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REQUIREMENT SPECIFICATION FOR STATION BLACKOUT GAS TURBINE GENERATOR IN A NUCLEAR POWER PLANT

Master of Science Thesis

Examiner: Professor Risto Raiko
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ABSTRACT

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The ultimate purpose of nuclear power plant safety systems is to prevent damage to the reactor and the possible release of radioactive materials into the surroundings following an internal or external event that interrupts normal power plant operation. Different design principles have been developed and they are incorporated to the safety design to ensure the safety functions are performed even if some components or whole systems fail to function as intended.

Many nuclear power plant safety systems rely on electrical power to operate. Following a loss of off-site power accident, the power plant electrical systems are supplied by the emergency power sources. Station blackout generators constitute an alternative source for AC power designed for situations where all the main emergency diesel generators a fail to function in accident conditions. To introduce diversity into the emergency power sources, gas turbine generator units are proposed to be used instead of diesel generators as station blackout power sources.

Current nuclear regulations regarding the emergency power generating facilities in a nuclear power plants only consider diesel engines for the application. The motivation for this research is the absence of a national or a global standard for the design and acceptance testing of gas turbines in this application. In this thesis the main goal is to determine the requirements for a station blackout gas turbine generator so that it fulfils its role in the overall nuclear power plant safety system design.

The requirement specifications composed as part of this thesis covers the requirements for design, operation, maintenance, qualification and testing of the station blackout emergency power facility including the facility layout, gas turbine engine, generator, instrumentation and control systems and auxiliary support systems such as fuel and lubrication systems. The decisions behind the technical or quality requirements will be explained and discussed to justify the chosen requirements.

TIIVISTELMÄ

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Ydinvoimalaitosten turvallisuusjärjestelmien perimmäinen tarkoitus on estää reaktorin vaurioituminen ja siitä seuraava radioaktiivisten ainesten vapautuminen ympäristöön jonkin normaalista käyttötilanteesta poikkeavan ulkoisen tai sisäisen tapahtuman johdosta. Ydinturvallisuuden varmistamiseksi on kehitetty erilaisia suunnitteluperiaatteita, joilla varmistetaan turvallisuustoiminnon toteutuminen, vaikka jotkin turvallisuusjärjestelmät tai -komponentit olisivat epäkunnossa.

Monet ydinvoimalaitoksen turvallisuusjärjestelmistä tarvitsevat sähkötehoa toimiakseen. Tilanteessa, jossa sähkönsyöttö ulkoisesta sähköverkosta menetetään, voimalaitoksen sähköjärjestelmiin syötetään sähkötehoa varavoimalähteistä. Station Blackout-generaattorit muodostavat vaihtoehtoiset vaihtovirtalähteet, jotka ovat suunniteltu sellaisia onnettomuustilanteita varten, joissa ulkoisen verkon menetyksen lisäksi ensisijaiset varavoimadieselgeneraattorit eivät toimi. Varavoimalähteiden diversiteetin eli erilaisuuden lisäämiseksi kaasuturbiinigeneraattoreita ehdotetaan käytettäväksi päädieseleiden lisäksi Station Blackout -generaattoreina.

Kaikki nykyiset ydinvoimalaitoksen suunnittelua ja käyttöä säännöstelevät ohjeistot eli YVL-ohjeet käsittelevät ainoastaan dieselmoottoreita varavoimakoneina. Tämän tutkimuksen lähtökohtana ja motiivina on kansallisen tai kansainvälisen kaasuturbiinin suunnittelu- ja hyväksytysstandardin puute tässä käyttötarkoituksessa. Tämän tutkimuksen päätavoite on kehittää työkalut vaatimusmäärittelyyn, jonka perusteella suunniteltu kaasuturbiini voitaisiin hyväksyä ydinturvallisuusluokitelluksi laitteeksi.

Tämän tutkimuksen ohessa kehitetty vaatimusmäärittely kattaa Station Blackout-kaasuturbiinin suunnittelun, käytön, huoltamisen, hyväksyttämisen ja testauksen sisältäen varavoimalaitoksen layoutin, kaasuturbiinin, generaattorin, säätöjärjestelmät, ja apujärjestelmät kuten polttoaine- ja voitelujärjestelmät. Päätökset teknisten vaatimusten ja laatuvaatimusten taustalla pyritään esittämään ja perustelemaan valittujen vaatimusten pätevyys.

PREFACE

This thesis study was carried out as part of the licensing feasibility studies of the Olkiluoto 4 nuclear unit procurement project by Teollisuuden Voima Oyj (TVO) in Olkiluoto, Eurajoki.

I would like to express my gratitude towards the staff of the OL4 Project for providing me an interesting research subject and a great working environment and also for introducing me to the specialities of the nuclear industry. Special thanks belong to my supervisor Dr. Mikko Lemmetty for his valuable guidance and insight throughout this thesis writing process.

I would also like to thank my fellow students for the enjoyable student years, and my family and friends for supporting me and making it possible for me to come this far.

Eurajoki, December 15th 2012

Joonas Hölttä

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

A	amplitude	[m]
c_p	specific heat capacity at constant pressure	[J/kg·K]
c_v	specific heat capacity at constant volume	[J/kg·K]
E_{ad}	adiabatic energy	[J]
g_c	standard gravity	[m/s^2]
h	enthalpy (specific)	[J/kg]
$\dot{m}$	mass flow	[kg/s]
n	rotational speed	[rpm]
P	power; probability	[W];[-]
p	pressure	[Pa]
Q	heat energy	[J]
q_f	fuel lower heat value	[J/kg]
s	entropy (specific)	[J/kg·K]
T	temperature	[K]
U	internal energy	[J]
u	blade velocity	[m/s]
v_θ	tangential velocity	[m/s]
W	work	[J]
w	relative velocity	[m/s]
x	displacement	[m]
$\dot{x}$	velocity	[m/s]
$\ddot{x}$	acceleration	[m/s^2]
γ	specific heat ratio; isentropic constant	[-]
δ	infinitesimal change	[-]
Δ	differential between states	[-]
η	thermal efficiency	[-]
η_c	compressor isentropic efficiency	[-]
η_t	turbine isentropic efficiency	[-]
ω	vibration frequency	[1/s]
π	pressure ratio	[-]

Abbreviations

AC	Alternating Current
AAC	Alternative AC source
ASME	American Society of Mechanical Engineers
BWR	Boiling Water Reactor
CDF	Core Damage Frequency

CS-E	Certification Specifications - Engines
DBC	Design Basis Condition
DC	Direct Current
DEC	Design Extension Condition
ECR	Emergency Control Room
EDG	Emergency Diesel Generator
EPR	Evolutionary Pressurized Reactor
EUR	European Utility Requirements
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
I&C	Instrumentation & Control
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission
INES	International Nuclear Event Scale
ISO	International Organization for Standardization
KTA	Kerntechnische Ausschuss
LCR	Local Control Room
LOOP	Loss of Off-site Power
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
MCR	Main Control Room
NRC	Nuclear Regulatory Commission
OL1-4	Olkiluoto Nuclear Units (1-4)
PRA/PSA	Probabilistic Risk/Safety Assessment
PWR	Pressurized Water Reactor
SA	Severe Accident
SAHARA	Safety As High As Reasonably Achievable
SBO	Station Blackout
STUK	Säteilyturvakeskus
TIT	Turbine Inlet
TVO	Teollisuuden Voima Oyj
UPS	Uninterruptible Power Supply

1. INTRODUCTION

Modern safety design of nuclear power plants is the result of lessons learnt from over five decades of operating experiences and the unfortunate severe accidents of Three Mile Island in 1979, Chernobyl in 1986 and Fukushima in 2011. Nuclear authorities regulating the nuclear operators update their regulations and guidelines frequently to cover all conceivable events endangering safety of nuclear power plants. Principles and tools such as Redundancy, Diversity, Separation, Defense-in-Depth, SAHARA and PRA are examples of common methods developed and used for improving the safety systems design. The goal is to reduce the core damage frequency (CDF), an industry standard quantitative measure used by regulators, operators and designers for the safety of a nuclear power unit.

Many safety features of nuclear power plants require alternating current electric power to operate. The preferred AC power supply for safety device is the external power grid, such as the 400 kV national transmission grid in Finland or the auxiliary backup 110 kV power grid, that are connected to the plant electrical systems. Connection to the outside power grid may be lost in several kinds of external or internal events such as earthquakes, severe storms or fires inside the power plant. To handle the loss of off-site power event, nuclear power plant units are equipped with emergency power generators, capable of supplying power to the necessary safety systems for keeping the nuclear reactor in safe conditions.

In the Fukushima accident in March 2011 the nuclear power plant site lost connection to the outside power grid and multiple nuclear units lost all main emergency diesels through a common cause event, an earthquake followed by tsunami. This resulted in a condition called station blackout (SBO), which could not be recovered from in time, and several units' reactor cores were damaged, and due to hydrogen explosions, radioactive materials were released to the surroundings. Newer nuclear power plant designs include alternative AC emergency power sources called station blackout generators, which supply power to critical safety systems in accident conditions. These emergency power units present a new layer of defense in the defense-in-depth concept against the station blackout event as they are designed to work independently of the main emergency units.

The use of gas turbine generators as station blackout power sources instead of the commonly used diesel generators is proposed by nuclear unit suppliers to bring diversity to the safety design of their nuclear units. This thesis research focuses on specifying the requirements and developing qualification tests for a gas turbine generator unit, so that it can function as a part of the nuclear power plant safety system and qualify as a Safety Classified equipment as specified in the Finnish nuclear regulations. To achieve sufficient reliability, testing procedures of gas turbine engines derived from aircraft propulsion application are studied and used to develop a qualification type test for the station blackout gas turbine.

Chapter 2 introduces the specific goals that are set for the research and what methods are used to approach them. The current standards that are used for qualifying emergency power sources and how their requirements are applied in this thesis are also introduced in this chapter.

The background of nuclear safety design and the contemporary safety concepts that are used while designing new power plants are discussed in chapter 3. The chapter also introduces the nuclear authorities that are the active bodies that have been given the authority by governments to supervise and license the commercial use of nuclear energy. The nuclear authority develops regulations that must be followed in the design process and operation of a nuclear power plant and also reviews if the safety design choices are acceptable.

The basics of gas turbine design is presented in chapter 4 beginning from the thermodynamic background and proceeding into the component-specific choices that are available to achieve the desired qualities in the engine. Focal point of this part of the research is to determine where decisions can be made to improve the operating reliability of the engine and reduce the probability of failures. The long service life time of the engine is also of great importance in the application so basic theory for analyzing the vibration characteristics of a gas turbine is also presented.

In chapter 5 the different systems of the emergency power unit (AAC unit) are considered and the justifications for the specified requirements are presented. The bases of the choices are explained, mainly through the nuclear regulations and legislation in Finland and the internationally accepted standards that are used by the nuclear industry. Gas turbine qualification testing is a major part of the process in achieving safety classification for the gas turbine engine type and the basic scope of the type test is also presented. Requirements for the control systems of the gas turbine and the whole emergency unit are also considered as well as the operational and maintenance requirements that need to be set for the AAC facility.

2. RESEARCH SCOPE

2.1. Research Objective and Methods

The objective of this thesis research is to establish requirements for a gas turbine engine to function as a nuclear power plant emergency power supply. The requirement specifications are developed as part of the licensing feasibility studies (LFS) of the nuclear unit designs in the Olkiluoto 4 project. The application of gas turbines for emergency power source operation is a relatively new in the nuclear industry, where diesel generators have been the standard choice for decades. The main driving design criteria in the requirement specification are high reliability and availability of the facility and ease of maintenance so the desired life-time of the unit can be achieved.

This thesis research involves examining different standards, which are the bases of nuclear power plant design and qualification process of the nuclear safety equipment. The relevant standards and regulations for the safety system studied in this thesis consist of various fields such as control systems, quality management of the engine and component production, measurement device and methods, safety design principles and certification testing protocols. Finding the right combination of requirements from the standards and nuclear regulations is a vital part of the process of specifying justified requirements. The goal is to develop such requirements that they are unambiguous, so there remains no room for misinterpretation, but at the same time the actual design choices are left for designer.

A common requirement for any safety system for nuclear power plants is that the system and all devices related to its safety function have shown high reliability when used in similar conditions elsewhere in nuclear power plants. In rare cases operating experience gathered in other industrial applications are used if better experience is not available and the industrial experience is deemed sufficiently reliable. A great challenge in specifying the requirements for a gas turbine generator as an emergency power source for a nuclear power plant is the lack of a globally accepted standard for the design of gas turbines used in this application. The only type test for gas turbine qualification for emergency power supply in a nuclear power plant has been performed by Mitsubishi Heavy Industries in 2010 to be accepted in their US-APWR plant design. (Mitsubishi Heavy Industries 2010)

The introduction of a gas turbine engine to a relatively new application requires combining current knowledge on gas turbines with some new improvements. The basic thermodynamics handbooks provide useful tools for evaluating the performance limitations of gas turbines and gas turbine engineering handbooks are used to evaluate different component choices available in modern gas turbines. Especially important for meeting the safety requirements as a part of the nuclear unit safety analysis is the reliability, availability and service life of the gas turbine, so the research on improving these characteristics in a gas turbine are studied. For example articles and studies concerning vibration analyzes on rotating machinery and development of new materials are useful in this research because the latest knowledge on these subjects provides the limits that are achievable in contemporary gas turbine designs.

2.2. Nuclear Regulations and Standards

The requirements for the design and operation of nuclear power plants are included in multiple levels of rules. The basic hierarchy for applying the different requirements to design process is presented in *Figure 2.1*.

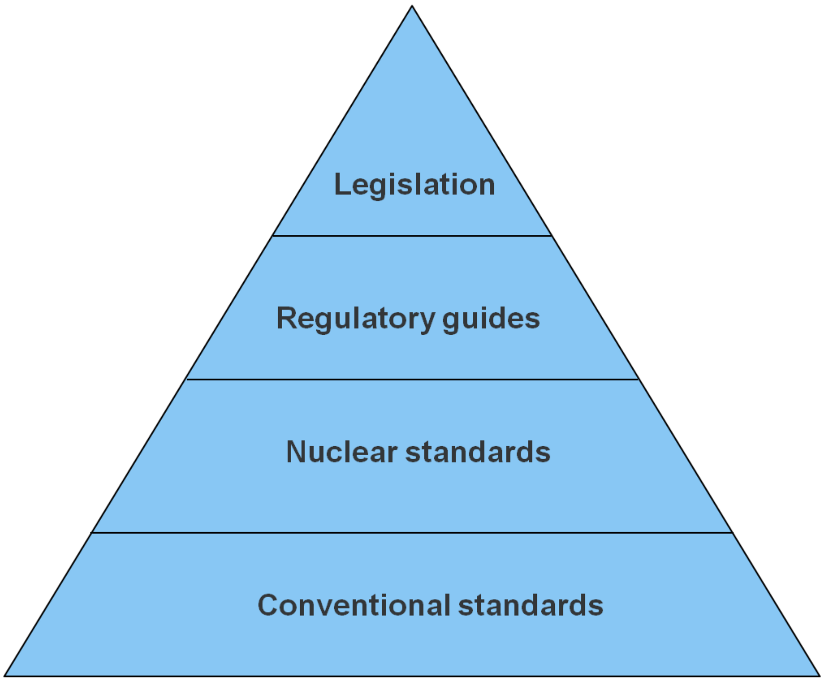

Figure 2.1: *Hierarchy of rules to be applied in nuclear safety design*

On the highest level on the hierarchy are the laws and governmental decrees, which define the general principles that need to be followed in the design and operation of a nuclear power plant. On the next level are the regulatory guides that give more detailed technical requirements for systems and components but generally do not specify how they must be achieved. Nuclear standards are the generally accepted design standards for components and systems that are critical for nuclear safety. On the lowest level are the conventional standards that are generally approved by other industry and they can be used for non-safety systems and components.

To meet the quality and reliability requirements of the nuclear regulations, the design of all components and systems in the nuclear power plants must follow strict guidelines presented in their respective standards. Following the standards ensures that different equipment and systems can be compared with each other and trusted to perform their intended function and qualified as Safety Classified systems and equipment.

YVL guides are the regulatory guides that regulate the design and operation of Finnish nuclear power plants. Currently the YVL guides are under a revision process to renew and update the guidelines to better incorporate the current knowledge of nuclear safety. The current YVL 5.1 guide that regulates the emergency power generating facilities refer to the German nuclear Standard KTA 3702:2000 "*Emergency Power Generating Facilities with Diesel-Generator Units in Nuclear Power Plants*" for technical requirements of Diesel engines and emergency power facilities. A lot of the qualities of an emergency power unit are independent of the actual engine that produces the driving force for the generator, so the KTA 3702:2000 standard forms a solid base for specifying requirements for the station blackout facility. Due to the extensive use of this standard, it will be referred to only as KTA 3702 later in this thesis.

The European Aviation Safety Agency (EASA) has given the requirements for engines used in commercial airplanes in the standard called "*Certification Specifications for Engines*" (EASA 2010), which will be abbreviated and referred as CS-E in this thesis. The qualification test programs presented in the standard for airplane gas turbine engines are rigorous and high reliability is required for the critical engine parts to ensure safe flight. The aircraft engines are also required to function in very wide operating ranges and harsh ambient conditions, which is also desirable for the emergency power source application. For this reason the CS-E standard is a good source for information about the testing of gas turbine engines' reliability, which can also be partly adopted for the testing programs for gas turbines meant for land-based power generation. Industrial gas turbine performance testing is standardized by American Society of Mechanical Engineers in ASME PTC 22 "*Performance Test Code on Gas Turbines*" (2005) and by International Organization of Standardization in ISO 2314 "*Gas Turbines - Acceptance Test*" (2009). These conventional standards are used as reference in addition to the KTA 3702 standard to develop performance testing guideline for the nuclear power plant station blackout gas turbine.

Other relevant standards that will be studied for the requirement specification include for example: electrical standards for the generator and other electrical components, mechanical standards for gas turbine performance calculations, measurement standards for vibrations and quality assurance programs for component manufacturing.

In addition to the regulations and standards, some general requirements for the AAC facility and auxiliary systems were adopted from European Utility Requirements (EUR), which is a program of major European electricity generation companies that strive to harmonize their requirements for the design bases of Light Water Reactors (LWR) to be built in Europe.

3. SAFETY OF NUCLEAR POWER PLANTS

3.1. Nuclear Safety Authorities

The peaceful use of nuclear energy is governed by organizations that have been given the authority to regulate the nuclear operators by their governments. The organizations responsible for nuclear safety have multiple missions such as maintaining nuclear safety regulations and legislations, developing standards and granting licenses for commercial companies for electrical power generation.

The national and global nuclear safety authorities work with each other and together with the nuclear industry to make sure all regulations are kept up to date and followed by the nuclear operators in order to produce safe nuclear energy. (IAEA 1956)

3.1.1. International Atomic Energy Agency

The leading global nuclear safety authority is the International Atomic Energy Agency (IAEA), which was founded in 1957 within United Nations. The IAEA works with its member states to promote peaceful use of nuclear energy. According to IAEA's Statute (IAEA 1956), its functions are: supporting the research on radiation effects and behavior of radionuclides in the environment, promoting information exchange through scientific publications and meetings, establishing standards, regulations and guides dealing with nuclear fuel cycle and radioactive waste management, helping member states develop infrastructure for nuclear safety and providing advice for them, promoting binding international conventions on nuclear safety. One notable example of IAEA's functions is to make sure all fissile material is accounted for and remains in authorized hands for power generating purposes only (IAEA 2005). One of the methods used by the IAEA is to monitor all nuclear reactors under their authority to make sure that nuclear fuel is not removed from the reactors without proper authorization and documentation.

IAEA has also developed a classification system (IAEA 1989) for nuclear events called INES (The International Nuclear and Radiological Event Scale) that is based on the severity and consequences of the event. The scale was first introduced in 1989 and its purpose is to communicate the technical aspects of the events to the public and make different kinds of accident events comparable. The INES scale consists of event classes from 1 to 7, where the classes 1 to 3 are defined as incidents and 4 to 7 as accidents. The evaluation is based on the severity and consequences of the event. The two accidents in history that have been given the highest rating of 7 on the INES scale are the Chernobyl accident in 1986 and Fukushima Daiichi accident in 2011 which both involved severe reactor core damage that lead to large uncontrolled release of radioactive materials to the environment.

The highest incidents on the INES scale in Finnish nuclear power plants have been rated INES 2, only two of them after the scale was introduced, the other five cases have been rated afterwards. The two cases were the following events: in 1991 Olkiluoto 2 unit lost connection to outside grid due to a fire, in 1993 Loviisa 2 unit had a feedwater pipe break in the secondary circuit due to erosion/corrosion. The safety systems worked as intended in both situations, so these cases remained as operating incidents instead of escalating to accidents. (Isolankila *et al.* 2004)

3.1.2. Finnish Nuclear Authority

The national nuclear regulatory body in Finland is the Finnish Radiation and Nuclear Safety Authority STUK, which is an abbreviation of the Finnish name Säteilyturvakeskus. STUK is under the administration of the Ministry of Social Affairs and Health and regulates the use of nuclear energy in Finland according to the Finnish Radiation Act (L 592/1991) and Government Decree on the Safety of Nuclear Power Plants (VNA 733/2008).

STUK develops regulations for nuclear operators in Finland called the YVL guides. These guides provide requirements, technical as well as organizational, that the nuclear operator must comply with to maintain their operator license. The regulations are updated when knowledge is gained from events and operating experiences from around the world and if new improvements in nuclear safety designs are deemed necessary for new power plants. STUK works together with the nuclear operators in Finland and performs inspections on the operating plants and nuclear power plant construction sites to ensure that the regulations are being followed accordingly. The YVL guides are currently under a revision process as this thesis is written and some information is used from the draft versions that might be revised later.

A major area of responsibility of STUK is also to handle the licensing process of new nuclear reactors in Finland. All design documents, certificates and quality control material related to the safety of the new power plant goes through an accepting process in STUK and possible issues with the design must be addressed by the supplier of the plant. The design and manufacturing, as well as installation and commissioning at the final plant site, of all systems and components relevant for the safety of the plant is subjected for review by STUK.

3.2. Modern Safety Design

Safety design of nuclear power plants is based on the legislation, regulations and guidelines provided for the nuclear industry by the nuclear authorities. The greatest nuclear accidents of the Three Mile Island reactor meltdown in 1979, the Chernobyl reactor core explosion and resulting fire of the graphite moderator in 1986 and the Fukushima loss-of-off-site power following an earthquake and a tsunami in 2011 and their accident analyzes (Corey 1979, IAEA 1992, TEPCO 2012) have taught important lessons regarding the safety design and safe operation of a nuclear power plant. These lessons are now incorporated in regulations in hopes that similar accidents could be avoided in the future. A few of the most common principles required by the laws and regulations for the design of nuclear safety are: defense-in-depth, successive physical containment barriers, separation, diversity and redundancy (Isolankila *et al.* 2004). A short description of these important principles is provided in this chapter to support the discussion of the role of the gas turbine in the safety functions later in the thesis.

The concept of defense-in-depth is used to design safety systems so that the nuclear unit can handle different operating conditions from the normal operation and design basis conditions to the severe accidents. The safety systems constitute 5 subsequent levels of defense that should prevent any operating condition from escalating further into accidents. First level consists of systems for normal operation, the second level holds the systems for the design basis conditions, the third level systems are for accidents, the fourth level consist of severe accident handling systems and finally on the fifth level is the preventive measures for exposure of the public to radioactive release. The systems in the subsequent layers should be independent such that failures in different levels of safety systems should not produce failures in other levels. (IAEA 1996, Isolankila *et al.* 2004)

The redundancy principle means that there are multiple independent components or whole safety subsystems performing the same function. Redundant components or systems can individually perform their intended function and are designed to be both physically and functionally separate from each other according to the separation principle. The goal of this separation is to increase the overall safety of the plant by making the systems more immune to common-cause failures such as fires or electrical faults that would incapacitate all of the safety systems and prevent their function which could potentially cause a severe nuclear accident. As required by the VNA 773/2008, the most important electrical and automation safety plants comply with the so called *N+2 criterion*, which can be achieved with 4 redundant safety subsystems, with 2 of them capable of driving the plant into safe state while 1 system is under maintenance and 1 system fails. On the other hand the N+2 criterion means that one faulty signal will not cause unnecessary initiation of safety function.

Another important safety concept used in the safety systems design is the diversity principle. Diversity between systems means that there are different mechanisms for performing similar safety functions. The strength of this concept is that a single event is unlikely to cause failure of the diverse systems because of the differences in their nature. This ensures that the desired safety function is performed by either one of the diverse systems. A case example of applying diversity principle in a Boiling Water Reactor (BWR) nuclear power plant is having both electrical emergency feed-water pumps and steam-turbine pumps which use the steam generated by the reactor in emergency operation. Having these diversely functioning pumps ensures that the coolant flow through the reactor core and the removal of residual heat from the nuclear fuel is maintained even if electrical power is lost from the power plant safety systems. Similarly, the choice of a gas turbine generator instead of the normal diesel generator combination can be seen as an improvement to the diversity of the emergency electrical systems as the engines have many diverse functions. (Isolankila *et al.* 2004)

3.2.1. Probabilistic Risk Assessment

Probabilistic Risk/Safety Assessment (PRA/PSA) is an engineering safety analysis tool for evaluating complex systems such as airliners, space shuttles or most importantly, nuclear power plant safety. The total risk for an event is evaluated by statistical methods the magnitude of its consequences stated numerically by some important quantitative measure, and the frequency of occurrence for the risk. The quantifying measure could for example be number of lives lost or total radioactive material released to the surroundings. The total risk of an event is the expected loss calculated by multiplying the quantified consequence with the probability of the event. (Isolankila *et al.* 2004)

Probabilistic Risk Assessment was first introduced to the nuclear industry by the U.S. Nuclear Regulatory Commission (NRC) in 1975, and significantly expanded the research on the subject after the Three Mile Island incident in 1979. This lead to the publication of NRC Fault Tree Handbook (NRC 1981) and the PRA soon became mandatory for operators under the NRC regulatory authority. The PRA combines Fault Tree and Event Tree Analyses (FTA/ETA), where an initiating event is assumed and its consequences in a system is systematically analyzed. Performing the Fault Tree Analysis has a standardized procedure in IEC 61025:2006. The initiating event can for example be a failure of a single component in the process followed by failures on the system level.

The possibility of failures propagating further in the fault tree can be reduced by implementing multiple parallel components to individual steps as shown in *Figure 3.1*,

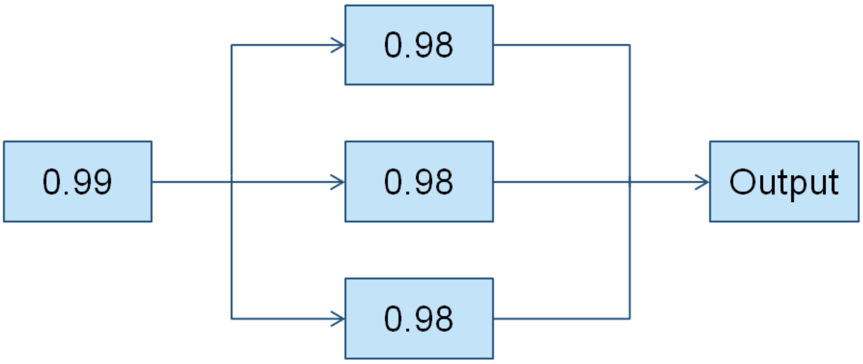

Figure 3.1: *Reliability of a system with redundant components*

where the numbers inside the blocks indicate the probability that the individual system performs its function. The total output probability P of this system can be calculated from

$$P = 0.99 - (1 - 0.98)^3 \qquad \text{(Eq. 3.1)}$$

which gives a probability of 0.989992. This shows the redundancy principle in effect in a simplified example. The PRA calculations used in nuclear power plants form much more complex systems and event chains that are analyzed but the output is also a probabilistic value.

Failure Mode and Effect Analysis (FMEA) is an important tool in quality engineering and the method is also standardized by International Electrotechnical Commission (IEC 60812:2006). FMEA is used for determining what kind of failures can occur in an individual component or part of a system and what the consequences of the failures are. The FMEA provides input data for the reliability calculations for determining the probability of the risk.

The most critical views of the PRA method claim that it is incapable of predicting human errors and that it is poor for representing complex systems such as a nuclear power plant safety system, or a space shuttle where all the failure modes are not known, as studied by Marais *et al.* (2004). Ramana (2011) claims that in the Fukushima accident the PRA did not fully cover the possibility of a tsunami-earthquake combination that could cause a common failure of the emergency power supplies and that many faults in analyzes were ignored or faults recognized were not taken care of (TEPCO 2012). These accidents caused by common-cause failures are so-called beyond design basis accidents that have not been accounted for in some PRA analyzes.

Despite its criticism, the PRA is the main tool used for analyzing and evaluating nuclear power plant safety in the design process and during operation of the unit. The nuclear unit suppliers, operators and regulators all use the PRA for evaluating the complex safety system of a nuclear power plant. The process of developing a PRA for a nuclear unit includes many choices whether to include some risks in the analysis or not, and as such the resulting core damage frequencies (CDF) for different nuclear power plant types cannot be compared with one another Some PRA analyzes for example do not include initiating events during refueling outages and instead only cover the events during power generating operation. This choice immediately changes the output of the PRA drastically as many initiating events are ignored and left out of the risk calculation. (Isolankila *et al.* 2004)

Modern power plants can for example have design limit values for cumulative frequencies of less than 10^{-5} / year for reactor core damage and less than $5 \cdot 10^{-7}$ / year for release exceeding 100 TBq of cesium-137 after a severe accident according to YVL B.1 draft 2 (2012). These frequencies show that the events are highly unlikely in the scope of the 60 year operating life-time of a nuclear power plant.

3.2.2. Operating Condition Classification

During power generating operation of a nuclear power plant, deviations from normal plant operating conditions are bound to be encountered. A deviation in the process values or failures in the safety equipment or an external event can cause abnormal plant conditions so that safety actions from either the control system or manual operation from the power plant operators is required.

Different operating conditions are divided into subgroups called design categories according to their occurrence frequencies and the severity of their consequences. Table 3-1 shows the different design categories as they are presented in draft 2 of YVL B.1 guide. The frequencies in the Table 3-1 are stated as probability *P* of occurrence during a year of operation.

Table 3-1: *Definitions of operating conditions (YVL B.1 draft 2)*

Defense-in-depth level	Plant condition category	Frequency	Design category	Upper limits of radiological consequences
Level 1	Normal operation		**DBC 1**	0,1 mSv / year
Level 2	Anticipated event	10^{-2} / year < P	**DBC 2**	0,1 mSv/ year
Level 3a	Accident initiated by single event - Class 1 - Class 2	 10^{-3} /y < P < 10^{-2} / y P < 10^{-3} /y	 **DBC 3** **DBC 4**	 1 mSv / event 5 mSv / event
Level 3b	Type A: anticipated event or Class 1 accident with common cause failure of a safety system Type B: multiple failure event Type C: rare event	10^{-7} / y < P < 10^{-4} / y	**DEC**	20 mSv / event
Level 4	Severe Accident	P < 10^{-5} / year	**SA**	Cs-137 release < 100 TBq

3.2.3. Postulated Accidents

Postulated accidents are used as bases of the design of safety systems of a nuclear unit using deterministic approach to analyze how an accident sequence propagates and what is required to stop it. The commonly analyzed postulated accidents presented here are the Loss of Coolant Accidents (LOCA) and the Loss of Off-site Power (LOOP). Normally the safety systems of the nuclear unit are able to handle these accident events and they remain in the DBC 2-4 categories. A common cause failure (CCF) of the main emergency diesel generators or their related safety systems, possibly coinciding with a DBC 2 or DBC 3 condition, is classified as DEC or SA.

The Large Break Loss of Coolant Accident (LBLOCA) condition is normally used in the western Light Water Reactors (LWR) for the design basis of emergency cooling systems of the reactor. The LBLOCA conditions varies somewhat between Boiling Water Reactors (BWR) and Pressurized Water Reactors (PWR): in BWR it results from a complete cut-off of a main steam pipeline, where in PWR the worst condition is caused by a pipe break in the cool side of the primary circuit. In the LBLOCA condition the reactor coolant needs to be quickly added to the reactor and circulated continuously to prevent fuel rods from becoming exposed and resulting in damage to the nuclear fuel. The LBLOCA causes the pressure of the reactor to drop rapidly in BWRs so that pumping coolant back into the reactor is easier than in the PWR where a large amount of coolant is evaporated quickly and the pressure remains high in comparison. This makes LBLOCA a slightly worse condition for the PWRs as the coolant needs to be pumped against a lot greater pressure, and so separate high pressure emergency coolant tanks are needed initially. (Eurasto *et al.* 2004, Pöllänen *et al.* 2004)

Another type of postulated accident that has potential to cause a Severe Accident is the loss of electrical power from the safety systems. If the reactor coolant is not continuously circulated in the reactor, the residual heat generation of the nuclear fuel decay begins to increase the pressure in the primary circuit and the coolant is blown away to maintain the pressure level. In this condition, the coolant is lost a lot slower than in LBLOCA, but the electric power needs to be restored to the unit or the eventually this condition leads to fuel damage and a Severe Accident. The time required for the restoration of AC power depends on the reactor type: for example the VVER type reactors in Loviisa require AC power after 4 hours. (Pöllänen *et al.* 2004)

3.2.4. Safety Classification of Equipment and Systems

Safety systems, structures and equipment in nuclear power plants are designated into groups based on the consequences of their failure to accomplish their tasks. The following definitions of Safety Classes are presented in the YVL B.2 draft 4 "Safety classification of systems, structures and components in nuclear facilities":

(317) Safety Class 1 shall include nuclear fuel as well as structures and components whose rupture could result in an accident compromising reactor integrity and requiring immediate actuation of safety functions. Safety Class 1 specifically includes the reactor pressure vessel and those components of the primary circuit whose rupture results in a primary circuit leak that cannot be compensated for by systems pertaining to normal plant operation.

(314) Systems shall be assigned to Safety Class 2 if they are designed to provide protection against postulated accidents by bringing the facility to a controlled state and by maintaining this state for as long as the prerequisites for a transfer to a safe state can be ensured.

(315) Safety Class 3 shall include systems that

1. *mitigate the consequences of operational disturbances, unless they are assigned to a higher safety class for some other reason*
2. *accomplish the diversity principle and are designed to ensure bringing of the facility into a controlled state in case the systems primarily taking care of the corresponding safety function fail*
3. *are designed to bring the facility into a safe state over a long period of time*
4. *are designed for the reactor main control functions (control of power, pressure, or make-up water supply) and which, in case of failure, initiate Safety Class 2 safety functions*
5. *relate to fuel handling and may, in case of their failure, cause fuel damage*
6. *are stationary and contribute to the monitoring of radiation level in the nuclear power plant's rooms, radioactivity monitoring of plant processes or the activity concentration of releases*
7. *are designed to cool spent fuel*
8. *are designed for severe accident management*
9. *prevent the spreading of radioactive substances in spaces that are outside the containment*
10. *are essential for the maintenance of control room habitability.*

Safety Class 1 equipment handle the normal operation conditions (DBC 1) as presented in Table 3-1, Safety Class 2 equipment perform safety functions required in Design Basis Conditions 2 to 4 and Safety Class 3 equipment are designed to function in DEC and SA conditions. Class EYT equipment are those that are defined non-safety, meaning that their failure has no nuclear safety consequences.

Considering the qualification of a system or component as a Safety Classified, the YVL B.2 draft 4 states the following:

(307) The quality requirements for systems, structures and components as well as the requirements for quality assurance shall be so defined that the requirement level is higher in a higher safety class. The requirements shall focus on matters affecting the reliability of safety functions: verification of the structural integrity of structures and components as well as the operational reliability of systems. The requirements shall, for applicable parts, cover the design, manufacture, construction, installation, inspection and actions during operation of the classified item. In the requirement specification, standards applicable to the item in question shall be used.

This statement provides the main criteria that are needed for the acceptance process for safety classified systems, most important being the reliability verification and especially defining the applicable standards in requirement specification.

3.3. Electrical Systems of Nuclear Power Plants

Many of the safety functions in nuclear power plants are performed by electrical equipment such as pumps, blowers, actuators or lighting and ventilation that need alternating current power to operate. During normal operation of the nuclear power plant, part of the electrical power the plant generates is used by the plant itself to operate the electrical systems. For the event where the connections to the external transmission power grid and the possible auxiliary standby power grid are lost, the nuclear power unit is equipped with multiple redundant emergency power generating units to supply power for the safety device, so the unit can be safely operated and driven into safe state. (IAEA 2004)

These safety systems including the power generating units and the safety equipment and systems supplied by them are classified according to their intended safety functions as either Safety Class 2 or Safety Class 3 as specified in the YVL B.2 guide. A simplified (only 2 subdivisions are shown) example of the general design of nuclear power plant electrical system including the emergency power sources and different loads connected to them, electrical system configuration diagram of a nuclear power unit is presented in *Figure 3.2*.

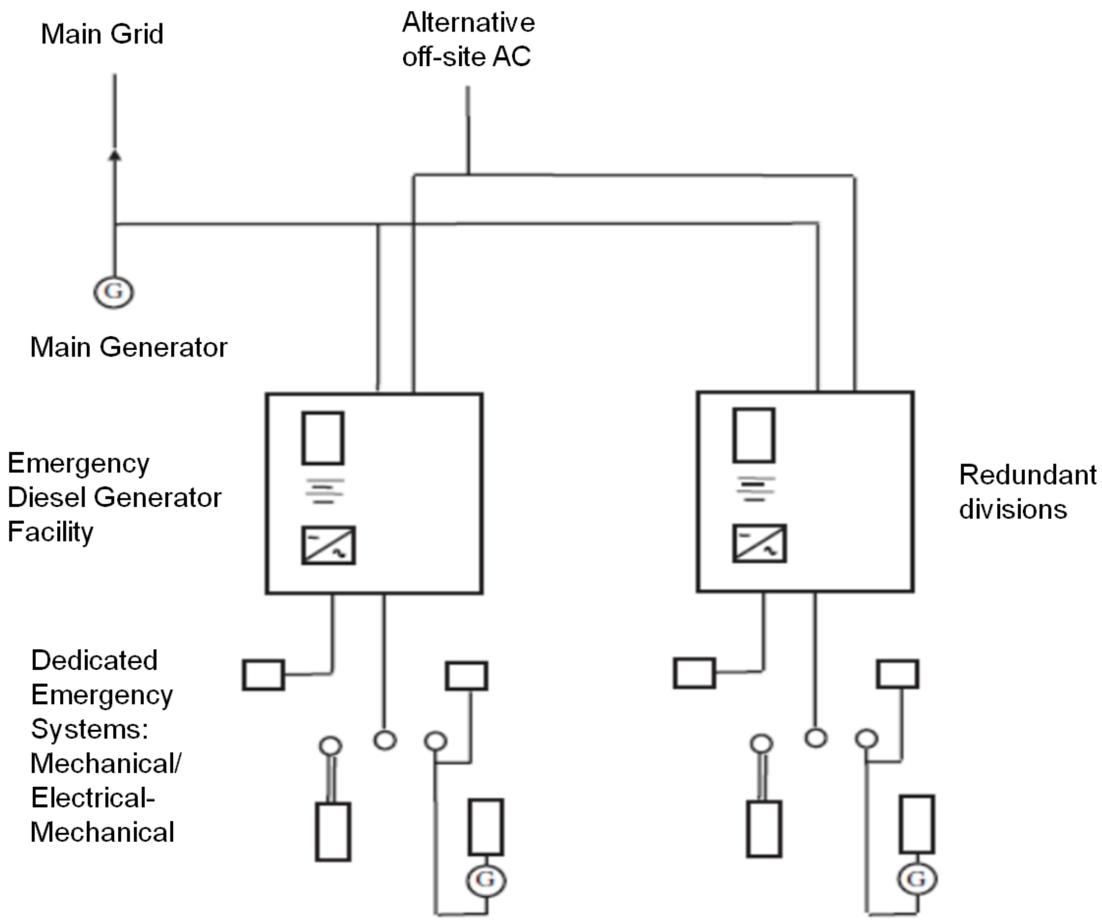

Figure 3.2: *Configuration of emergency power sources (modified from IAEA 2004)*

In *Figure 3.2* the electrical system of the nuclear power plant consists of 2 outside sources: the main grid and alternative transmission line, and the emergency diesel generators followed by the dedicated emergency systems and may also include additional power supply sources. *Figure 3.3* shows the power sources available in the OL1 and OL2 nuclear units.

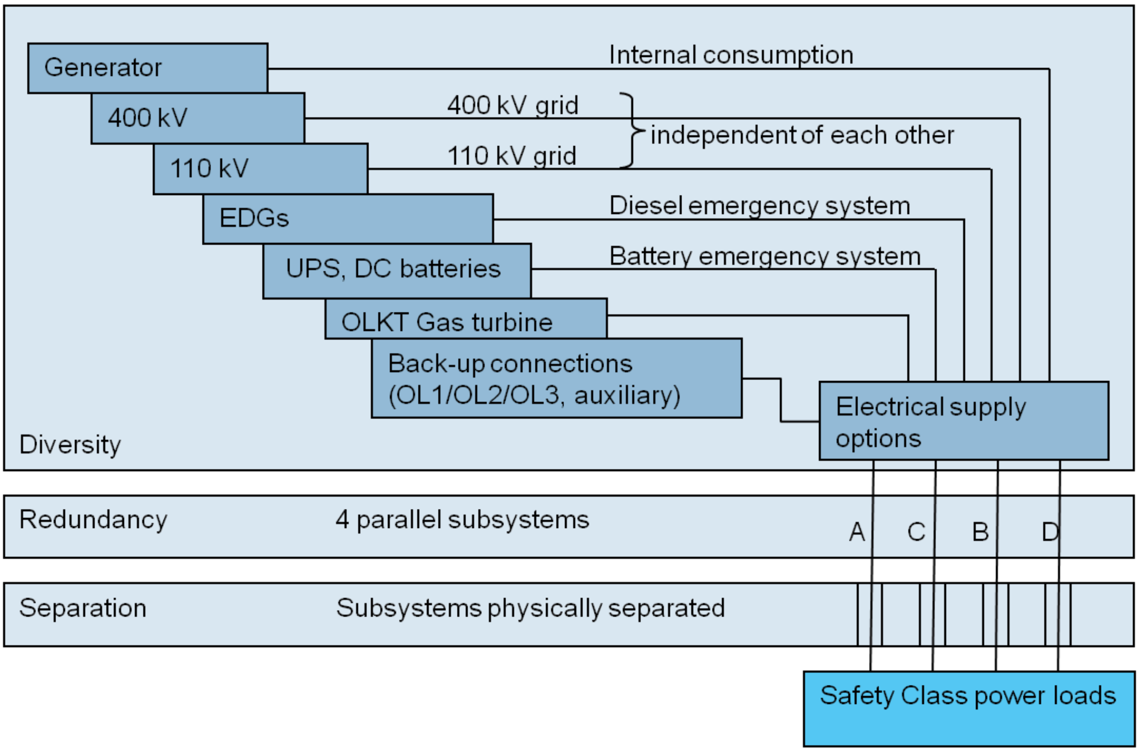

Figure 3.3: *Electrical power sources in the OL1/OL2 nuclear units*

The plant electrical systems consist of multiple different voltage trains to better serve equipment of different power levels. For example the OL1 and OL2 AC power systems have the following voltage trains: 6.6 kV, 660 V, 380 V and 220 V. During normal operation the electrical system is supplied power by the generator or the outside power grid first to the 6.6 kV train and progressively to lower voltage levels with transformers. The lower voltage level trains are supplied with the emergency power sources if the feed from the 6.6 kV train is lost. The diesel generator of course requires some time before it can supply the safety train (start-up and power sequencing), so those equipment that cannot handle the power loss are additionally powered by Uninterrupted Power Supplies (UPS).

The electrical system of the newer nuclear unit of OL3 differs from the older units, for example in the voltage levels. *Figure 3.4* shows an extremely simplified diagram of the configuration of electrical systems of the OL3 nuclear unit showing only a single safety division.

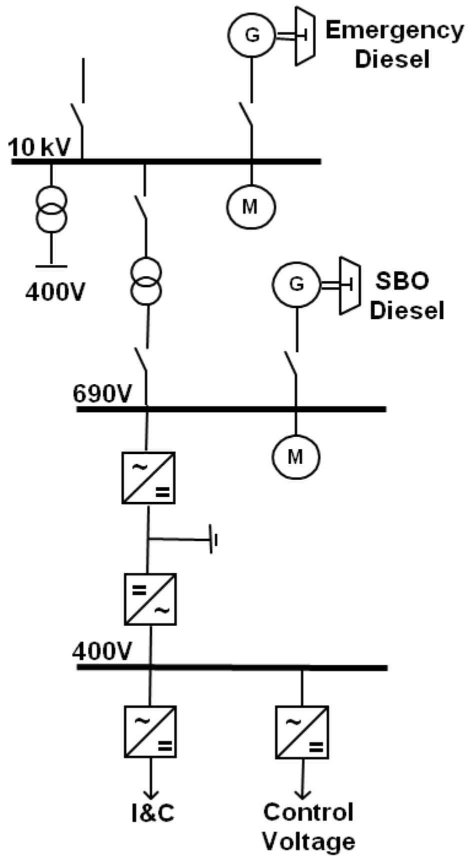

Figure 3.4: *Simplified example of the OL3 electrical system (TVO 2010, p. 50)*

The single subdivision of the OL3 electrical system shown in *Figure 3.4* includes the voltage levels of 10 kV, 690 V and 400 V, with the emergency diesels connected to the 10 kV train. Notable difference to the OL1/2 system is the SBO diesels that are connected to the 690 V train providing an alternative on-site AC source.

3.3.1. Main Emergency Power Units

The nuclear unit electrical systems are commonly designed such that the main emergency units are connected to the safety system power trains and receive a start-up signal automatically following a sufficiently large voltage disturbance in the connection to external power sources. The main emergency units, all auxiliary components vital for their function and the power trains they supply are classified as Safety Class 2 equipment in YVL B.2 draft 4. This classification means that the emergency power units shall supply power to the nuclear power plant safety system in DBC 3 and 4 events as explained in Table 3-1.

The Safety Class 2 main Emergency Diesel Generators (EDGs) supply AC power to the designated safety trains for as long as needed until the connection to the outside grid is restored, the engine malfunctions, or uses up all fuel or other operating media storage reserves. The necessary duration for the continuous function of the emergency power sources must be evaluated in the design phase and should be based on the analysis of the events that can cut the connection to outside grid and how long it should take to re-establish connection. (IAEA 2004)

The design of the main emergency power systems follows, as required by VNA 733/2008, 14 §, the N+2 Criterion. This requirement can be met with either 3 independent trains with 100 % capacity or with 4 independent trains of safety equipment with 50 % capacity as in the OL1 and OL2 units as shown in *Figure 3.2* (subdivisions A,B,C,D). Both of these systems ensure that the safety function is performed even if one train is unavailable due to maintenance and one system fails to operate due to a single failure. The advantage of the 4·50% system is that a single faulty signal will not cause activation of safety functions.

The normal power requirement of a safety train in a modern nuclear power plant is from 3 to 10 MW. This gives an indication of what size of an engine and generator is needed for emergency power generation. For example, the main emergency power trains in the OL3 power plant, which is of the Areva-Siemens EPR design, are powered by 7.8 MVA EDGs. The OL1 and OL2 have slightly smaller diesel engines, with 1.79 MW rated power and they supply the 660 V, 380 V and 220 V trains.

3.3.2. Alternative AC Units

Alternative AC (AAC) unit is a facility that constitutes an alternative source for AC power to the nuclear power plant in case of loss of off-site power (LOOP) event coincident with failure of the main emergency power units. The station blackout (SBO) condition and the need of AAC units to protect the nuclear power plants in this condition have been evaluated for example by the U.S. nuclear regulator NRC (Eide *et al.* 2005). In the study, the improvements in the core meltdown frequency of the PRA calculations were evaluated for over a 100 nuclear power plants and concluded that the improvements were significant.

The AAC unit, all safety loads it supplies power to, all auxiliary components relevant for its emergency power generating operation and the control systems are classified as Safety Class 3 equipment in the YVL B.2 draft 4. The systems powered by the AAC units are designed to perform safety functions in the Design Extension Condition (DEC) and Severe Accident (SA) conditions meaning that they are the next level of defense after the main EDGs. The AAC systems are not used in DBC 3 and 4 conditions, which are normally handled by the Safety Class 2 equipment.

The Safety Class 3 systems are connected to the Safety Class 2 electrical systems in such way that the lower class system may not cause failure in the higher class safety systems, which holds true in every case where equipment of different classes have a connection according to the YVL B.2 draft version 4. The AAC units are required to fulfill the N+1 Criterion, which means that 1 unit with 100 % capacity is available for emergency operation at all times. This requirement naturally means that at least 2 independent AAC unit need to be designed for the nuclear unit as one of the units has to remain functional while the other is out of operation due to maintenance or a single failure.

Careful consideration is needed when designing the physical and electrical layout of the whole nuclear power plant unit. According to the separation and redundancy principles the AAC units should be separated functionally and physically from both the main emergency power sources and each other. The separation should be extended to important auxiliary systems the fuel lines and cabling to ensure that all of the power sources are unlikely to be cut off or damaged by a single event such as a storm or an earthquake, or a fire inside the nuclear unit. (IAEA 2004)

4. FUNDAMENTALS OF GAS TURBINE DESIGN

4.1. Thermodynamics of Gas Turbines

The analysis of the performance and characteristics of gas turbines requires understanding of basic thermodynamic concepts. The laws of thermodynamics and flow dynamics equations give boundaries of what performance can be achieved with the different design solutions and how different conditions affect the performance and reliability of a gas turbine. (Çengel & Boles 2007, Boyce 2012)

Conservation of energy is a fundamental quality of nature and thus represented in the first law of thermodynamics, which was first postulated by Rudolf Clausius in 1850 in his paper "*On the mechanical theory of heat*" (Clausius 1850; via van Voorst 1870) in two different ways. The first one referred to the cyclic nature of the law and the other one to the incremental nature of the law and both of them are equally true. The first law of thermodynamics can be represented in equation form in following manner:

$$dU = \delta Q + \delta W \qquad \text{(Eq. 4.1)}$$

which states that the change in the internal energy dU of a closed system is the sum of the heat energy δQ transferred through the system boundaries and the work done on the system boundaries δW. If there is no change of internal energy present, the complete amount of heat brought to the system could be extracted as work. The first law of thermodynamics introduces the concept of internal energy but does not account for the direction of progress of the natural processes. Essentially the first law states that energy never dissipates in a process, it just changes form to another. (Çengel & Boles 2007)

The second law of thermodynamics introduces another physical property called entropy to explain the natural direction of processes. In ideal, reversible processes, the change of entropy is zero. In all real thermodynamic processes involving finite temperature differences, the change of entropy is positive. This means that all real processes are irreversible and entropy increases. Mathematically this can be expressed as

$$dS \geq \frac{\delta Q}{T} \qquad \text{(Eq. 4.2)}$$

where dS is the infinitesimal change of entropy, δQ is the infinitesimal change of heat in the process, T is the equilibrium temperature. Adiabatic process means that no heat energy leaves or enters the closed system; however there is still some degree of irreversibility from friction or other sources. Ideal, reversible adiabatic process is called isentropic, where dS equals zero. Reversibility can never be totally achieved in real processes and adjustments have to be made on the ideal process analyses and calculations to accommodate the unavoidable losses. (Çengel & Boles 2007)

Gas turbine is a heat engine that operates in a thermodynamic cycle called the Brayton cycle, named after its founder George Brayton (1830-1892). Originally Brayton utilized the thermodynamic cycle in a piston engine but its contemporary use is widely in gas turbine applications. Most of contemporary gas turbines operate on an actual open Brayton cycle using air as working fluid and a fossil fuel for heat addition in the combustor.

Closed Brayton cycle engines have their uses and they are being developed for various new concepts in power generation. An example of a closed cycle gas turbine concept is the helium gas turbine, where helium gas is heated up with nuclear fission and the power is extracted from the process in a gas turbine (Beck *et al.* 2010). The closed cycle gas turbines will be excluded from further analysis in this thesis as they are highly unlikely and unfitting choices for the application at hand.

The ideal and actual Brayton cycles are presented in T,s -diagram in *Figure 4.1*. The states (1, 2, 3, 4) form the ideal cycle and states (1, 2', 3', 4') form the actual cycle.

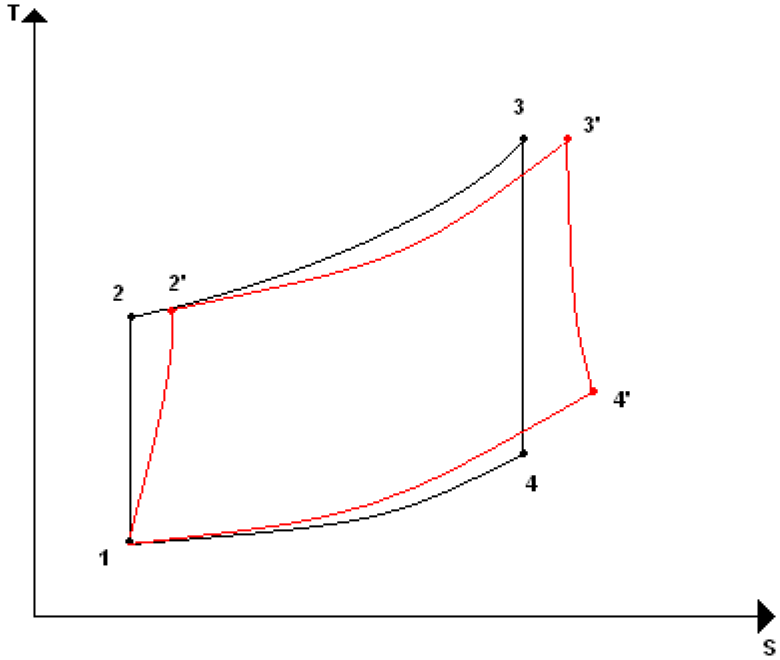

Figure 4.1: *Ideal and actual Brayton cycles*

and it consists of four processes: (1-2) isentropic compression of the working fluid, (2-3) isobaric heat addition, (3-4) isentropic expansion of the working fluid, (4-1) isobaric heat rejection.

In the actual Brayton cycle, as presented in *Figure 4.1*, the working fluid air comes into step (1) slightly below atmospheric pressure resulting from air inlet duct pressure losses. The compression of the air between states (1) and (2') is performed by the compressor. The heat addition process is achieved in the combustor between states (2') and (3') with minor pressure losses. Finally the air is expanded in the turbine between (3') and (4') and the exhaust gases are released into the atmosphere slightly above atmospheric pressure. A simple schematic flow diagram of the gas turbine components and corresponding steps are presented in *Figure 4.2*.

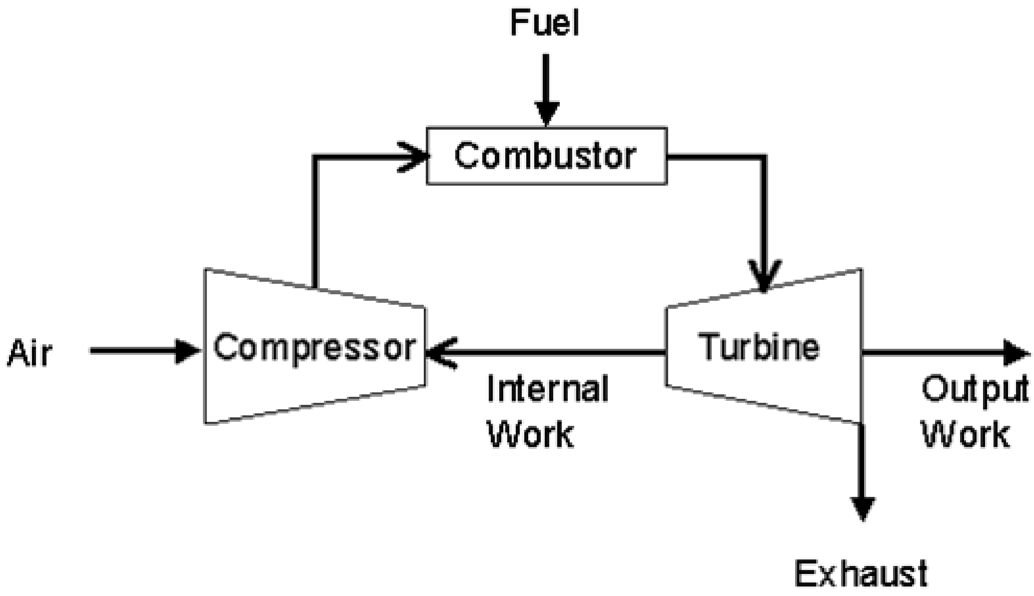

Figure 4.2: *Open-cycle gas turbine process*

The total work output of the Brayton cycle is the difference between the work extracted in the expansion process W_{t} in step (3'-4') and the work input in the compression process W_c in step (1-2'):

$$W_{\mathrm{cycle}} = W_{\mathrm{t}} - W_{\mathrm{c}} \qquad \text{(Eq. 4.3)}$$

where W_{cycle} is the work output of the cycle, W_{t} the expansion output work and W_{c} is the compression work. The thermal efficiency of the Brayton cycle η_{Brayton} is derived from the ratio of useful work extracted from the system W_{cycle} to the amount of heat brought into the system between steps (2) and (3') $Q_{2,3'}$:

$$\eta_{\mathrm{Brayton}} = \frac{W_{\mathrm{cycle}}}{Q_{2,3'}} \qquad \text{(Eq. 4.4)}$$

A useful method of demonstrating the efficiency of the Brayton cycle is with the pressure ratio in the compression and expansion processes, which in the ideal case is assumed to be the same for both:

$$\pi = \frac{p_2}{p_1} = \frac{p_3}{p_4} \qquad \text{(Eq. 4.5)}$$

where π is the pressure ratio, p_2 the pressure at compressor outlet and p_1 the inlet pressure, p_3 pressure at turbine inlet and p_4 pressure after the turbine. In the ideal case the efficiency can be expressed as follows assuming constant pressure heat addition and rejection:

$$\eta_{ideal} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} \qquad \text{(Eq. 4.6)}$$

where c_p is the specific heat at constant pressure, and temperatures at the corresponding steps from 1 to 4. In isentropic processes 1-2 and 3-4 the relationship of temperatures to pressures are:

$$\frac{T_1}{T_2} = \left(\frac{p_1}{p_2}\right)^{(\gamma-1)/\gamma} \qquad \text{(Eq. 4.7)}$$

and similarly:

$$\frac{T_4}{T_3} = \left(\frac{p_4}{p_3}\right)^{(\gamma-1)/\gamma} \qquad \text{(Eq. 4.8)}$$

where γ is the ratio of the specific heats of the working fluid (isentropic constant). For diatomic gases such as N_2 and O_2 (together forming most of atmospheric air), the specific heat ratio is 1.4. Combining equations 4.6, 4.7 and 4.8 the ideal cycle efficiency can be expressed as a function of the pressure ratio π:

$$\eta_{\mathrm{ideal}} = \left(1 - \frac{1}{\pi^{\left(\frac{\gamma-1}{\gamma}\right)}}\right) \qquad \text{(Eq. 4.9)}$$

The Eq. 4.9 demonstrates that the efficiency of the ideal Brayton cycle increases as the pressure ratio increases.

Useful method for taking into account the losses and the deviation of the isentropic processes in the compression and expansion processes is introducing the individual isentropic efficiencies of the components: η_c for the compressor and η_t for the turbine, which can be defined as follows with enthalpies h of different states:

$$\eta_{\mathrm{c}} = \frac{h_1 - h_2}{h_1 - h_{2\prime}} \qquad \text{(Eq. 4.10)}$$

$$\eta_{\mathrm{t}} = \frac{h_3 - h_{4\prime}}{h_3 - h_4} \qquad \text{(Eq. 4.11)}$$

where the numbering of the states correspond with the of *Figure 4.1*. Applying these isentropic efficiencies, the turbine work W_t and compressor work W_c can be expressed in the following manner:

$$W_c = \frac{\dot{m}_a(h_2 - h_1)}{\eta_c} \qquad \text{(Eq. 4.12)}$$

$$W_t = \left(\dot{m}_a + \dot{m}_f\right)(h_{3\prime} - h_4)\eta_t \qquad \text{(Eq. 4.13)}$$

where $\dot{m}_a$ is the mass flow of air through the engine, $\dot{m}_f$ the mass flow of fuel into the combustor. Introducing an efficiency for the combustion process η_b, the heat addition process $Q_{2,3}$ can be written:

$$Q_{2,3} = \dot{m}_{\mathrm{f}} q_{\mathrm{f}} \qquad \text{(Eq. 4.14)}$$

where q_f is the lower heating value of the fuel, which represents the amount of heat energy gained from the combustion of the fuel. Combining the presented equations, the efficiency of the cycle is:

$$\eta_{\mathrm{cycle}} = \frac{W_{\mathrm{t}} - W_{\mathrm{c}}}{\dot{m}_{\mathrm{f}} q_{\mathrm{f}}} \qquad \text{(Eq. 4.15)}$$

Examining the above equations 4.10-4.15 shows that the work done per unit of air flowing through the engine can be increased by increasing the pressure ratio, decreasing the compressor inlet temperature T_1 or increasing the turbine inlet temperature T_3.

The optimum pressure ratio calculated for work with the same firing temperature is lower than the pressure ratio optimized for the adiabatic thermal efficiency. A method for calculating the optimum pressure ratio π_{opt} for extracting maximum work from the cycle is presented in Boyce (2012):

$$\pi_{\mathrm{opt}} = \left[\left(\frac{T_3 \eta_{\mathrm{c}} \eta_{\mathrm{t}}}{2T_1}\right) + \frac{1}{2}\right]^{\frac{\gamma}{\gamma-1}} \qquad \text{(Eq. 4.16)}$$

where T_3 is the turbine inlet temperature and T_1 the compressor inlet temperature, γ the specific heat ratio and η_{c} compressor isentropic efficiency, η_{t} turbine isentropic efficiency.

The turbine inlet temperature (T_{tit}) is most commonly the defining factor and used in standards such as ASME PTC-22 (2005) for power ratings of gas turbines as the turbine blade temperatures limit the performance of the engine. The more detailed gas turbine performance analysis takes into account the losses in actual gas turbine processes such as pressure losses in inlet, bleed air mass flow, compressor and turbine mechanical and thermal losses, combustion inefficiency *et cetera*. Detailed performance analysis including the different correction formulae for ambient conditions can be found for example in Chapter 20 (p. 769-802) of Gas Turbine Engineering Handbook (Boyce 2012).

Improving the cycle efficiency can be done in numerous ways and it is normally the driving force in the gas turbine design development process. Greater efficiency directly increases profit made in the electricity market as more power is gained from the same amount of fuel, or equivalently, less fuel is needed for a given amount of power. The normal cycle efficiency improvement methods are for example: cooling the inlet air; injecting water, steam or compressed air between compressor stages; using regeneration or recuperation processes where the air is heated before combustor by exhaust gas heat; increasing the firing temperature in the combustor (Boyce 2012). The improvement of thermal efficiency of the cycle is not the focal point in the design process of a gas turbine, when the intended use of the engine is in standby emergency power operation, and the improvements are actually undesirable as they unnecessarily complicate the gas turbine design.

The design choices should not strive for the highest possible firing temperatures and pressure ratios, but instead focus on stable operation on wide power range and with different ambient conditions. More important use in the emergency application for the above equations than considering the efficiency improvements is to consider the effects of the ambient conditions on gas turbine performance. The effects of ambient temperature on gas turbine performance are shown in *Figure 4.3*, which is constructed from data of GE gas turbines.

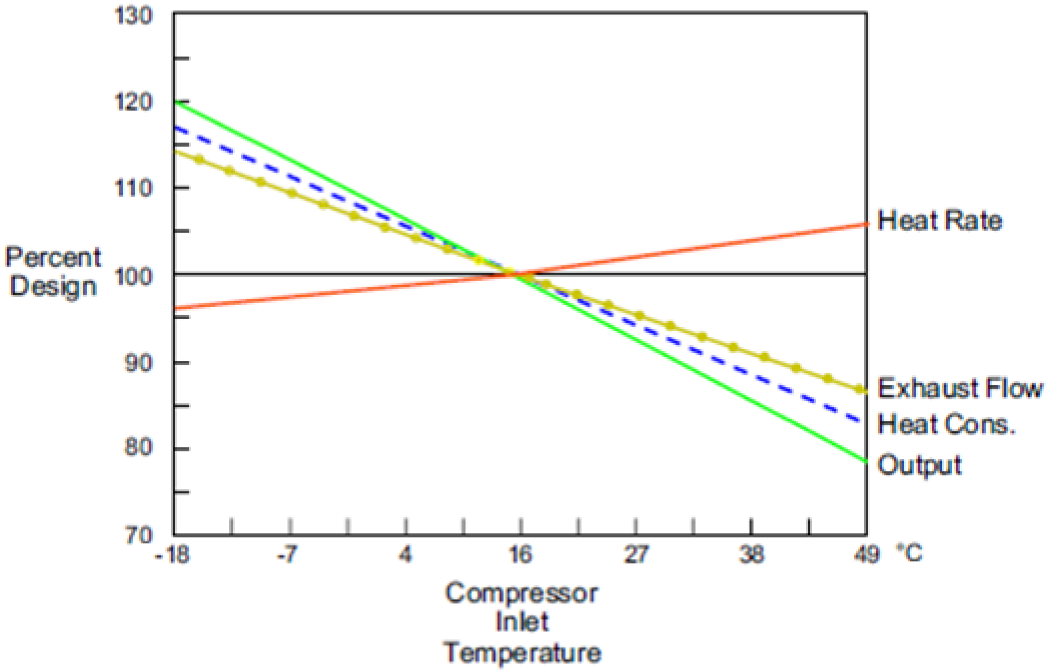

Figure 4.3: *Effect of ambient temperature on gas turbine output (Brooks 2000)*

As stated earlier, the inlet temperature and pressure affect the performance of the engine greatly and when sizing the engine this must be noted. For example as the ambient temperature rises, more work is consumed by the compressor to achieve same pressure ratio and this results in less power output from the engine. This means the engine must be sufficiently oversized in power that the required safety functions can be performed in extremely hot conditions. This fact leads to running the engine at partial loads in cold conditions, which might bring challenges to the operating stability.

4.2. Design Aspects of Gas Turbines

Major part in the design process of gas turbines is determining the right main components of the gas turbine to achieve the desired balance between performance qualities, reliability and costs. The different processes of the thermodynamic Brayton cycle can be performed various components and no single solution is right for every application. Thus it is important to identify the characteristics of different types of components used in gas turbine engines and choose the components that fit the desired operating range best.

For power generation and industrial applications, the optimization of the cost-efficiency of the gas turbine is naturally the main driving force. Increasing the thermal efficiency of the engine is important as the largest individual cost of a gas turbine during its life-time is the fuel. The greater thermal efficiency of the engine directly reduces specific fuel consumption and therefore also costs. Another source of costs in gas turbines is the governmental restrictions on the emissions from the engine, which requires special attention in the gas turbine design. Emissions are becoming increasingly controlled and taxed by governments that strive to reduce the environmental effects of burning fuels with international agreements. Emissions produced by the combustion processes cannot be completely avoided but with the choice of right components, they can be reduced significantly. (Boyce 2012)

A different set of criteria is more relevant when the gas turbine is meant to be used as an emergency power unit. The operating time of the engine annually is limited, and the fuel costs are relatively insignificant in comparison with the costs caused by the non-availability of the engine. The standby gas turbine units forgo the design choices for maximum efficiency and replace them with robust design for maximized availability and reliability for starting up and continuous operation.

Most of the development of new technologies in gas turbines in last decades has focused on increasing the efficiency through increased pressure ratios and firing temperatures, but this has reduced the availability of the gas turbines in many cases and thus offset the economic advantage of the higher efficiency. (Boyce 2012, Hansen 1996) Recognizing the different characteristics of the main components of the gas turbine is the key to finding the right combination of components for intended application and operating ranges.

4.2.1. Compressor

Compressor is the gas turbine engine component where the working fluid, normally atmospheric air, is pressurized by external work. The three main types of compressor are the axial-flow compressor, centrifugal compressor and the positive displacement compressor. Positive displacement compressor can be used for low flow but high pressure systems, such as the lubrication system of the gas turbine. (Boyce 2012)

Centrifugal and axial-flow compressors are the main compressor choices for the compression process of the Brayton cycle. Both are continuous flow compressors that are used for pressurizing the atmospheric air up to the discharge pressure before the combustor by exerting shaft work to the flow. The gain of static pressure in a compressor rotor stage is observed as a rise of specific enthalpy Δh, which can be calculated as in Larjola (1997):

$$\Delta h = \frac{1}{2}(w_1^2 - w_2^2 + u_2^2 - u_1^2) \qquad \text{(Eq. 4.17)}$$

where w_2 is the relative flow velocity at blade exit, w_1 relative velocity at inlet, u_2 blade tip speed at exit and u_1 blade tip speed at inlet. Summing up the enthalpy gains in all compressor stages, the total enthalpy gain of the complete compressor can be determined and further obtain the pressure ratio produced in the compressor. As described earlier the pressure ratio is a significant value as it directly relates to the efficiency of the gas turbine engine, and so it is commonly used to evaluate gas turbine performance.

Another deciding factor when choosing the compressor type is the desired flow rate through the engine. The axial-flow compressor type is used when a high flow rate is desired. The axial-flow compressor increases the fluid flow velocity with the rotor blades and then the flow is diffused in the stator blades to achieve the conversion of dynamic pressure to static pressure in the working fluid. Additionally, before the first stage of the compressor, inlet guide vanes are often used to direct the flow in a desired angle to the rotor blades. A single set of rotor blades and stator blades is called a stage. The first stage of an axial-flow compressor following the inlet guide vanes can be seen in *Figure 4.4*.

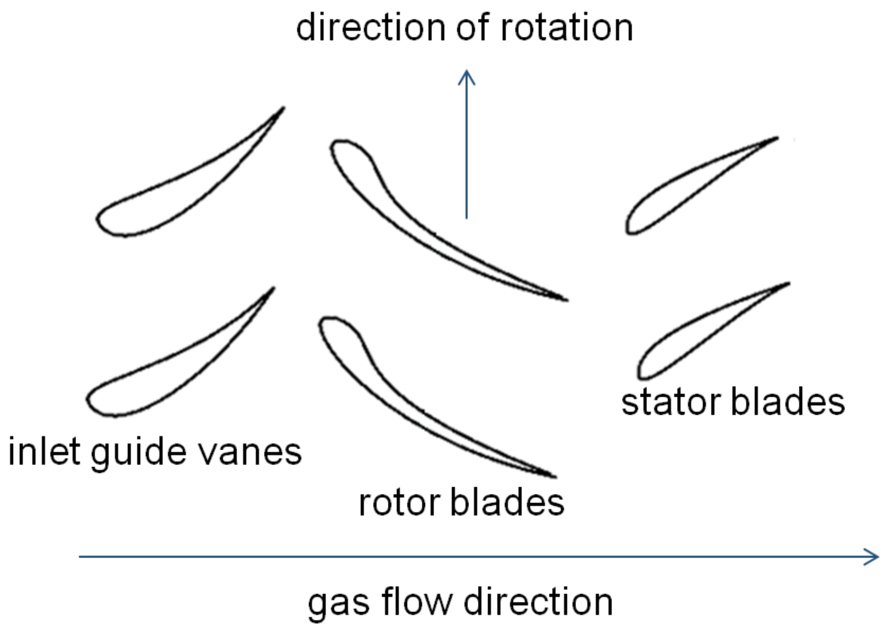

***Figure 4.4**: Inlet guide vanes and the first stage of an axial-flow compressor*

The compressor can have multiple successive stages depending on the desired pressure ratio and the size of the engine. Axial-flow compressors generally have higher efficiencies than centrifugal compressors, but it comes with a price as the operating range is usually much more limited. Axial-flow compressors are the more widely used option in the power generation industry as the higher efficiency becomes the deciding factor and also the size of the engine becomes large enough that the axial flow compressor is actually the only feasible choice.

Centrifugal compressors are generally more suited to be used in smaller gas turbines with smaller heat rates because of their worse efficiency in comparison. Centrifugal compressors have the advantage of smooth operation and larger tolerance of fluctuations in the required power, a desired quality in process industry where chemical processes have large power requirement changes. The centrifugal compressors are also considerably more reliable and produce higher pressure ratio per stage than axial-flow compressors.

In a centrifugal compressor the air flows axially into the rotating impeller, where the impeller blades increase the velocity of the fluid and it then exits the impeller in radial direction. The conversion of the dynamic pressure of the fluid flow to static pressure according to the Bernoulli principle is achieved in the stationary diffuser, which consists of vanes tangential to the impeller.

An example of a centrifugal compressor performance map is presented in *Figure 4.5* with pressure ratio as the ordinate and corrected mass flow as abscissa. The performance map for an axial-flow compressor is similar, with a slightly narrower operating range.

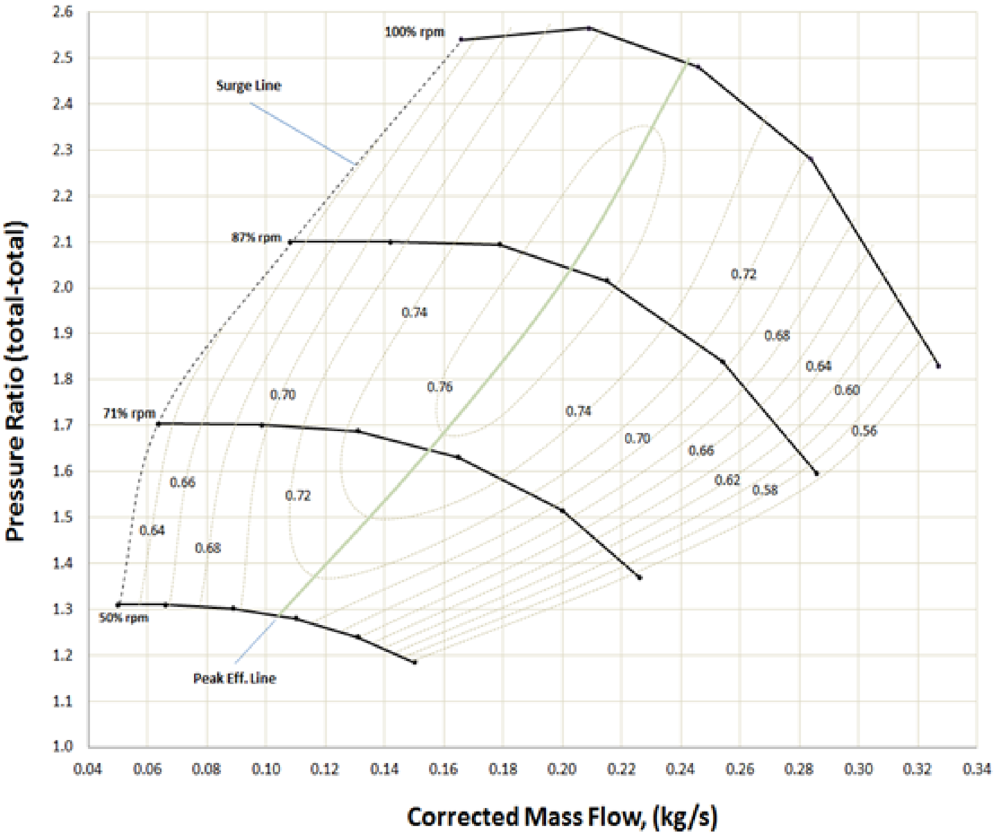

Figure 4.5: *Centrifugal compressor performance map (Mkronowski, 2011)*

As the pressure ratio is increased with a constant mass flow in the compressor, and the values approach the surge line, a condition called compressor surge starts occurring. Surging causes the flow inside the compressor to rapidly reverse direction due to dropping of backpressure and then reversed back to the original direction. The instability caused by the compressor surge is quickly destructive for the engine and must be avoided to preserve the integrity of the components. The condition of surge is usually easily noticeable as excessive vibration and audible sound occurs in the compressor. According to Boyce (2012), extensive investigations have been conducted on surge but predicting it exactly in the design phase remains difficult. Safest approach to avoiding the condition is operating the compressor well below the surge line.

As the mass flow through the compressor increases, eventually the choke point is reached. This is the point where the mass flow reaches its maximum value and "stonewalls", meaning the flow can't be increased further at the same operating speed as the gas flows at sonic speed. As the choke point is approached, the pressure losses increase and the efficiency of the compressor drops rapidly so this condition must also be avoided in the operation. The operating range of the gas turbine lies between the surge and choke lines with sufficient margin on both ends to avoid the conditions of surge and choke.

4.2.2. Combustor

The function of the combustor in the gas turbine is to increase the enthalpy of the high pressure working fluid, which can be further converted to useful shaft work in the expansion process in the turbine. From the thermodynamic point-of-view, the heat addition of the Brayton cycle is achieved in the combustor, ideally with minimal pressure loss. Important input values for the combustor are the pressure and temperature after the compressor because they affect the performance and material requirements of the combustor. Combustor output is the high-temperature working fluid including the exhaust gases from the combustion that are lead to the turbine inlet.

The inlet temperatures of combustors normally range from 454 ºC up to 857 ºC depending on the compressor pressure ratio and whether the gas turbine has regeneration or not. Newer aircraft engines can reach as high as 45:1 pressure ratio and combustor inlet temperatures between 541 ºC and 925 ºC and exit temperatures between 957 ºC to 1593 ºC, limited by the material properties of the turbine blades. The temperature data presented here has been collected by Boyce (2012) from the gas turbine industry.

Contemporary combustor research and development goals focus on improving the firing temperature meanwhile reducing nitrogen oxide (NO_x) emissions, which are increased directly proportionally to the firing temperature. The NO_x emissions are regulated by governments based on international agreements such as the Directive 2001/81/EC of the European Union. Emission reduction is extremely relevant in the design of gas turbines for commercial power generation; in the standby and emergency gas turbine cases emission levels are pretty insignificant when the annual operating times are low and especially in the case of a safety equipment of a nuclear power plant it is excluded from the emission control scope.

More focus in the combustor design in a standby safety application is directed to the ease of maintenance and reliability of operation as with other components of the engine. The simplest and most commonly used type of combustors is the conventional diffusion combustor. The name diffusion combustor comes from the way the incoming air is diffused to slow it down so the flame can be maintained more easily and reliably, and to prevent the flame from being carried on downstream of the combustor. Diffusion combustor uses only about 10 % of the compressor air in the combustion process and the rest is used for mixing and cooling purposes. The simplicity and proven reliability makes the diffusion combustor a very likely choice for a safety-critical gas turbine, when the emission reduction technologies are not needed.

4.2.3. Turbine

Turbine is the component of the gas turbine engine where the energy stored in the working fluid flow is converted to mechanical shaft work. In the axial-flow turbine this is achieved by successive stages of rotating and stationary turbine blades. Radial-inflow turbines are very similar to centrifugal compressor, only the direction of the flow is reversed and the rotation is in the opposite direction. The names of the components also change according to their function: where the flowing fluid in a centrifugal compressor exits through the diffuser, radial-inflow turbines have nozzle guide vanes to direct the flow to the turbine impeller blades.

The flow interacts with the turbine blades, decreasing its velocity, and the energy of the flow is converted into a more useful form in the shaft. The energy recovered from a turbine rotor (single stage) per unit mass flow is given by the Euler turbine equation (p. 784, Boyce 2012),

$$E_{ad} = \frac{1}{g_c}(u_1 v_{\theta 1} - u_2 v_{\theta 2}) \qquad \text{(Eq. 4.18)}$$

where E_{ad} is the adiabatic energy generated on the rotor, g_c is the standard gravity, u_1 is the rotor blade speed at inlet, $v_{\theta 1}$ tangential component of flow absolute velocity at inlet, u_2 and $v_{\theta 2}$ respectively at the exit.

The turbine can be either axial-flow or radial-inflow depending on the intended application and desired performance of the turbine similarly to the compressor. The relationship between the turbine types is similar to the centrifugal and axial compressors'. The greatest advantage the radial in-flow turbine has compared to the axial-flow turbine is the higher work produced per stage, which can be even 2 to 3 times higher. The power output of a turbine is a function of the square of the blade tip speed, and this value is higher in radial-inflow turbines, so at any given flow rate the work is greater in the radial-inflow turbine.

The usefulness of radial-inflow turbines is limited by its poorer efficiency performance in almost all operating ranges. Also the cooling of the turbine is harder to design than in the axial turbine, which severely limits turbine inlet temperature. These facts, combined with the similarity of the axial-flow to steam turbines, which have a long development history, have made the axial turbine the most common choice for gas turbines. (Boyce 2012)

4.2.4. Cooling

The most critical part of the engine that requires cooling is the first stage of blades in the turbine. Turbine blade cooling system of the gas turbine can be designed in multiple ways depending on the size of the engine and intended operation. If the turbine inlet temperature is very high, the materials of the first stage turbine blades in an axial-flow turbine are subjected to great thermal stresses and to reduce these, the blades have to be cooled. The cooling can be either air cooling or water and steam may also be used when more efficient cooling is required.

Different air cooling techniques include: convection cooling, impingement cooling, film cooling and transpiration cooling (Boyce 2012). Bleed air from the compressor are usually used as a coolant for the turbine blades as only a part of the working fluid is needed in the actual combustion process. If the firing temperatures are low, the air cooling is sufficient to maintain the temperature of the turbine blades low enough. In water and steam cooling systems the coolant is passed through tubes inside the blade and ejected as steam from the tip of the blade, which provides very efficient cooling of the blade. These systems have the drawback of requiring much more complex coolant circulation and blade design. Steam cooling of the turbine blades is normally used in combined cycle process where steam is readily available from the waste heat steam boiler.

Convection cooling is the most widely used form of cooling in contemporary gas turbines. In convection cooling the radial air flow inside the turbine blades and vanes passes through the blade from hub to tip and removes the heat through the wall. Impingement cooling is a form of convection cooling where the cooling air is blasted on the inner surface of the blade by high-velocity air jets. Film cooling forms a thermal insulation layer between the hot gas stream and the turbine blade and thus achieves lower blade temperatures. Transpiration cooling requires the blade material to be porous as the coolant removes the heat directly from the hot gas stream by passing through the porous wall of the blade. The goal of all these different methods is to increase the heat flux from the turbine blade material to the coolant air. (Boyce 2012)

4.2.5. Rotor Dynamics

As a high-speed rotating machine, a gas turbine is subjected to large mechanical forces caused by vibrations inside the engine itself and is also relatively sensitive to external forces. Continued vibrations can be harmful for the engine components and cause wear, or in the worst case they can even lead to quick destruction of the engine. To prevent these problems, detailed analysis of the vibration characteristics of the engine has to be conducted by the engine manufacturer. Rotor dynamics calculations give tools for identifying critical speeds of operation and the balancing requirements of the engine.

Vibration systems can be roughly divided into two different groups; free vibration and forced vibration. A free vibration system has no external forces acting on the system, and so only the internal forces of the system causes vibrations. Because of no external forces, a free vibration system will oscillate at one or more of its natural frequencies. Forced vibration, on the other hand, is vibration caused by external force acting on the system called the excitation force. A forced vibration system oscillates at the frequency of the excitation force, which is independent of the natural frequency of the corresponding free system. If the frequency of the excitation force coincides with a natural frequency (harmonic) of the system, problems arise; a condition called resonance is encountered and it can quickly enhance the vibration amplitude to such degree that the system is damaged. (Boyce 2012, Nelson 2007)

A gas turbine is a complex system of vibrations, both natural and forced. One important point to consider is the existence of multiple natural frequencies of rotation generally called critical speeds. If the gas turbine is operated well below the first critical natural frequency, it is called a subcritical system. A subcritical engine would be safe to operate without any consideration of the vibrations and would be highly desirable, but their use is limited to only very small applications. As the size of the rotating machine increases, the mass of the rotor also increases and an upper limit for the shaft size that could be subcritical is reached. These facts combined with high speeds mean that subcritical operation is not feasible, and the machine is required to be operated above the first critical speed (supercritical). Normal supercritical operation of the system is stable, but the main problems arise during start-up or shut-down sequences when the rotational speed of the engine goes through the critical speed range. To avoid damage to the engine, the amplitude of the vibrations must be kept under control by adequate damping performed by bearings and foundations.

Many different kinds of excitation forces act on different parts of a gas turbine and the resulting vibrations vary in mechanisms as well as severity. Some are quickly destructive; some are smaller in amplitude but nevertheless cause damage in the long run due to alternating stresses on the engine components. The forces affecting the rotor-bearing system can be external forces affecting the system through the casing and foundations or internal instabilities caused by the rotor motion and material properties.

Examples of external forces that are transmitted through the casing and foundations of the engine are strain caused by misalignment of piping or nearby reciprocating machinery. Forces acting on the casing and foundation of the engine usually cause destructive vibration in the gas turbine but these problems can be avoided through proper layout design of the whole facility and taking these factors into account in the vibration analysis.

Forced vibrations are caused to the rotor-bearing system by the rotor motion inside the gas turbine. The frequencies of these forced vibrations are the shaft rotating speed or multiples of this speed. Also blade passing frequencies or other component frequencies can be present in the forced vibration spectrum. The critical frequency of the forced vibration remains constant at any shaft speed, damping does not affect the frequency, it only reduces the amplitude of the vibration. Forced vibrations have peak amplitudes in narrow frequency bands, so operating above or below these frequencies prevent the problem they present.

Another type of rotor-bearing instability is the self-excited vibrations which have an onset shaft rotational speed, above which they occur with increasing amplitude. The frequency of these vibrations is relatively independent of the shaft speed after onset and the only ways of eliminating these self-excited vibrations are operating below the onset shaft speed or introducing sufficient damping to reduce the effects of them. The self-excited vibrations result in force components on the rotor shaft which lead to motion of the shaft around its center of axis. This type of motion is called whirl and there exists several types of it depending on the inducing mechanism. Examples of whirls exhibiting in a gas turbine are hysteretic whirl, dry-friction whirl, oil whirl and aerodynamic whirl. These whirl conditions are harmful for the engine components in the long run and cause friction losses, so they should be eliminated as well as possible in the design phase.

Vibration measurements are based on the three different characteristics of the vibration: displacement, velocity and acceleration. These monitored values emphasize different parts of the vibration as shown in the following example. A simple harmonic vibration can be mathematically expressed as follows:

$$x = A \sin \omega t \qquad \text{(Eq. 4.19)}$$
$$\dot{x} = A\omega \cos \omega t \qquad \text{(Eq. 4.20)}$$
$$\ddot{x} = -A\omega^2 \sin \omega t \qquad \text{(Eq. 4.21)}$$

where x is displacement, $\dot{x}$ is velocity, $\ddot{x}$ is acceleration, A the vibration amplitude and ω the frequency. Considering the maxima of the above equations it can be observed that the displacement is independent of the frequency (it is only present in the periodic sine function), velocity is proportional to frequency and the acceleration is proportional to the square of the frequency. If the frequency and displacement is known, the acceleration and velocity can be simply calculated by integration. Due to the slight differences between these values, the measurement methods also differ and generally several types of sensors are needed to sufficiently analyze the vibrations in a gas turbine.

Fourier analysis is a mathematical tool that is used for analyzing the vibration behavior of a gas turbine through the measurements. The vibrations measured during balancing of the engine are continuous and periodic, and so they can be expressed as a sum of periodic functions, which is called the Fourier series. The Fourier transformation of these time-dependent functions converts the functions into frequency domain where the natural frequencies of the vibrations can be analyzed from the frequency spectrum. These natural frequencies are the often called critical speed harmonics of the gas turbine. Example of results obtained from vibration analysis by Fourier's methods is presented in *Figure 4.5*.

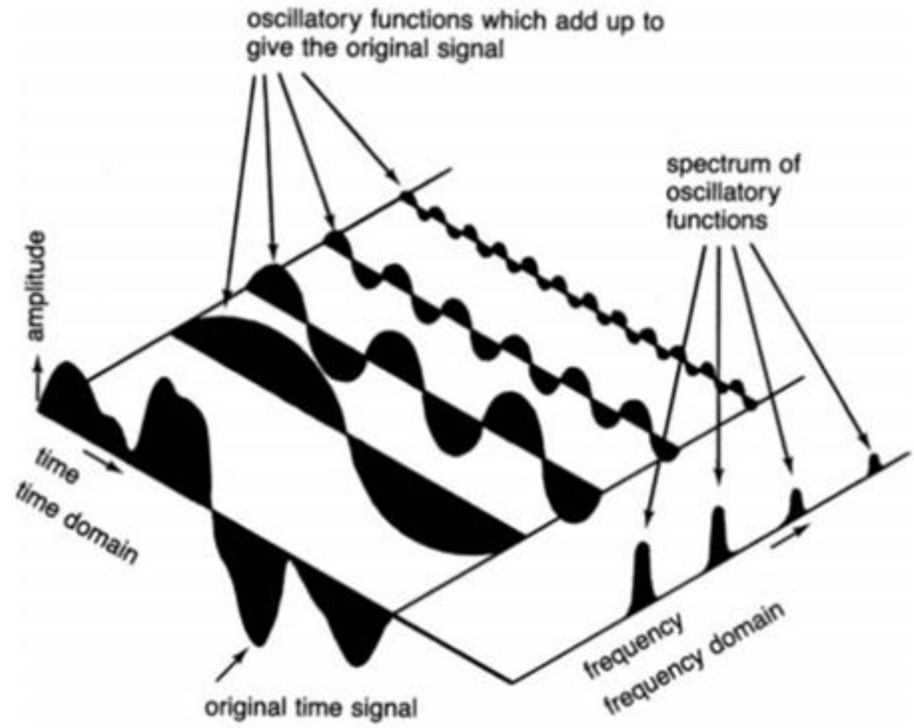

Figure 4.6: *Fourier analysis of vibrations (Boyce 2012)*

Figure 4.6 shows how the Fourier transform converts the parts of the original time signal to a spectrum of oscillatory functions into the frequency domain.

The Campbell diagram is a useful tool for plotting the vibration behavior of a gas turbine in respect to the shaft speed. It shows the natural frequency regions and different excitation frequencies of the gas turbine system that should be avoided in operation to prevent shaft or blade failure (Boyce 2012). A simplified example of a Campbell diagram is presented in *Figure 4.7*, where a few blade passing harmonic frequencies (1st, 2nd, 3rd mode) are plotted vs. shaft rotational speed and 3 excitation frequencies are present.

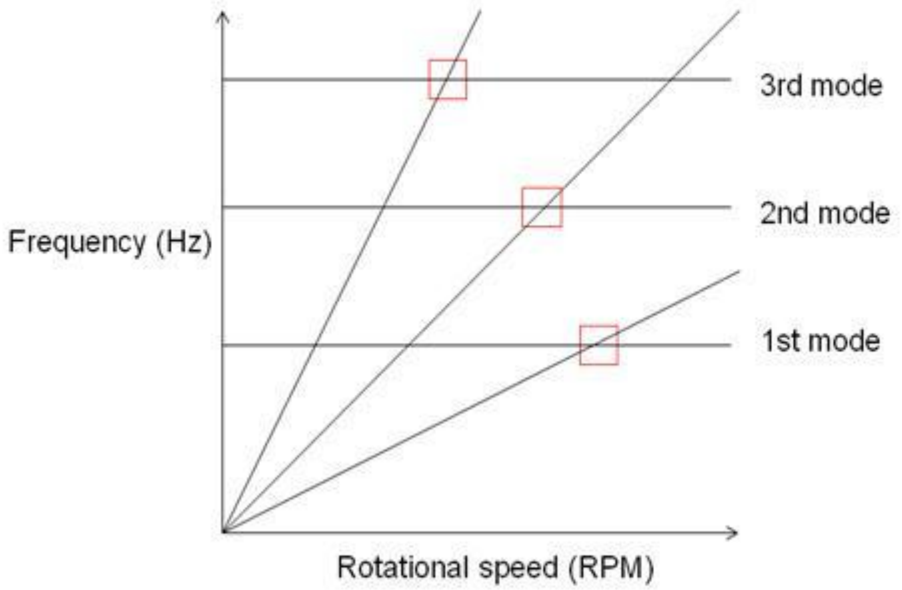

Figure 4.7: *Campbell diagram*

If the engine is continuously run in the vicinity (speed and frequency regions inside the red squares in *Figure 4.7*) of the critical speeds, the excessive blade vibrations might be excited and this can potentially lead to blade failure due to material fatigue. Blade and rotor vibration conditions and methods for measurements are constantly studied (for example: Forbes & Randall 2009, Ogbonnoyanna & Theophilus-Johnson 2011) to gain better knowledge and make it possible to predict the behavior of blade-rotor systems.

The Campbell diagram can be generated from design calculations of the engine by computing analytical eigenfrequencies or from actual operating data, where measured vibration response spectrum is plotted vs. the shaft rotation speed. Comparing the analytical results with the measured values can be used for verification of the vibration analysis. These results from the vibration analysis are used to establish the ranges of rotational speed, where the engine may be run continuously, and which speeds need to be avoided.

4.2.6. Gas Turbine Reliability and Availability

The engine reliability upon demand is of high importance as the AAC unit is essentially the last emergency power source for alternating current that powers the safety systems that mitigate the consequences of a severe nuclear accident. Similarly, the availability factor of the unit must be as high as achievable, meaning the downtime due to maintenance operations are kept to a minimum. Starting up and operating reliably is extremely important for a safety-critical engine and most contemporary gas turbines can't achieve sufficient reliability to be considered for the application without improvements. In fact the developments in the gas turbines have gone the opposite direction than the desired. The problems in gas turbine reliability developments according to Curley *et al.* (1994) as stated by Hansen (1996) have been related to the fast advancements in the thermal efficiency and emission reducing combustion techniques. The advantage considering the application of the gas turbine as emergency power source is that these improvements are not desired and older, proven design can be used.

Gas turbine reliability is established for both the start-up and continuous operation of the engine. Start-up reliability of the engine is defined as the percentage of successful start-ups from the total start-up attempts. This figure is very vital for the intended application, more so than in commercial gas turbine applications, where the failure of the start-up leads has no immediate severe consequences. Failure to start usually leads to downtime as the turbine side needs to be purged from any fuel that has not been combusted, a condition which naturally needs to be avoided. (Boyce 2012)

The reliability of the gas turbine can be analyzed from the component level with the FMEA method as described earlier in chapter 3.2.1. The data for these analyses is gathered from operating experiences and tests, where the likely sources of failures in a gas turbine are identified. The sources of failures can for example be materials failing from fatigue due to high temperatures or variable vibration conditions as studied by Cruse *et al.* (1997) and Forbes & Randall (2009) or problems in the combustor as studied by

Rafsanjani & Nasab (2012). Appendix A shows an example compilation of component diagnostics that can be observed with monitoring systems as presented by Boyce (2012). Fuel or lubrication oil systems are also very critical as obstructions in these systems quickly lead to a need for engine shutdown (Boyce 2012). Most of the common failure sources can be eliminated with good quality control. Redundant design is used to further increase reliability where possible, but inevitably there remains some probability of failure for all components.

Failure-rates for all critical components of the engine should be established in the reliability analysis with sufficient proof. The data is then combined to form an overall probability of failure-to-operate for the complete gas turbine engine. This final output of the FMEA is incorporated in the overall Probabilistic Risk Assessment for the nuclear power plant. Example requirements for failure probabilities are presented in the EASA CS-E (2010) standard section 510 "*Safety Analysis*". For aircraft turbine engines the requirement is a probability of $1 \cdot 10^{-8}$ failures per flight hour for hazardous engine faults that prevent further use of the engine, and $1 \cdot 10^{-5}$ for major engine faults where output power is at least partially lost. A similar reliability confidence is desirable for the emergency power source gas turbine as the operating hours of the gas turbine in this application are relatively low, only a few thousand hours between overhauls. This brings the failure-rate of the complete engine to acceptable level to achieve safety equipment classification.

To achieve this reliability goal, the correct choices should be made in the gas turbine design process. To summarize, the following measures should be considered to increase the reliability of the gas turbine: simplicity of design, using proven technology solutions, well analyzed performance and vibration behavior, avoiding those operating speeds where vibrations might be excited or compressor surge starts occurring, correct component and materials choices, and redundancy and diversity of critical control and support systems.

The availability factor is another important value in a safety device and it should be kept as high as possible. Availability factor for the gas turbine generator can be calculated as the percentage of the time that the engine is available for emergency operation from the total number of hours during a year. The availability factor is improved by well designed maintenance operations that can be performed as fast as possible to reduce downtime and also using reliable components so that no unexpected forced outages are encountered.

4.3. Gas Turbine Types

Gas turbines are suited for many different applications from base-load and peaking power generation to providing shaft power to process equipment or even propulsion power for ships and aircraft. Choosing the right gas turbine engine for the right application is a matter of finding the right balance between required power, efficiency, starting time, ambient conditions, emission limits, service lifetime or other criteria significant for the user of the engine. (Walsh & Fletcher 2004)

Gas turbines can be used in many different roles in electrical power generation. Power grids require base-load power plants to meet the average daily energy demand of the grid. The base-load power plants are designed to be operated as much as possible so they must have high power and efficiency to be profitable. Combined cycle processes have made the gas turbine engine very competitive despite high fuel costs even in base-load operation due to high thermal efficiency of the combined cycle. (Boyce 2012)

Peaking power is another important part of the energy market and especially power grid stabilization. The energy demand of the consumers in a power grid fluctuates greatly depending on time of the day, the day of the week or the outside temperature. During times of high demand, the prices of electricity also rise and these kinds of peak energy demands are met by peaking power plants which can be started up and connected to the power grid quickly. Smaller units that have low initial investment costs are best suited for peaking power plants as the higher price acquired from the energy markets makes up for the higher fuel cost resulting from the use of low-efficiency engine. (Walsh & Fletcher 2004)

Gas turbines can also be in standby emergency power units in facilities such as hospitals that need emergency power for life-saving equipment as well as basic heating, lighting and air conditioning during power outages in the main power grid. These engines must have the capability of starting in a black-out condition, which means that no power is available from outside grid. (Walsh & Fletcher 2004) The application of gas turbines as nuclear power plant emergency power source can be seen as an extension of this application, only the requirements for reliability and quality of the engine are even stricter than normal.

Short description of different applications and types of gas turbines is in order. The data regarding temperatures, powers and efficiencies is presented by Boyce (2012), which have been collected from the gas turbine industry. Directions of development in the various gas turbine types are also briefly examined.

4.3.1. Frame-type Heavy Duty Gas Turbine

Base-load power generation utilizes heavy duty frame-type gas turbines with rated powers up to 480 MW. These gas turbines can be either used alone, or more efficiently, in combined cycle processes where the high heat energy content of the exhaust gases is utilized in a boiler to generate steam which in turn drives a steam turbine. The combined cycle processes have high thermal efficiencies, as high as 60 % can be achieved with very high turbine inlet temperatures of 1500 ºC. These kind of high temperatures introduce problems with the turbine blade materials as the blades are subjected to extreme conditions where hot corrosion and thermal fatigue and creep of the materials are all likely to occur without proper protection. The thermal problems of the blades can however be avoided by sufficient cooling and the right choice of materials. Development of materials and cooling techniques have projected that inlet temperatures of even 1650 ºC could be reached, which would push the power and efficiency of the unit even higher.

The frame-type heavy duty gas turbines utilize axial-flow compressors and axial-flow turbines with pressure ratios from 5:1 in conventional models up to 35:1 in some modern designs. The frame-type heavy duty gas turbines are designed to be robust to increase life-time of the components and reduce the downtime of the engine due to maintenance. This increase in the availability of the engine is important in base-load operation where the power plant is expected to produce electricity constantly. (Boyce 2012)

4.3.2. Aircraft-derivative Gas Turbine

Gas turbine engines for aircrafts have always been leaders in the new technologies for gas turbines and many of the advancements are made in the research projects for military purposes. The design criteria for aircraft engines are high reliability, high performance with many starts and flexible operating range. These qualities are also very attractive for many land-based applications and this has lead to the development of aircraft-derivative gas turbines. (Boyce 2012)

Aircraft-derivative gas turbines are modified aircraft engines, where a turboprop or turbofan engine is used as a gas generator, when the bypass duct of the compressor is removed and a few compression stages added. The gas generator has a separate turbine for producing internal work for the compressor. The gas generator is connected to a free power turbine that produces shaft work from the flow energy that normally provides thrust for an aircraft. The coupling between the gas generator and the power turbine is usually only aerodynamic and they have separate concentric shafts. This design gives the advantage of greater flexibility for part load operation as the gas generator and the power turbine can rotate at different speeds. The aircraft-derivative gas turbine engines have power range from 2.5 MW up to 50 MW, with efficiencies between 35 and 45 %. (Boyce 2012)

As well as for industrial process power operation, the aircraft-derivative gas turbines are well suited for peaking power plants as they have low initial costs and require little space and start up quickly in comparison with base-load power plant types such as frame-type gas turbines or steam power plants. The important qualities for this application of gas turbines are fast starting capability and ease of operation from a distance and relative ease of maintenance. The pressure ratios and efficiencies are similar in peaking power gas turbines and the frame-type heavy duty gas turbines but the operation is easier and requires less expensive cooling systems and materials. Generally aircraft-derivative gas turbine components have had shorter life-times than frame-type gas turbines because of the high-performance choices but advancements have been made in this field lately to bring the life-time of aircraft-derivatives closer to those of frame-type gas turbines.

The 50 MW TwinPac developed by Pratt & Whitney is an example case of an aero-derivative gas turbine with 2 converted FT8 aircraft engines as gas generators connected to a single generator, which improves reliability as the unit can be operated at partial load with only 1 engine starting up. (Boyce 2012)

4.3.3. Small Gas Turbines

Small gas turbines that produce 5 MW or less are a flexible group as they can be similar in design to larger frame-type gas turbines or aircraft-derivatives using basically any combination of the radial and axial components. The radial turbomachines are often used in smaller gas turbines to bring comparatively high pressure ratio for few stage processes.

Radial-flow components are inherently less efficient than their axial counterparts and the small gas turbines usually don't have any turbine blade cooling which lowers the possible maximum firing temperature. These features make small gas turbine poor in thermal efficiency but the added reliability of the engine components makes them suitable for applications where other criteria dictate the choice of components. Even multiple compressors can be connected to a single power turbine improving availability of the unit as the engine can operate on part load if one of the compressors fails to start up initially.

An example of a small gas turbine in standby application is the 1895 kW gas turbine manufactured by Kongsberg, with a one-stage centrifugal compressor and a single stage radial-inflow turbine, running at 16.7% efficiency, which is used as a standby power unit with a 99.3% starting reliability. (Boyce 2012)

4.4. Gas Turbine and Diesel Engine Comparison

Gas turbines and diesel engines are largely similar in that they can be used as small to mid-range standby power units running at medium-speed. The few key differences between the engines are however significant and should be discussed to determine what advantages would gas turbine engine have as an emergency power unit for nuclear power plant.

One of the greatest advantages of the diesel engine is clearly the proven reliability for decades in nuclear safety application as nearly all modern commercial light-water reactors have diesel engines and generators for emergency power supply. The diesel engine starts up a lot faster, after 10 seconds power loads can be connected to the generator, whereas even the fastest gas turbines have at least 40 seconds to 1 minute starting time. This makes gas turbines unlikely choices for main emergency power source as the quick start-up is more critical for them.

Diesel engine has better fuel economy than a gas turbine almost through all operating conditions but especially in part load and load changing conditions. Also, the reciprocating diesel engine can be kept in idle running with low fuel consumption as opposed to gas turbines which have very poor idling capabilities (at least efficiency-wise). The higher fuel requirement of the gas turbine is counterbalanced by the significantly lessened amount of lubrication oil consumption.

A gas turbine engine has a better power-to-weight ratio meaning at any given power rating the gas turbine is smaller by both volume and weight, the reason why gas turbines have become so popular in aircrafts. Another good reason to use gas turbine instead of a diesel engine is that the vibrations transmitted to the structure from operating the gas turbine are significantly smaller because of the difference in the motion of the engine; reciprocating motion of the diesel engine generates larger forces than the rotating gas turbine. Gas turbines have a large moment of inertia because of the high speed of rotation, which in turn helps accept large individual loads without stalling.

Another advantage of the gas turbine is that with a low turbine inlet temperature, it can be operated without external cooling circuit, instead using bleed air from the compressor to cool the blades. This is a major advantage as fewer components and systems are less likely to fail and thus the reliability of the engine grows. Additionally the noise generated by a gas turbine differs from the diesel engine in that the high-pitch noise is easier to suppress. (Walsh & Fletcher 2004)

4.5. Gas Turbines in Nuclear Power Plants

Gas turbines have not been thus far used as safety related equipment meant for emergency power generation in nuclear power plants. Mitsubishi Heavy Industries (MHI) have proposed the concept of using gas turbines for both as main emergency power sources and as alternative AC sources in their US-APWR nuclear power plant design. In designs offered for TVOs Olkiluoto 4, a number of vendors propose to use gas turbines as alternative AC sources to be used as emergency power sources for DEC and SA.

Presently, the Olkiluoto nuclear power plant site has a gas turbine power plant OLKT in a joint ownership of TVO and Fingrid, the company responsible for the Finnish national electricity transmission grid. The OLKT plants purpose is to be used by Fingrid as back-up power source for grid stabilizing, in case of power plant disconnections, or other abnormalities in the transmission grid. The OLKT unit also has a role as investment protection power supply for TVO and can be connected to the nuclear power plant electrical systems but is not classified as a safety related device (Class EYT). The OLKT unit is equipped with two TwinPac 50 MW aero-derivative gas turbines.

The Forsmark (Sweden) nuclear power plant site owned by Vattenfall AB also has a gas turbine unit with 40 MW capacity. The gas turbine is connected to the power plant electrical systems in case the outside electrical power is lost and all diesel generators fail to function (SBO). The gas turbine energizes the diesel bus bars in all units (Forsmark 1-3) at the plant site. (Heimbrand & Dominicus 2011)

5. JUSTIFICATION OF REQUIREMENTS

5.1. Alternative AC Unit

The requirement specification decisions for the alternative AC facility for a nuclear power unit and justifications for them are discussed in this chapter. *Figure 5.1* shows the basic scope of the systems that are critical for the operation of the AAC unit.

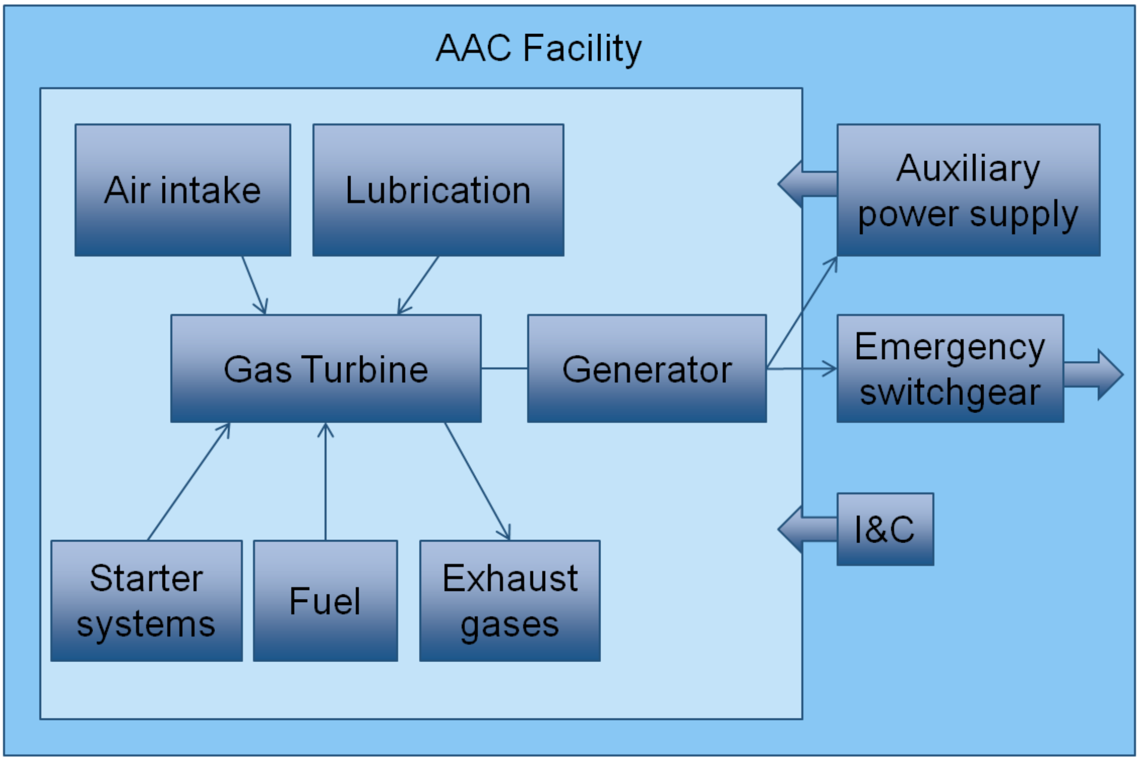

Figure 5.1: *Scope of AAC facility systems*

Utilizing the background knowledge and guidelines presented earlier in this thesis, requirement specifications for a station black-out gas turbine and AAC unit were developed as part of the Licensing Feasibility Studies (LFS) of OL4 nuclear unit procurement project for Teollisuuden Voima Oyj (TVO). The detailed specifications document will remain confidential. The choices are based on the regulations for nuclear safety and industry-approved standards that ensure quality and function of the gas turbine and all auxiliaries related to the safety function.

5.1.1. Gas Turbine Power Rating

The power rating of the gas turbine engine is defined as the nominal power the gas turbine is able to generate continuously operating at nominal speed. The power rating is an important factor in the gas turbine selection process: the greater the rated power, the larger the engine size and more complicated engine design is required, which in turn increases susceptibility to failures. Power rating is a limiting factor considering some components such as the centrifugal compressor or radial-inflow turbines as they become unacceptable choices if the power rating of the engine grows too high. Also, higher power rating requires higher turbine inlet temperature, which in turn increases the need for cooling the turbine blades, further complicating the engine design.

The required power rating for the gas turbine generator is determined by calculating the peak apparent power balance from the loads in the circuit the gas turbine generator supplies power to. In nuclear power plants these circuits are called emergency power trains, which consist of all the safety equipment that are needed for handling different operating or accident conditions. As an alternative AC source, the facility is designed to start up and provide power for the safety systems allocated to it in case of a DEC or SA condition as defined in the nuclear regulations and safety analyzes.

The power rating calculations should take into account at least the following power loads: motor loads of the safety device such as pumps, fans or blowers, other power loads such as heating, ventilation, air conditioning (HVAC), and lighting systems, non-uniform distribution of the power loads, power load switching, transmission and generator losses. The power factors of the individual devices in the power trains must also be taken into account in the power balance calculations to achieve the required actual power.

The engines and generators are required to be rated for higher power output than the value acquired from balance calculations would require at the time of purchase to cover design uncertainties. This added margin in the power rating calculations is called the design margin. The regulations for nuclear safety also state that the engine rated power should be higher than the result of the balance calculations for added safety. YVL 5.1 (only the old YVL version is available, in the new system it is the YVL E.10) and the standard for emergency diesel generators (KTA 3702 2000) state that the safety margin of at least 10% of the required power is added to the engine. In addition, the nuclear power plant owner may require a spare margin in the power rating to cover for possible increase in the power loads if the power plant is later modified. In this case we determined that 10% owner margin is required for future enlargements. Eq. 5.1 shows an example calculation of the rated power adding the different design margins:

$$P_{rated} = P_{balance} * Design\ Margin * Safety\ Margin * Owner\ Margin \quad \text{(Eq.5.1)}$$

The power rating of a gas turbine depends greatly on the ambient conditions, as the required compressor work increases when the temperature of the air at the inlet increases and less useful work can be extracted from the engine. This makes the gas turbine susceptible to major variations in output power throughout the different ambient temperatures present during a normal year at the installation site of Olkiluoto, Finland. Using the deterministic approach to the power plant safety analysis, the power rating required has to be calculated with the worst-case scenario in mind, using the most adverse combination of ambient conditions of air temperature, pressure and wind speed. Physically impossible situations such as extremely hot temperature combined with heavy snowing should naturally be omitted from the power balance calculations.

During normal steady-state operation of the gas turbine when the compressor and turbine are running at nominal speed, the power at the generator output should be able to supply the power train reliably with required power from anywhere between the minimum power load to 100 % of the rated power. The minimum power load the gas turbine engine can safely continuously supply has to be established by the engine manufacturer and tested before the engine is accepted. Possible conditions where the engine would be idle running should be limited in the design process to prevent damage to the gas turbine.

In addition to the safety margins presented in Eq. 5.1, the gas turbine engine is required to have capacity to be operated above the maximum rated power for a short duration, similarly to diesel engines in the same application. The KTA 3702 standard requires diesel engines to be able to operate at 110 % of the rated power for one hour duration and afterwards maintain continuous rated power. The CS-E standard (EASA 2011) for aircraft turbine engines has a similar overload power rating which is called the OEI-rating (One-Engine-Inoperative), which means the engine has to be able to produce power in excess of its normal rated power if one engine of a multi-engine fails. Turbine engines for aircraft normally have multiple OEI-ratings for different durations starting from a few minutes to half an hour and even continuous OEI-ratings exist. Setting the overload capacity requirement for the gas turbine for the standby AAC operation follows the diesel engine overload requirement of 110 %. When operating a gas turbine on the overload capacity, it should be noted that the additional thermal and mechanical stresses reduces the maximum time between maintenance overhauls as the engine components wear out faster.

5.1.2. Alternative AC Facility Layout

The gas turbine engine is operated as an Alternative AC source as Safety Class 3 equipment for DEC and SA conditions as specified earlier. As a backup system for the Safety Class 2 main emergency diesel generators (EDG), the AAC system should be completely separated both functionally and physically to prevent common cause failures knocking out all systems. The physical and functional separation and independence from the main EDGs required by the nuclear regulations is achieved in the layout design of the nuclear unit when all the electrical cabling, instrumentation and control systems, piping and fire protection systems are designed to be separate. The goal of this separation principle is that a failure of any individual system in either the EDGs or the AAC facility does not cause any further failures in other systems.

The independent AAC sources also follow the same principle, so that they have the minimum amount of common systems. One recommendable option for the physical separation is to place the independent AAC facilities to opposite sides of the nuclear unit as this certainly would ensure that an internal hazard such as a fire could not possibly cut off both AAC sources. The fuel storage tank located at the nuclear power plant site is one the AAC systems share, but the fuel pipelines feeding the AAC units should be separate and have sufficient distance between them so that the breaking of both pipelines from a common cause would be highly unlikely. Similarly the electric cables and cables of the control systems must be put in different cable trays and routed away from the cabling of the other AAC unit.

The layout design of the AAC unit should include a Local Control Room (LCR), where the gas turbine engine can be started up and operated with authorization from the main control room of the nuclear unit. Functional test runs of the engine are normally performed from the LCR periodically according to the safety and maintenance requirements of the nuclear unit. The local control room should be designed such that it is accessible from elsewhere than the engine room and the sound level inside the LCR should remain low enough so that the facility can be operated without protective equipment. This ensures that the high sound pressure levels generated by the engine will not prevent operation of the unit in emergency cases. Finnish Governmental Decree VNA 2006/85 on protection of workers from excessive noise requires working environments with noise levels of less than 80 dB so this is the maximum allowable noise level inside the LCR during operation.

Another important point to consider in the AAC unit layout design is the maintainability of the unit. The passageways to the facility and the placement of different components should allow easy accessibility so that the components can be reached and exchanged without the need for major disassembling. The goal of this is to perform the required maintenance operations as quickly as possible and thus reduce the total unavailability time of the facility. The passageways to the AAC unit should also allow for hauling of the largest individual components of the gas turbine engine so they can be exchanged in case they are damaged beyond on-site repair.

5.1.3. Gas Turbine and Generator Connection

The choice of method for connecting the gas turbine engine to the driven equipment - in this case the generator - depends on the engine components and desired performance qualities. The simplest design choice is the single-spool engine, where the compressor, turbine and generator rotate all at same speed. This type of gas turbine engine avoids using a transmission gearbox, and instead uses simple couplings between the shafts. This is a major advantage as the gearing constitutes an additional source for failures that could lead to unavailability. The downside of the single-spool engine is that the operating range and capability to withstand load variations decrease as the rotation speeds of all components are the same, defined by the generator (generally rotating at 1500 rpm in 50 Hz systems).

The use of a reduction gearbox between the gas turbine and the generator brings the advantage that more stable operating speeds can be achieved for the compressor side of the gas turbine. As the components rotate at different speeds, the critical speeds acquired from the vibration analysis can be avoided. Another major advantage is that also the compressor surge and choke conditions can be safely avoided when the rotating speed of the compressor can be kept well under control. The drawback of using the gearbox is that the gearing face very severe conditions when the gas turbine is operated at different, quickly changing power loads. The gearing teeth are subjected to high vibrations in during power load step changes and this can quickly result in gear failure and lead to unavailability of the engine, especially if problems arise in the lubrication of the gearbox.

Considering the large and stable operating range required for the safety classified gas turbine, single spool design seems unfit for the application. The requirement for the connection of the gas turbine and the generator set in the specification leave the choice of whether to use gearbox or not to the gas turbine supplier. The reliability of the reduction gearing, however, needs to be sufficiently proven by both analysis and testing. The design and quality of the gearing must to be such that it can withstand without failure the vibration conditions and thrust loads resulting from the gas turbine engine throughout the complete operating range with sufficient confidence.

5.1.4. Service Life-time of the AAC Unit

The life-time expectancy of the complete AAC unit and all of the components that are subject to wear during operation of the gas turbine has to be established by the supplier of the gas turbine. The designed service life-time should cover the functional test runs including the start-up procedures, which are normally performed on the gas turbine at least once a month. The service life-time of the main components of the engine is prolonged by well designed condition monitoring as well as maintenance operations, where the engine is inspected thoroughly and any possible signs of wear in the materials are observed well in advance before failure occurs.

The desired life-time requirement set by the purchaser for the gas turbine and the AAC unit as a whole is connected to the overall life-time of the nuclear unit. The design life of the complete nuclear unit is generally based on the main components of the nuclear reactor that are irreplaceable. These mechanical components usually have design life-times of 60 years, so this is normally considered as the maximum life-time of the nuclear unit. The requirement for the life-time of the gas turbine should of course be as high as reasonably possible, so that complete overhauls of the engine should not be required multiple times during the 60 year period. Considering these arguments, a 30 years life-time requirement is set for the AAC facility and the main engine and auxiliary components accounting for all the start-up and testing procedures over the whole life-time. This requirement is achieved with well designed maintenance operations and monitoring systems that indicate any damage to components well in advance. These aspects shall be discussed later.

5.1.5. Gas Turbine Vibrations

Vibrations in the mechanical components of the gas turbine always eventually lead to damage of the components and parts which are subjected to them. Large vibrations on the critical frequencies quickly lead to the destruction of the engine and smaller vibrations cause cyclic stresses and wear the components out slowly but surely. Vibration conditions may result in for example blade tip rubbing on the seal or bearings wearing out and this reduces the life-time of these components significantly. Using the correct materials in the bearings, shafts and blades helps prolong their life-time against vibration loads. The vibration characteristics are initially established in a testing and balancing rig where the rotor system is balanced as well as possible.

The next step after balancing tests in vibration damage prevention is avoiding the critical speeds of operation by constantly measuring the vibrations in different parts of the engine, the shaft and the bearings by the means of displacement probes, velocity pick-ups and accelerometers, all of which utilize a vibration transducer to convert the information to a time-varying signal that can be analyzed.

The vibration measurement equipment design and measurement methods should follow the standards ISO 10814 "*Mechanical vibration. Susceptibility and sensitivity of machines to unbalance*" and API 616 "*Gas Turbines for the Petroleum, Chemical, and Gas Industry Services"* concerning vibrations in gas turbines. Standards regarding the vibrations in the generator are: ISO 7919-2 "*Mechanical vibration on non-reciprocating machines - Measurements on rotating shafts and evaluation criteria*" for general guidelines on rotating shafts, ISO 10816-2 "*Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts*" for bearings. The standards demand the range of operation speeds to be well outside the torsional or lateral undamped natural frequencies of the shaft to avoid reaching the critical frequencies that would lead to damage of the engine. The standards mentioned above give maximum values for the displacement and velocities measured in the rotor shaft and bearings. For example, ISO 7919-2 defines 4 zones for qualitative assessment of the machine conditions and gives boundary values for peak-to-peak displacement that are dependent on the rotational speed. The gas turbine was required to be in the highest class of zone A meaning the highest allowed peak-to-peak displacement in the shaft is $4800/\sqrt{n}$ µm, where *n* is the rotational speed in revolutions per minute (rpm).

The CS-E standard gives detailed requirements on the vibration surveys that need to be conducted on the engine. These surveys cover the conditions where the vibrations are excited and their consequences and the CS-E demands that the engine materials can withstand the possible vibrations with sufficient margin. The vibration surveys are validated by testing of the engine similarly to the requirements for land-based gas turbines so that the vibration conditions present throughout the complete operating range will not cause irreparable damage to the engine that would prevent further operation. The CS-E requires the engine to withstand 5 minutes operation on the most critical speed and temperature conditions present in the operating range. This quite demanding requirement is set also for the gas turbine in the AAC unit.

In addition to the engine internal vibrations, also the vibrations transmitted to the foundation and civil structures have to be limited in such degree that no structural damage is expected to occur from operating the gas turbine during the life-time of the plant. KTA 3702 standard for example limits the vibrations of diesel engine to be less than 3 % of the static load. The gas turbine inherently transmits less large-amplitude vibration to surroundings than a reciprocating engine (Walsh & Fletcher 2004), so the vibrations limit could be set even lower for gas turbines than diesel engines if deemed necessary for some reason.

5.1.6. Suitability of the Gas Turbine

As discussed in chapter 3, there are many different variants of gas turbines that have the same fundamental thermal process cycle but have very different technical solutions to perform the individual processes. Centrifugal, axial or mixed-flow turbomachinery may be used to compress or extract work from the working fluid; the heat addition can be done in various types of combustors or even external heating circuit. The entire gas turbine and generator combination may be installed in one driven shaft-train or the engine can be of multi-spool design, where the compressor, turbine and generator may have individual concentric shafts. The configuration choices greatly affect the performance and operating range of the gas turbine, so different types of gas turbines are suited for different applications.

The requirements for the engine configuration are left on the general level to leave sufficient room for the engine designer to manoeuvre and decide how best achieve the engine qualities required elsewhere in the requirement specifications document. The main point is that the suitability of the gas turbine is analyzed with all the available information and the choices are justified with the right criteria.

The suitability analysis for a gas turbine intended to be used as a nuclear power plant back-up power unit should mainly be focused achieving the highest possible reliability of the gas turbine for starting up and running without failures and additionally with high availability factor. As discussed earlier in Chapter 4.2.6, the best reliability of the engine is achieved with simple design solutions using proven technologies, which is helped by the small power rating requirement of the engine and freedom from emission control.

Although conducting a rigorous suitability analysis is very important in the early design phase, the suitability of the engine is ultimately proven only by type testing the engine to verify its capability to perform the intended power operation throughout the complete operating range.

5.2. Operational Requirements

The AAC unit, the gas turbine engine and the auxiliary systems, is kept continuously in a condition where it can immediately start emergency power operation. The engine is started up with the starting systems and the power is loaded on the generator sequentially according to the safety design of the unit as soon as the engine has reached nominal rotating speed and generator achieved the nominal voltage and frequency. The start-up sequence program should be separate for testing and emergency operation. A quick power load sequencing program is effective for emergency operation and during periodic function test runs, the engine should be started up with a slow starting procedure. This measure is taken to improve the life-time of the engine components that are prone to thermal wear and fatigue.

The starting reliability requirements for the gas turbine in the emergency power unit are stricter than those for common industrial or even peaking power gas turbines. The starting reliability data of diesel generators comes from the many years operated as an emergency power source for nuclear power plants whereas gas turbines have no such operating experience. This lack of operating experience means that the verification of the gas turbines start-up reliability has to be done in the certification type test.

The starting time is the property of the engine where the gas turbine loses most to the diesel engine as described earlier as the starting times of gas turbines are normally multiple times slower than diesel engine of comparable size. For example Walsh & Fletcher (2004) state that diesel engines normally start up in 10 to 60 seconds while gas turbines can take minutes to achieve rated speed after start up signal receipt. The fast start-up is not, however, as critical for the Safety Class 3 emergency power source as it is for the Safety Class 2 main EDGs because the nuclear unit is normally designed to survive in SBO condition without alternating current power for at least a few hours in DEC.

Transient conditions resulting from power load changes are a major concern in the AAC unit design, as they can cause failures in the engine function and even damage the gas turbine or the generator if their protections fail. Even if the protections functions properly, shutdown of the engine is of course undesirable as the engine is then unable to perform the intended safety function. An example of the operating transients that could present is over-speeding of the gas turbine engine or the generator due to sudden load dropping or out-of-step load connections. Should these failures occur, and the engine or the generator shaft reach over-speeds of 120 % of their nominal rotation speeds, the protections should trip the engine or the generator to protect the integrity of the components. The maximum over-speed value of 120 % nominal speed is based on the protective shutdown limit of the diesel engine and generator presented in the KTA 3702:2000. In addition to setting the upper limit tripping value of the rotational speed, also the transient speed changes resulting from load accepting or load dropping has to be limited so the engine is not subjected to excessive transient forces potentially harmful to the engine, generator or the possible gearbox.

The operating transients may also include voltage and frequency disturbances in the generator, and they are required to be limited in such way that the safety function can be performed uninterrupted and no damage is caused to the safety equipment operating in the emergency train. The standards such as KTA 3702:2000 in Table 3-2 and IEC 60034-1:2010 "*Rotating electrical machines - Part 1: Rating and Performance*" give tolerance limit values such as maximum transient frequency or voltage increase or decrease, frequency and voltage adjustment times and voltage deviation during power level changes. The same requirements are set for the generator connected to the gas turbine in the AAC facility, as the same voltage and frequency deviation characteristics are used as design basis for all electrical safety equipment connected to the safety trains.

In addition to the operational requirements that are related to the emergency function, the nuclear unit user may require other operational modes such as synchronous operation of the AAC unit with the power plant electrical systems as well as the external power grid. These operational modes require additional design effort in the sizing of the electrical components such as the switchgear and bus bars, which may need to be sized higher than the normal emergency operation of the AAC unit would require.

5.3. Auxiliary Systems

The gas turbine engine and generator have multiple supporting systems that are not as such part of the engine, but are vital for the continued function and as such must remain operational during standby and enable immediate start-up of the engine at any time. These auxiliary systems include for example the fuel oil, lubrication oil, cooling, exhaust and starting systems, and the electrical systems supplying power to them. Following the separation principle, the auxiliary systems have to be functionally and physically separated from auxiliary support systems of other emergency power sources. Some exceptions can be made such as connecting the fuel and lubrication oil storages of the unit to other storages, but even in these cases the connection is sufficiently protected and failure propagation between them should be limited.

Similarly, electrical connection between the different auxiliary systems can be made, keeping in mind that a failure in lower Safety Class equipment should never cause failure in higher Safety Class equipment as required by the YVL B.2 draft version. The auxiliary systems as well as the whole AAC unit have to be well protected from both external storms, earthquakes, floods and internal hazards such as fire or explosions. These protections are mostly the same as those for the whole nuclear unit, but the special cases will be discussed for each system separately.

5.3.1. Starter Systems

The starter systems of the gas turbine engine are an important part of a standby unit and as such also worth considering in this application. The reliability to start up is one of the breaking points of the acceptability of the engine as a safety classified device for emergency operation in nuclear power plant unit. As the engine is required to be started up from station black-out condition (SBO), it should be equipped with a starting system - preferably multiple systems for redundancy - which are capable of performing the black start.

To achieve even greater degree of reliability, the diversity principle should be applied to the design of the gas turbine starter system, meaning the starter systems should have different operating mechanisms. For example the initial start up of the gas turbine could be achieved with air turbines from a compressed air storage tank. The KTA 3702 presents a similar solution for diesel engines, where compressed air is acted on the pistons initially. Other options for initial power to the starter motor is using small diesel motor or even electrical motor powered by DC batteries.

The required energy stored for the starter systems should be established by the purchaser according to the safety requirements that regulations and the PRA of the unit demand. The KTA 3702 standard demands sufficient energy stored for the starting system of the diesel engine for 3 complete starting sequences, but the purchaser of the nuclear unit may deem more safety margin is required here by probabilistic safety analysis, for example. In this case, the requirement for start-up capacity was set for 9 complete starts.

To enable successive starts following a failure in the start-up sequence in the gas turbine, the engine must be purged from all excessive fuel accumulated in the engine. This is needed to prevent any damage resulting from the fuel combusting in wrong places such as in the first turbine stages. If allowed to happen, this process destroys the first stage nozzle blades of the turbine or damages other parts of the turbine. Boyce (2012) states that a flow of at least 5 times the total volume must go through the turbine to expel all fuel from it.

5.3.2. Fuel and Lubrication

The fuel and lubrication oil systems are of course vital for the gas turbine as dysfunction of either system prevents emergency operation of the gas turbine. As such, the requirements of the fuel and lubrication systems have to be well defined to meet the operational requirement of the whole unit.

Being the operating media of the gas turbine, both lubrication and fuel oil storage quantities define the maximum operating time of the gas turbine unless they are refilled. The nuclear unit purchaser, supplier and the nuclear authority have to evaluate the duration that the gas turbine has to be self-sufficient during the accident conditions assuming the operating media storages cannot be refilled. The required duration the emergency power is needed varies as different reactor designs may have very different safety solutions. The alternative AC unit has to be able to perform the safety functions required from it in Design Extension Conditions (DEC) and Severe Accident (SA) as defined earlier and these conditions require that the engine is able to operate continuously for a sufficient period of time until power is restored to the nuclear power unit from another source, preferably the national 400 kV power grid.

Usually the emergency power units have a 24 hour operation fuel oil tanks located at the unit. Additionally the fuel storage tanks at the power plant site hold additional fuel that is transferred to the operating fuel tank by a pump if additional fuel is needed. In the KTA 3702 the requirement for the total quantity of fuel located at the plant site is set for 72 h operation but the purchaser may deem even more time, such as a week (168 h) is required before the need for refilling the fuel reserve. The quantity of lubrication oil in the day tank should naturally correspond to the fuel quantity so that it will not become a bottle-neck for the operating time of 24 hours. To account for temperature differences, the operating tanks should be sized with sufficient expansion margin so that the oil expansion will not damage the tank.

As a part of the fire protections of the AAC facility, the fuel and lubrication oil pipelines and connections should be placed in such ways that any possible leakages from them are prevented to come in contact with high-temperature surfaces of the engine. This prevents fires and use of fire protection systems that could potentially inhibit the use of the gas turbine engine for emergency operation.

The nuclear power plant site also presents in itself requirements for the lubrication and fuel systems as the ambient conditions, mainly temperature, greatly affect the properties of the oils. In cold climates the oil viscosity increases drastically meaning it becomes in essence thicker. The high viscosity of fuel and lubrication oil results in blocking of filters and difficulty of pumping so the engine may become deprived of fuel or lubrication, which necessitates shutdown of the engine. The cold weather conditions may also cause water contamination of the fuel as water condensates from the air inside the fuel tank and this has to be prevented. The solution for preventing this has been left to the designer.

Cold filter plugging point (CFPP) is the lowest temperature that a diesel fuel oil passes through a standard filter and the acceptable value for the CFPP of the fuel the engine can operate with needs to be required by the purchaser. Cloud point of a fuel oil is another property related to low temperatures, where the wax in diesel oil starts to precipitate and form a "cloudy" appearance in the fuel. This wax then may plug filters and small holes and eventually prevent engine function.

Applicable standards for the diesel oil used in the AAC unit are for example the BS CWA 15940:2009 and EN 590:2010, both of which cover the production and testing methods of the diesel fuel oils and contain the classification according to the CFPP and cloud point values of the fuels. Considering the installation site, which is in a climate zone with cold winter, the gas turbine engine should be able to operate on all fuels with CFPP and cloud points as low as the arctic grade (-44 ºC/-40 ºC).

To prevent problems resulting from the cold weather conditions, both the lubrication and fuel oil systems should be equipped with pre-warming systems that keep the operating media temperatures at desirable level. During normal operation of the nuclear unit, the central heating system of the unit may be used for warming up the fuel and lubrication oils. In emergency operation, the pre-warming systems could use the heat energy of the exhaust gases to maintain operation.

Contaminants in the lubrication or fuel oil can quickly lead to damage in the engine as the performance of the lubrication oil degrades, when the contaminants change the characteristics of the oil, and the foreign materials in the fuel might affect the combustor or turbine of the engine. For this reason, requirements have to be specified for the filtering that prevents contaminants entering the engine and damaging the engine components or clogging up nozzles etc. The filtering systems should be equipped with monitoring that indicates any arising clogging problems or other difficulties, so the nuclear unit operators can react to them beforehand. To maintain the quality of the fuel and lubrication oils, their condition should also be inspected regularly by sampling. The filtering should include bypassing possibility so that they can be cleaned and exchanged even during operation of the unit.

The filtering and oil quality requirements set in the specifications are similar to the KTA 3702 standard and other diesel requirements as the differences between the engines regarding the fuel are not great. The consumption rates are slightly different with gas turbine using more fuel but requiring less lubrication oil affecting the storage requirements slightly.

5.3.3. Cooling

The use of water and steam for cooling turbine blades are very efficient methods to lower the blade temperature and improve thermal efficiency but their advantages outweigh the disadvantages only in the base-load power generation, preferably in combined cycle power plant applications, where the steam from the waste-heat boiler of the secondary circuit can be used as a coolant.

The more efficient and complicated cooling methods are mainly for engines that are optimized for efficiency and thus have high firing temperatures, which directly leads to higher turbine inlet temperatures. Following the same train of thought, the use of a gas turbine which runs on a thermodynamic cycle including regeneration/recuperation or inter-cooling is also largely impractical in the standby power source application of a gas turbine. As the emergency power unit, the thermal efficiency increase of the process cycle is not the focal point of the design, and the increased complexity only servers to hinder the reliability and availability of the engine.

In the application discussed in this thesis, sufficient cooling of the turbine blades should be achievable by bleed air cooling which simplifies the engine and decreases the amount of components demanding maintenance operations. This also reduces the filtering, monitoring and sampling equipment that would be needed for the quality control of the coolant similar to those of the fuel and lubrication oils.

5.3.4. Intake Air and Exhaust Gas

The gas turbine requires atmospheric air for working fluid and expels it including the combustion products in the exhaust gases. The intake and exhaust systems are thus a vital part of the engine and some requirements need to be set for their design.

The intake air system should be equipped with filtering system to prevent contaminants entering the engine. Clogging of the intake air should be monitored as the pressure loss increase in the intake filter directly decreases the power capacity of the engine as less air is drawn in to the engine. The intake air properties also directly affect the performance of the gas turbine and constant monitoring of the thermal properties of the intake air is important.

The cold weather climate of the installation site of the nuclear unit presents challenges to the design of the air intake duct and filter as the intake duct pressure losses drop the temperature by multiple degrees and may result in ice forming into the duct and the intake filter in right conditions. This could be potentially disastrous as the engine would be deprived from the operating fluid and become unavailable. The potential need of an anti-icing system for the air intake should be carefully evaluated by the AAC facility designer and prove by analysis that the possibility of blocking of the intake air system can be deemed low.

The gas exhaust system removes the exhaust gases from the AAC facility and is also equipped with a silencer to reduce the noise generated by the gas turbine. One major concern is that the intake air system would draw back in the exhaust gases of the engine, which would deprive the engine of combustion air and potentially carry contaminants into the engine that could cause damage in the compressor or other parts of the engine. The problem should be mostly avoided with a simple solution, where the air intake and exhaust outlet are installed sufficiently far from each other.

Gas turbine exhaust gases contain high amounts of heat energy that normally is expelled to the sky. The gas turbine exhaust system should be designed such that the waste heat can be collected and used to heat up the operating fuel tank of the gas turbine during emergency operation. This provides added availability as the AAC unit is not reliant only on the central heating system of the nuclear unit in case of emergency during cold weather.

5.3.5. Energy Supply for Auxiliaries

Many of the auxiliary devices of the AAC facility such as pumps, blowers or actuation devices require electrical power to operate. In emergency operation of the unit, these systems and equipment are powered by the DC batteries that are allocated for them and located nearby the facility.

The DC batteries should always have sufficient capacity for the unit to remain operational for a reasonable time, and the batteries should normally be charged by the engine as it starts operating. The DC battery capacity requirement corresponds with the time requirements that the nuclear unit has to remain self-sufficient in accident conditions such as DEC or SA. The time requirement for DC batteries is usually specified to be the same as DC battery capacity of other safety related DC systems in the nuclear unit, which means a capacity of 8 hours.

5.4. Instrumentation and Control

The control systems and all their instrumentation are naturally critical for the engine function and follow the same system and component classification requirements as other safety systems and components. The classification of the instrumentation and control (I&C) system is based on the nuclear regulations as presented in the YVL B.2 guide. The control systems of the AAC unit should have separate functions for emergency operation (Safety Class 3) and periodic testing operation (Class EYT). According to requirements of the YVL B.2, these separate control functions have to be designed in such way that the Class EYT equipment cannot cause failures in the Safety Class 3 functions.

To achieve the reliability of control functions required by the regulations, the manufacturing, design and operation requirements of the I&C system are controlled by approved standards. For the Safety Class 3 I&C, the approved standards that are: IEC 61508:2010 *"Functional safety of electrical/electronic/programmable electronic safety-related systems"* and IEC 61513:2011 *"Nuclear power plants - Instrumentation and control important to safety - General requirements for systems"* composed by the International Electrotechnical Commission. Following these standards ensures that the I&C functions that are effective during emergency are based on technologies with proven reliability gained from operating experiences in nuclear power plants.

The qualification testing of the I&C systems also has to be assessed by an accredited body with certifications such as EN 45011 "*General requirements for bodies operating product certification systems*" or ISO 17020 "*Conformity assessment -- Requirements for the operation of various types of bodies performing inspection*" and the type tests of the I&C equipment are to be performed by an organization approved according ISO 17025:2005 "*General requirements for the competence of testing and calibration laboratories"*.

The Class EYT non-safety-related control functions of the gas turbine engine effective during non-emergency operation may use more modern instrumentation, monitoring and control concepts. The Class EYT system may thus be more sophisticated and give more accurate readings and in-depth information about the engine. On the other hand the Class EYT control functions they are not considered as reliable as the Safety Class 3 equipment and functions and the standards their designs follow are not as tightly controlled. The Class EYT control functions should follow the generally accepted standards used by the gas turbine industry in non-nuclear applications.

5.4.1. Functional Requirements for Control Systems

Requirements for the functionality of the control systems cover the conditions where the gas turbine is started up and how it is operated. As defined earlier, the safety function of the AAC facility is to provide AC power to the dedicated safety equipment required for DEC and SA conditions, where the main EDGs fail to function. The switch-over from the Class EYT to the Safety Class 3 functions should be automatic when the nuclear unit electrical systems lose connection to the outside AC source.

Depending on the design of the reactor safety functions required in DEC and SA conditions, the start-up time requirement of the AAC gas turbine varies from immediate up to a few hours. The start-up of the engine can be either automatic following the failure of main EDGs or manually activated by an operator from either the main control room (MCR), emergency control room (ECR), or the local control room (LCR). The start-up of the engine in any other conditions should be prevented by the I&C system so that it cannot cause any failures in other safety equipment. The authorization for the use of the LCR is ensured by a high-quality locking system, so that the operation is possible only with an authorization key. The LCR is normally used for testing the gas turbine periodically so the operators in the MCR can concentrate on the nuclear unit handling. The MCR operators should still be able to supervise and control the AAC unit during manual operation from the LCR.

To make the manual start-up of the unit feasible under stressful conditions, the actions required from the operator in the manual start-up sequence of the engine should be limited, and the rest of the operations should be automatic. The I&C systems should also give sufficiently detailed feedback to the operator during the start-up on the progress and completion of commands so any abnormalities can be observed.

After the gas turbine has been started up, the and power loading and operation of the unit should require no manual operator actions for 30 minutes, which is a general requirement for consideration time for the operators in a nuclear unit. This requirement ensures that the operator has sufficient time to think and react to the accident conditions. The control functions should be designed with minimal potential for human error.

Shutdown of the engine should normally only be initiated by a manual operation, after the connection to an off-site AC source is restored by the nuclear unit electrical systems. Engine protective shutdown signals are of course a separate case and will be discussed in Chapter 5.4.3. While not normal operation condition of the AAC gas turbine generator, it should also be able to be synchronized to the external power grid with good reliability without losing power in the emergency power trains.

5.4.2. Performance and Condition Monitoring

Gas turbines are equipped with a performance and condition monitoring system which normally controls the operation of the engine and also shows any process fluctuations to the operator so he can react to them accordingly. The monitoring system also notices if the performance of the engine or the generator is somehow decreasing. Identifying the sources of performance drops in advance is important so that no unexpected loss of performance can occur while in emergency operation of the engine.

The gas turbine and generator performance and condition monitoring is important for the AAC unit safety function, as any gradual wearing in the different component materials can lead to sudden failures further causing performance issues or even complete unavailability of the engine if the damage is severe enough. According to Boyce (2012) condition monitoring systems have become more and more part of the gas turbine designs as a proactive maintenance method that gives early warning of problems instead of fixing the engine only after failures have already occurred. Condition monitoring systems are important from both the cost and safety point-of-views, as increased availability of the engine is desirable in every application.

Vibration measurements are one of the most important aspects of the condition monitoring as any changes in the vibration conditions can quickly lead to component damage due to friction or cyclic stress forces. Vibration measurement device are usually placed to measure either the shaft or the bearings that provide damping against the vibrations. The maximum displacement of the bearings and the shaft are usually the limiting measures used by standards against vibrations as they depict the amplitude of the vibration.

Common examples of monitored process values are: rotation speed, bearing and shaft vibrations, exhaust gas temperature, pressures at different stages of the engine, pressure differentials in filters, operating media temperatures and pressures. The electrical performance of the generator is also monitored. Examples of monitored values of the generator are: rotation speed, active power, voltage and frequency. The final scope of the monitored values is dependent on the gas turbine type and thus left to the supplier.

5.4.3. Engine and Generator Protection

A gas turbine engine and the generator must have sufficient protective equipment initiating immediate shutdown procedures of the engine if any protective limit values are exceeded. Two separate limit values are normally set for the protective measurements: lower limits issues warning for the operator while the higher value initiates shutdown of the engine, which is often called "tripping" the engine. The safety-critical engine protection system uses the monitoring systems of the gas turbines but may be independent of them to ensure the protective shutdown if needed.

The engine protective functions should also be split into two separate groups according to the Safety Classification in YVL B.2 guide as with the rest of the I&C systems. The nuclear safety overrides the engine condition-preserving protections so only those protective systems for signals which would lead quickly, directly to the destruction of the engine should remain functional during emergency power operation of the gas turbine. The protective equipment effective during emergency operation are classified as Safety Class 3 and the equipment protecting the engine during periodic operation are classified as Class EYT. The Class EYT protective equipment include more extensive collection of tripping as their goal is to prolong the life-time of the engine instead of nuclear safety. During emergency operation of the AAC unit, the Class EYT protective alarms signals should be displayed to the operators, and warn of impending problems even if shutdown is not initiated.

To ensure the safety functions are performed, the protective equipment effective during emergency operation (Safety Class 3) should be designed with redundancy to ensure high reliability. Also a preferred design option is that the shutdown is only initiated if multiple separate signals are received. This prevents erroneous signals resulting from faults in the instruments of shutting down the engine. During testing operations, preserving the engine condition is more important, and so only 1 shutdown signal is required from the Class EYT equipment. The source of the problem should be then identified and possible faulty instrumentation replaced. If the engine shutdown is initiated by Class EYT protections, the operators should be able to intervene. On the other hand, if the Safety Class 3 equipment initiate shutdown, the operators should have no possibility to stop the sequence. This measure is taken to ensure operator error may not cause destruction of the engine or cause damage to the AAC facility or the nuclear unit.

The normal mechanical values used by the protective device of the gas turbine generator include for example high rotational speed of the shaft, pressure loss in the lubrication system, compressor surge signs, high exhaust gas temperature, excessive bearing vibration and temperatures. The generator electrical performance that can initiate shutdown include for example: generator differential, reverse power, over-current and excitation failure. The final scope of the alarms and tripping values are decided by the gas turbine supplier but the choices need to be well analyzed and justified.

5.4.4. AAC Unit Facility Protections

In addition to the mechanical protections in the gas turbine and generator, the AAC facility has protections for unit internal events such as fires that could prevent its operation in emergency conditions. Other protections that the facility requires are for the external events such as floods, earthquakes or storms. The facility protections must ensure the AAC unit stays operational after these events.

The fire protections of the unit should be designed in such way that their operation should not lead to long unavailability of the engine. If wet fire protections (such as sprinklers) are used, the mechanical and electrical components inside the facility must be sufficiently protected, so that the AAC unit may be operated after the fire has been extinguished without major maintenance operations. If the fire protection system is instead based on inert gas protections, the facility has to be equipped with alarming device to warn any personnel before they are activated as they deprive oxygen from the facility which is possibly lethal for any personnel remaining inside.

5.5. Gas Turbine Testing

Testing of the gas turbine is important to ensure it functions as intended according to the specified requirements throughout the whole operating range in the worst possible conditions. Suitability and compliance with the requirements must first be confirmed and afterwards the operating condition must be maintained and inspected throughout the intended service life-time of the engine.

The important tests performed at different stages of delivery include: qualification type test, production test, commissioning test and finally periodic functional testing. The most important one of these considering the scope of this thesis is the qualification type test. All testing prior to the handover of the complete nuclear unit to the nuclear licensee is done by the supplier or its subcontractors. An important part of the quality control is that the nuclear authority STUK is permitted to attend these tests upon request to make sure they are done according to approved methods.

5.5.1. Qualification Type Tests

The gas turbine engine type intended to be used as an emergency power supply of a nuclear unit must subjected to a type test, where its performance regarding startup times and startup reliability, power rating, continuous operating stability and power loading capabilities are proven to be as designed. The gas turbine engine is tested on a test bed that simulates the auxiliaries that are not integral to the engine. The main auxiliary systems connected to the engine and naturally the gas turbine itself should be the same that are intended to be used in the actual final AAC facility at the installation site.

The type test is a first step for a gas turbine to be accepted for the application and as such should be the most rigorous of the tests and include a combination of all the harshest conditions (ambient pressure/temperature) that are possible at the installation site. The engine is run with cyclic loads as well as continuous power operation to cover all operating modes. To achieve high reliability, the guidelines of the CS-E standard for aircraft engine type approval are used develop the type test program. The type test program includes testing the capability of the starter systems to start up the engine from SBO and also includes multiple hot starts, where the engine is only just shutdown and also sufficient amount of cold starts. Important feature tested in the type test is also the capability of recovering from a failed start and establishing the duration it takes to drain excess fuel and restart the engine.

The power test portion of the engine type test includes at least a 100 hours of continuous operation which includes shorter periods running on partial loads (25%, 50 %, 75%) to ensure the operation stays stable throughout complete operating range. Also the overloading capability of the engine must be verified with running the engine on 110% rated power for at least the required 1 hour. To simulate sudden power load drops and connections, the engine should also be tested with rapidly changing power loads between maximum power and partial loads.

The maximum number of malfunctions allowed during the test run and the time to re-establish the stable operating of the engine are things that need to be specified. The KTA 3702:2000 standard requires the diesel engine to be unavailable no more than 20 minutes during the whole type test run. Malfunctions caused by external reasons or problems from the test bed are of course exempted from the unavailability time consideration, however, all malfunctions still need to be well documented by the tester for the engine to achieve approval. The CS-E standard (CS-E 740 (b) (1)) for aircraft engine type approval also states that any interrupted testing stages must be repeated unless considered unnecessary. Additionally the complete test may be required to be repeated if the interruptions become excessive.

The type test is considered successful if the gas turbine performance fulfils the requirements concerning output power and stays within given tolerance operating values. The engine is also inspected thoroughly by disassembling it and made sure that no signs of wear or damage are found in any engine components. The nuclear authority STUK assesses the type test records and documentation and decides whether the engine can be classified as Safety Class 3 equipment as intended and be used as an emergency power unit for DEC and SA.

5.5.2. Production Tests

After a successful qualification type test, the gas turbine type may be utilized as a Safety Class 3 device. Production test is a part of the normal quality assurance program required from all safety equipment. The goal is to make sure all the components are manufactured with high quality and perform as intended and shown also by the type test.

The production tests have to be extended on all the safety-critical auxiliary components of the engine to make sure the complete package can be accepted and installed. In the production test of the engine, the performance of and compliance with tolerance requirements are once again verified and documented.

Achieving the desired operating reliability for the whole AAC unit begins from the design and production of each individual component of the engine and the auxiliary systems. The design and manufacturing of all components and systems should be done by organizations with certified quality management programs as required by the YVL regulations. This ensures that the components and systems can be trusted to function in their intended function for the designed life-time.

5.5.3. Commissioning Tests

Commissioning tests are performed on the complete alternative AC unit, which the gas turbine engine is a part of, before the handover of the nuclear unit from the supplier to the purchaser. In the commissioning tests the final proof of functioning of the gas turbine and all the components and systems that perform the safety function are tested. The complete scope of the commissioning test is decided between the supplier and the purchaser of the nuclear unit according to the commissioning plan of the whole nuclear unit and becomes more relevant in later stages. Only the basic scope of the commissioning acceptance test is discussed in the requirements specifications developed in this thesis.

Tests that could be included in the commissioning tests for example are: starting up the engine without external power with the starting systems to prove their function, loading up the generator according to the emergency power load sequencing program and meeting the possible requirements of load acceptance times and variations in the output. The commissioning tests should be sufficiently long to establish that the engine truly performs continuously as intended at the final installation site. The difference to earlier tests is that the AAC facility is connected to the complete nuclear unit I&C systems, so the functions of the complete safety trains such as automatic start-up signaling by reactor protective signals may be tested in the commissioning phase.

5.5.4. Periodic Tests

Testing of the gas turbine engine and the emergency power generating facility at the nuclear power plant site is conducted regularly in order to ensure that the facility is functional and operates as intended. The functional test run is especially important after unavailability of the engine resulting from maintenance operations and especially after a failure of the gas turbine.

The periodic tests are scheduled together with other emergency power facilities so that others remain functional as one is tested. Normally a nuclear unit has two AAC sources and 4 main emergency sources if the *N+1* and *N+2 Criteria*, as specified earlier, are applied to them. The independent Class 3 AAC units should be tested separately and also with sufficient main emergency power sources available for operation.

The testing interval of the AAC units must be specified by the purchaser of the nuclear unit according to the nuclear unit's safety assessment. Similarly to the main emergency diesel generators, normal interval for the test is once per month per engine, which means every 2 weeks one of the AAC facilities is tested. The startup of the gas turbine in periodic tests should normally be manually activated but at least once a year, the test should be performed by realistic signal. Also the overload capacity of the gas turbine must be tested at least once a year to verify it.

The periodic testing programs may, in addition to just testing the function of the engine, include testing of the control systems by initiating the emergency startup of the gas turbine or shutdown by tripping the engine protection signals. Most of the times the startup and shutdown sequences used in the periodic tests should be slow, however, as this significantly extends the life-time of the components that are subject to wear or aging. The Class EYT protective signals, as earlier described, are effective during the periodic testing of the AAC unit. Results of the function test run are recorded so the performance can be compared to earlier tests and the designed performance characteristics.

5.5.5. Inspections on the Operating Media

To maintain the quality of the fuel oil, lubrication oil and possible coolants, they must be inspected periodically. The quality of the fuel to be used in the engine must always be tested and inspected before they are used to refill the storage tank. Additionally the fuel inside the storage tank should be tested at least in yearly intervals. To achieve sufficiently representative samples, the fuel storage tank must be equipped with a mixer and a sampling line. The fuel is tested for viscosity, filterability, water content and other critical properties. If the quality of the fuel is in some way degraded, the fuel should be replaced.

The quality of the lubrication oil used by the engine is also very critical as any contaminants will quickly damage the engine or block filters. The lubrication oil is also tested by taking samples with sufficient intervals determined by the engine supplier. Normally the oil should be sampled after the periodic function test runs of the engine to determine if its quality is somehow changed.

5.6. Maintenance Requirements

The requirements for the maintenance operations are specified as part of the procurement process and the main driving goal for these requirements is to maintain the function of the engine throughout the intended service life-time. The supplier of the unit develops a maintenance schedule and detailed guide how to perform the maintenance operations for the gas turbine according to the safety analysis of the AAC unit and as part of the complete nuclear unit maintenance concept. The maintenance guide supplied with the unit includes specific maintenance schedule that takes into account the testing schedules of other emergency power sources so enough of them remains available for emergency operation.

The maintenance documents provided by the supplier need to be comprehensive to give the nuclear unit operator capability to perform the required maintenance operations on-site with their own personnel. The guide should also give sufficient information about the critical spare parts that are needed at the plant site and their replacement schedules so long times of unavailability are avoided.

5.7. Documentation Requirements

Documentation on the AAC facility provided by the supplier is extremely important in the licensing process of a nuclear power plant as it proves that the design concept follows the requirements of the nuclear regulations and those that are set by the power plant purchaser. The procurement of the complete nuclear unit is a long project and includes many stages, each including various documentation regarding the designs or testing protocols and certifications that need to be submitted by the supplier for review by the nuclear authority and the power unit purchaser.

The AAC unit and the gas turbine are a part of the electrical system of the complete nuclear unit and form a group of safety classified equipment according to the YVL B.2 draft 4 as specified earlier. The requirements specification document demands that the design, fabrication, assembly, maintenance, I&C and testability are ensured with detailed analysis and testing by accredited bodies. The documentation of these analyses and tests are the proof that is submitted for review to the power plant owner and the nuclear authority, which eventually grants the operating license. The required documentation requirements are split for separate systems so that the following systems are covered: AAC facility, gas turbine generator, auxiliary systems, I&C system, testing protocols and operation & maintenance.

The documentation provided of the AAC facility should include a general arrangement drawing of the facility, electrical circuit drawings, component certificates, piping and cabling routing. Additionally the documentation should include analysis of the protections of the facility from internal and external events such as fires, earthquakes and floods. Important quality to prove to fulfil the redundancy principle is the physical and functional separation of the AAC facility from the other AAC sources. The I&C documentation should include detailed analysis of the system boundaries and separation of the control functions during emergency and periodic testing operation.

The documents regarding the gas turbine generator unit should include detailed analysis of performance in different ambient conditions that can be encountered at the installation site and proof that surge and choke conditions are avoided. Also the vibration analysis of the engine should be sufficiently documented so the operators can properly avoid the operating speeds causing destructive vibration conditions. The reliability and availability analyses of the gas turbine should also be well documented. Documentation on the testing procedures for the gas turbine is one of the most important parts in the qualification process for safety classification so much emphasis should be put into it.

Operation and maintenance documentation should include detailed guides how the engine is operated in different conditions and how the maintenance operations are performed. The maintenance guide should include lists of critical parts that need to be stored at the plant site so the engine is kept available as much as possible.

6. CONCLUSIONS

The licensed use of nuclear power plants in Finland is regulated by legislation that defines the general principles that need to be followed in the design and operation of the plant. More detailed technical requirements are set by the nuclear regulations called YVL guides and they define the safety system and equipment classification criteria according to their safety function. Achieving the Safety Classification for mechanical and electrical equipment requires applying approved standards to the design and qualification testing process.

The application of alternative AC source for power supply in accident conditions requires the gas turbine engine to be classified as Safety Class 3. The research problem was that there is no nuclear standard, Finnish or international, that covers the design and testing of a gas turbine engine for the application. The objective of this thesis research was to specify the requirements for the design and testing procedure for a gas turbine intended to be used as nuclear safety equipment. The goal was approached by constructing the requirements specifications document using different standards so that the gas turbine would have sufficient reliability and availability to achieve qualification.

The gas turbine is a flexible engine type suited for many different applications and wide range of power rating. The high-power-rating engines are used as base-load plants in combined cycle processes and smaller gas turbines are excellent for producing peaking power. The gas turbine industry is generally concerned about the increased costs caused by an inefficient engine or the NO_x emissions generated by the engine. This means that most research focus is put into the improvements of efficiency by increasing turbine inlet temperatures and compressor pressure ratios and reducing emission by modifying the combustor. Even though major improvements have been in these fields, they have come with the price of reduced reliability and availability. The safety application of the gas turbine requires much less power and the efficiency of the engine is relatively irrelevant, instead striving for a wide operating range with stable operation in all conditions.

The requirements specifications developed in this study cover the AAC facility layout, the gas turbine, the instrumentation and control, the auxiliary systems, operation and maintenance, testing and inspections and the documentation. Most of these requirements are very similar to emergency power generating facilities using diesel generators and can be incorporated from the KTA 3702:2000 standard; the main difference is the actual gas turbine and its specific auxiliary systems. Special consideration in the requirements was put into the performance of the engine and the supporting systems in the wide range of ambient temperatures present at the installation site of Olkiluoto, Finland.

The qualification of the instrumentation and control systems for Safety Class 3 requires using proven components with redundancy, diversity and separation. This challenges the gas turbine designer to modify the control systems logic so that the system generally used by the gas turbine in other applications is used as Class EYT during the periodic testing procedures, and separate control functions are active during emergency situations. The difference between the control functions is that during emergency, the main focus is performing the safety function for the required duration, while during periodic testing additional engine protections may be active to better preserve the engine condition.

Gas turbine engines are widely used in aircrafts and their reliability requirements and testing procedures to achieve airworthiness certification are extremely strict. Similar reliability for the gas turbine is needed for the safety qualification, so the testing procedures of the aircraft engine were adapted to the emergency power gas turbine type test program. The certification type test includes starting up the engine multiple times from different conditions and running the engine continuously on various loads in a wide range and verifying that the requirements are met regarding the operating tolerance values throughout the test.

The hardest part of the gas turbine qualification process is actually still ahead as no gas turbine engine has been used as nuclear safety classified equipment. Following the design and testing requirements specified as part of this study, I believe that a gas turbine engine type can achieve qualification to be used as Safety Class 3 power source in a Finnish nuclear power plant.

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APPENDIX A: FAILURE DIAGNOSTICS

Table A-1: *Compressor Diagnostics (Boyce 2012)*

	η_c	π	T_2/T_1	$\dot{m}$	Vibration	$T_{Bearing}$	$P_{Bearing}$	$P_{bleed\ chamber}$
Clogged Filter	-	↑	-	↓	-	-	-	-
Surge	↑	↑↓	-	↓	-	↑	↑	↑↓
Fouling	↓	↓	↑	↓	↑	-	-	-
Damaged blade	↓	↓	↑	↓	↑	-	-	↑↓
Bearing failure	-		-		↑	↑	↓	-

Table A-2: *Combustor Diagnostics (Boyce 2012)*

	P_{fuel}	Unevenness of combustion	Exhaust temperature spread	Exhaust temperature
Clogging	↑	↑		↑
Fouling	↑ or ↓	↑	↑	↑
Crossover tube failure	↑ or ↓	-	↑+	-
Detached or cracked liner	↑ or ↓	↑	↑	-

Table A-3: *Turbine Diagnostics (Boyce 2012)*

	η_c	π	T_3/T_4	Vibration	$T_{Bearing}$	$P_{cooling\ air}$	$T_{wheel\ space}$	$P_{Bearing}$
Fouling	↓	-	↓	↑	-	-	↑	-
Damaged blade	↓	-	↓	↑	-	-	-	-
Bowed nozzle	↓	↓	↓	↑	-	-	↑	-
Bearing failure	-	-	-	↑	↑	-	-	↓
Cooling air failure	-	-	-	-	↑	↓	↑	-