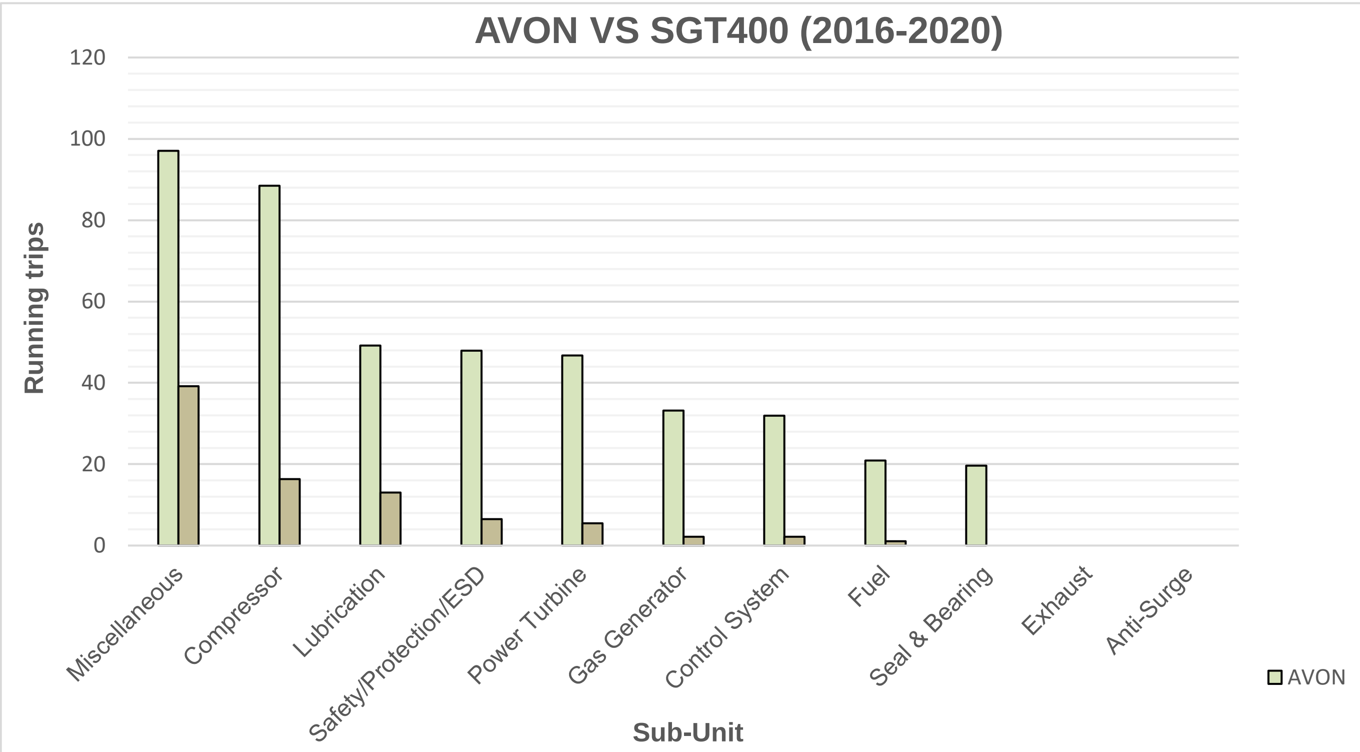
Appendix 1 - 11: SGT400 running trips by failure mode

Failure Mode	Sub-Unit	No. of Running Trips	Distributed Running Trips	MTTF (hours)
	Unknown	7	-	-
Control System	Control System	1	1.1	17099
Process Condition Other Station Failures	Miscellaneous	19	20.7	900
Lube Oil System	Lubrication	9	9.8	1900
Fuel System Control System	Fuel	1	1.1	17099
Process/Safety System	Safety/Protection/ESD	3	3.3	5700
Gas Generator Other Temperature	Gas Generator	10	10.9	1710
Power Failure Other Station Failures	Miscellaneous	2	2.2	8549
Other Station Failures	Miscellaneous	7	7.6	2443
Vibration	Miscellaneous	1	1.1	17099
Gas Compressor Vibration	Compressor	2	2.2	8549
Gas Generator Vibration	Gas Generator	2	2.2	8549
Oil System	Lubrication	1	1.1	17099
Hydraulic Oil System	Lubrication	5	5.4	3420
ESD Process/Safety System	Safety/Protection/ESD	3	3.3	5700
Other Temperature	Miscellaneous	7	7.6	2443
Fuel System Turbine Control System	Fuel	4	4.4	4275
PLC Turbine Control System	Power Turbine	2	2.2	8549



Appendix A - 12: Bar chart of sub-unit running trips for Avon vs SGT400 units (2016-2020)

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Appendix 1 - 13: SGT400 repair categories & associated MTTR

System	Repair Category	MTTR	Probability (%)
Control System	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
ESD Process/Safety System	Trips	8 hours	63%
	Minor Repair	16	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
Fuel System Control System	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
Fuel System Turbine Control System	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	6-12 months	1%
Gas Compressor Vibration	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1-2 days	18%
	Major Repair	6 months	1%
Gas Generator Other Temperature	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
Gas Generator Vibration	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	1 week	1%
Hydraulic Oil System	Trips	4 hours	63%
	Minor Repair	8 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
Lube Oil System	Trips	4 hours	63%
	Minor Repair	8 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
Oil System	Trips	4 hours	63%
	Minor Repair	8 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%

[redacted]

	Repair Category	MTTR	Probability (%)
Other Station Failures	Trips	1 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 months	1%
	Repair Category	**MTTR**	**Probability (%)**
Other Temperature	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
	Repair Category	**MTTR**	**Probability (%)**
PLC Turbine Control System	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	6-12 months	1%
	Repair Category	**MTTR**	**Probability (%)**
Power Failure Other Station Failures	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	4 hours	18%
	Major Repair	4 hours	1%
	Repair Category	**MTTR**	**Probability (%)**
Process Condition Other Station Failures	Trips	1 hours	63%
	Minor Repair	8 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	2 weeks	1%
	Repair Category	**MTTR**	**Probability (%)**
Process/Safety System	Trips	8 hours	63%
	Minor Repair	1-2 days	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	12-18 months	1%
	Repair Category	**MTTR**	**Probability (%)**
Vibration	Trips	2 hours	63%
	Minor Repair	4 hours	18%
	Minor Repair - Spare Not Available	1 week	18%
	Major Repair	1 week	1%

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