Learning from Aeronautics - Materials and Acoustics

New Challenges of Oil & Gas Exploration

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Thesis to obtain the Master of Science Degree in

Aerospace Engineering

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December 2014

Be on your guard; stand firm in the faith; be men of courage; be strong.

Corinthians 16:13

Acknowledgments

To Professor Manuel Valsassina Heitor, who led me throughout this thesis and helped me to open my mind in such different areas of interest, contacts and the fantastic opportunity to work with him.

I would like to thank specially to Engenheiro Rui Pimentel Santos for all the help and ideas during my time at IN+.

To all interviewers I want to leave here a word of gratefulness for their help in this thesis. Specially to the EMEPC ROV coordination team who were an exceptional help during this project.

To the Aerospace Course Coordination, in the person of Professor Fernando Lau, I would like to thank these amazing five years as representative of my colleagues and the support that the coordination gave us throughout these times.

My Friends at Conselho Pedagogico with whom I learned a lot.

I wish to thank all my Friends to whom I will be eternally grateful for supporting me throughout the past years and with whom I'm expecting to count on for the rest of my life.

Last and most importantly, I would like to thank my Family for their never ending support, patience and dedication.

Abstract

The oil and gas industry is under major developments and changes with the discovery of new deep-sea offshore oil and gas repositories in the south Atlantic and the exploration of subsea environments.

This work presents two case studies that evaluate two different concepts developed over the years for aerospace applications that are being used to help to overcome the existing challenges in subsea exploration: underwater acoustics, essentially on data transmission and acoustic positioning, and materials under severe conditions, essentially in terms of the evaluation of ageing and design approaches. Attending to each technology's applications, limitations, technological overview and foresights a discussion is performed, in a risk governance basis.

In the first case the main limitations concern to the range of operability of acoustic equipments. The acoustical positioning systems present, for example, a broad scope of ranges, starting with a few centimetres (less than 10cm) to several kilometres (up to 6km). The frequency bands used can also vary from a few kHz to hundreds kHz though the deeper the frequency can reach, the less accurate the measure is.

For the second case study, composite materials, such as fibre-glass and carbon-fibres, change their mechanical behaviour abruptly showing changes in the Young modulus and tensile and flexural properties after 1 week of exposure to salt water (fibre-glass tested at around 350bar.) Evidence of total degradation of materials (glass and carbon fibres) when exposed do hydrocarbons gases has been observed in literature related to the oil and gas exploration.

The two technologies have been further assessed in terms of their application in an existing ROV operated by the EMEPC, in Portugal (i.e. the ROV Luso). Analysis to the limitations and ranges of operability are presented for the acoustic systems (mainly positioning) and for the existent composite materials.

Keywords

Aerospace; Oil & Gas; Risk Governance; Acoustic communications; Composite Materials; ROV

Resumo

O sector energético está sob grandes desenvolvimentos e mudanças com a descoberta de novos depósitos de petróleo e gás nas áreas do Atlântico Sul e a exploração do ambiente submarino.

Este trabalho apresenta dois casos de estudo que avaliam conceitos tecnológicos desenvolvidos ao longo de anos para aplicações aeronáuticas que são usados para ajudar a ultrapassar os desafios da exploração do mar: acústica submarina, essencialmente em termos de transmissão de dados e posicionamento acústico, e materiais compósitos sob condições severas, essencialmente no estudo dos processos de ”ageing” e ”design approach”. Atendendo aos detalhes de cada tecnologia e limitações, conclusões são retiradas, numa forma de análise de riscos e benefícios.

No primeiro caso a principal limitação é a gama de operabilidade dos equipamentos. Os sistemas de posicionamento acústicos apresentam uma vasta gama de operabilidade desde poucos centímetros (menos de 10cm) até vários quilómetros (até 6km). As bandas de frequência utilizadas também pode variar largamente, notando que com a profundidade pior o desempenho.

Para materiais compósitos, o segundo estudo de caso, como a fibra de vidro e fibra de carbono, o comportamento mecânico mostra mudanças abruptas no módulo de elasticidade e de resistência à tração e propriedades de flexão após 1 semana de exposição à água salgada (fibra de vidro com pressões de 350bar) e evidências de degradação total dos materiais (fibras de vidro e carbono) quando expostos a gases de hidrocarbonetos como se pode observar na literatura relacionada com a exploração de petróleo e gás.

As duas tecnologias são aprofundadas através do estudo efetuado às aplicações existentes no ROV operado pela EMEPC, em Portugal (i.e. o ROV Luso). É feita uma análise às limitações e gamas de operação dos sistemas acústicos presentes (de posicionamento essencialmente) e dos materiais compósitos existentes.

Palavras Chave

Aeroespacial; Oil&Gas; Governança de Risco; Comunicações Acústicas; Materiais Compósitos; ROV

Contents

List of Figures

List of Tables

Abbreviations

ACFM Alternating current field measurement

AUV Autonomous underwater vehicle

BOP Blowout Preventer

CAPEX Capital Expenditure

CCT Composite Coiled Tubing

CLT Classical Laminate Theory

CP Cathodic protection

DVL Doppler Velocity Log

EMEPC Estrutura de Missão para a Extensão da Plataforma Continental

FRP Fibre Reinforced Plastic

FSO Floating, Storage and Offloading

FPSO Floating, Production, Storage and Offloading

GRP Glass Reinforced Plastic

HTHP High Temperature and High Pressure

IRGC International Risk Governance Council

LBL Long baseline

MPI Magnetic particle inspection

MODU Mobile Offshore Drilling Units

NDT Nondestructive testing

OIPG International Observatory of Global Policies for the Sustainable Exploration of Atlantic

OPEX Operational Expenditure

OTC Offshore Technology Conference

ROT Remote operated tool

ROV Remote operated vehicle

SBL Short baseline

SOFAR Sound Fixing And Ranging

UAV Unmanned Air Vehicle

UMV Unmanned Maritime Vehicle

USA United States of America

USBL Ultra Short Baseline

1

Introduction

Contents

1.1 The Context

The aerospace sector has developed, over the years, new goods, services and frameworks that can fulfil consumers' needs and improve the quality of life, not only aerospace related but also in several other industries and sectors. The aerospace industry has introduced many technologies creating and enabling products from the ARPANET (internet predecessor) to improved imaging to breast cancer detection.[1]

The deep sea exploration sector is under continuous change and interested in technology that may help to increase levels of productivity and efficiency and to minimise challenges and risks [2]. The new locations of oil wells on the Brazilian offshore, the pre-salt discoveries, are an example of a challenge that the industry of sea exploration must handle.[3]

The production on offshore locations remounts to the beginnings of the twenty century but the major technological developments only happened when the need to extract the North Sea oil and gas appeared [3]. The experiments in the Mexican Gulf and United States of America (USA) led to the first and the most important, so far, technological jump in this sector (around the sixties). The Brazilian oil and gas industry is far more recent and is now taking its first steps towards new big changes and different perspectives that arise from the need to serve the world's energy demands.[2–4]

One may ask where it can be the connection between the aeronautical sector and the deep-sea offshore oil and gas industry. With the increase of the technological demand in all the sectors worldwide, adapting technology from the aerospace sector is allowing considerable developments in different areas.

The development of technologies in aeronautics, as for example in areas like composite materials, electronics, control systems, numerical analysis methods (aerodynamics, structural, hydrodynamics), communications and several others, as also, working frameworks to deal with the increase uncertainty, are resulting in having better performances and lower costs. These developments are being adapted to other industries like the deep-sea off-shore oil and gas in which technological trajectories [2] there is an exceptional need for radical and innovative solutions.

1.1.1 Towards an International Observatory of Global Policies for the Sustainable Exploration of Atlantic

The identification of vast hydrocarbons resources in the Brazilian pre-salt formation (1.1, [5, 6]) and the technological innovations that led to the rapid increase of shale hydrocarbons resources in the USA, are a sign of change in the world's energy market [7]. The increase supply of hydrocarbons in the North Atlantic (USA and Canada) and in the South Atlantic (Brazil), West Africa (Angola), East Africa (Mozambique) and Caribbean's (potentially Venezuela) diminishes the economic risks of the disruptions in the Middle East oil supply for Europe and the Atlantic nations.[8]

The International Observatory of Global Policies for the Sustainable Exploration of Atlantic (OIPG) has as main goal to promote a cluster in the form of a observatory to stimulate the industry of sea exploration, and all the adjacent businesses and services. New and innovative dynamics are pursuit

for the offshore industry with a view of sustainability to the sector in the South Atlantic and Sub-Saharan Africa [4]. The need for radical innovations (though regulation, essentially in Brazil, has lately diminished this evolutionary pattern [2]) and the already in place clusters that are actively searching for technologies for subsea processing [2] are a contributing factor for the creation of this observatory.

The hydrocarbons resources of the Portuguese speaking countries will play a significant and growing role in reshaping the geopolitics of energy[2, 5, 6]. There is a need for technologies and policies to govern the new offshore discoveries and exploration in such a way to promote the clean, safe and cost effective development of these resources while simultaneously promoting social and economic development across the region.[2, 7, 9] Also of great importance is the technological competition between the supergiant oil fields of the Brazilian pre-salt and the shale resources of North America [10]. The emergence of a technological break-through such as fracking brought new challenges in terms of cost effective development (due to the vulnerability of the crude price, per barrel [7]) making the regulatory frameworks in both countries to have a determinant role in their innovation processes.

New industrialization strategies around the South Atlantic and Sub-Saharan Africa are of significant interest to Latin America, Africa, as well as to Southern European and Mediterranean countries, including Portugal, Spain, Algeria, Tunisia and Morocco. Literature suggests that the process by which countries or regions can develop and foster their industrial structure in a sustainable and responsible way, is to either explore different combinations of the capabilities they already possess, or accumulate new capabilities [8]. Although exogenous shocks may create opportunities to explore different activities, endogenous growth is a complex and time consuming process, very much dependent on the structure and level of infrastructures, incentives and institutions, which are particularly affected by existing regulatory frameworks.[2, 8]

Pilot case studies will be performed in terms of emerging opportunities for the deep-sea off-shore oil and gas supply chain, including subsea technologies (submarine drilling and energy supply; submarine robotics, submarine processing units, among others), the construction of new and specialized platforms support vessels (including and integration of renewable off-shore energy sources), the development of reliable onshore gas exploration processes as well as strategies designed to minimize health, safety and environmental risks across all elements of the these systems [8]. Also a major vector on the investigation will cover the areas of sustainable sea exploration in a moment of the extension of the Portuguese coastal influence in the Atlantic.

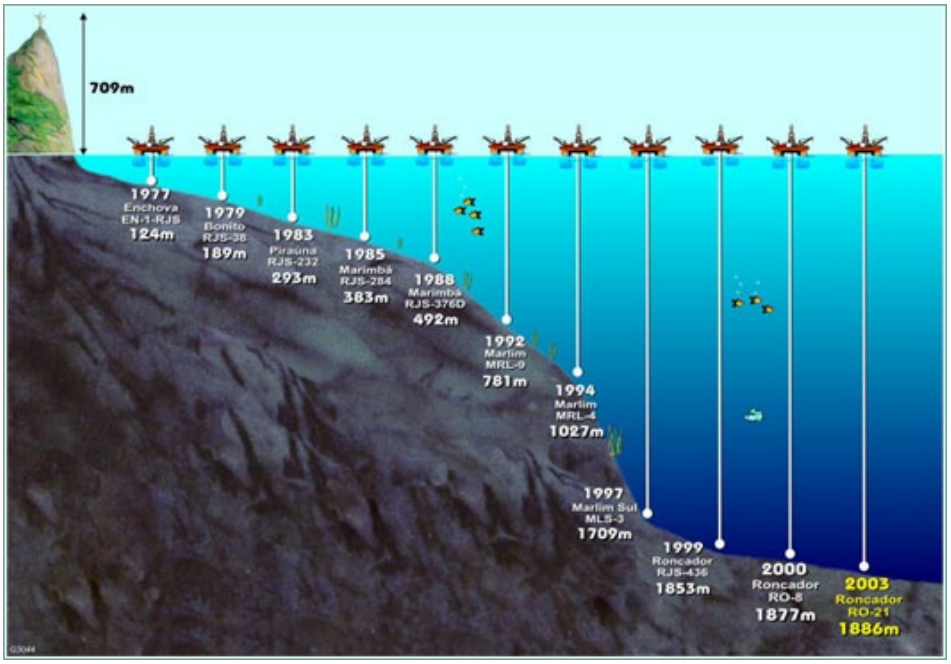

Figure 1.1: Evolution of the depth and distance to land of explored hydrocarbon reservoirs in Brazil, 1977-2003 (source: www.geoexpro.com/articles/2008/04/pioneering-production-from-the-deep-sea - 24th November 2014)

1.2 Motivation

Today's energy sector is involved in major changes mainly due to the appearance and development of new types of technology. These events triggered the exploration of more complex and, even more important, richer areas of our world.

Finding new approaches to problems and situations has become a new challenging matter for science nowadays. Mainly due to the connections between different concepts, technologies and backgrounds, companies from today are continuously searching for innovative concepts to understand, analyse, prevent, solve and manage situations that could not be considered in the past few years.

The discovery of the pre-salt oil reservoirs, and the will of using new offshore production systems, despite its enormous economic potential of this new reserves, brings the number of technological obstacles to be overcome, to a high level.[2, 5, 6] Also the expected battle between the offshore and onshore, as explained earlier, will exponentiate the development of new technological solutions in the foreseeable future.[2]

The motivation for this thesis is therefore to explore the potential for the use of aerospace technology to the deep sea exploration in a way to overcome the foreseeable challenges and allow the sustainable exploration of the sea by:

- presenting two case studies that evaluate two different concepts and their limits of applicability: underwater acoustics and its limitations, mainly driven by the several parameters that limit the transmission: depth, salinity and temperature; and materials under severe conditions (connection with the use of composite materials in aeronautics) essentially in terms of the evaluation of ageing and design approaches, which change accordingly to the behaviour of materials under

these conditions;

- evaluate both on a case study basis, using an extensive bibliographic research, interview methodology and field work, applying the gathered knowledge to a concrete case study of the only remotely operated underwater vehicle used in deep sea activities in Portugal, the Remote operated vehicle (ROV) Luso from the Estrutura de Missão para a Extensão da Plataforma Continental (EMEPC).

1.3 Deep-sea Offshore Oil & Gas Industry's Value Chain

1.3.1 Introduction

The O&G industry includes three main segments: the upstream, the midstream and the downstream. The upstream can be divided into two phases: the first phase consists only in the search and prospection of oil, gas or ores reserves in different terrains. Following this, one has the most technology related segment, in which are developed technologies that allow the extraction of the raw materials. This phase is where the subsea exploration and all the related technology can be found.[11, 12]

The midstream can be defined as the segment of transport and processing of the raw materials and where one can also find some technological challenges as the result of the locations of the extraction stations. The transport is an extreme challenging process and in which several technological innovations can come up, as for example in the pipe construction industry but also in the naval industry.

The final segment, the downstream, is in which the oil processing and refining is done and is presented the final product to the client.

1.3.2 Description of the Upstream Value Chain

The Upstream value chain for offshore exploration (E&P) is divided in smaller segments.

Reservoir Information

This phase consists of the exploration of the subsoil through technology as the reservoir imaging systems and geological/geophysical equipments. Both onshore and offshore, the mappings of the wells are made as also the seismic analysis.[11, 12]

This step is mostly conducted by geologists, using satellite images, who examine the terrain and rocky areas. Small changes in Earth's gravitational field and significant changes in magnetic fields can be indicators of the presence of reservoirs. Still the most widely used technique offshore consists in evaluating the seismic reactions through:

- Compressed-air gun - shoots pulses of air into the water (for exploration over water)
- Explosives - detonated after thrown overboard for exploration over water[11, 12]

These techniques can perceive through the reflection of shock waves with the help of high sensitivity microphones and vibration detectors, the thickness of the various layers of the soil and thus build detailed maps of the subsoil.[11, 12]

Drilling and Casing of Wells

Once chosen the field, and seismic feasibility study has been done, it is time to prepare the site, both physically and legally.

Multiple holes are drilled in the ground so that it is possible to prepare the main hole and it is in this main hole that is possible to introduce the so-called conductor pipe (that will connect to the rest of the production equipment) but remote locations require special attention and equipment.

For example offshore fields need support from specific modules: Mobile Offshore Drilling Units (MODU). These devices can also be further adapted to the production process since the conditions require that the technology readily adapt and become more versatile, given the need for high levels of productivity and efficiency there are four types of MODU: submersible MODU that usually consists of a barge that rests on the sea floor at depths of around 30 to 35 feet; jackups that are rigs that sit on top of a floating barge and can operate in depths of up to 160 meters; drill ships that have a drilling rig on the top deck and can operate in deep water conditions; and semi-submersibles which float on the surface of the ocean and that can be converted from drilling rigs to production rigs, reducing the need for a second rig to take its place once oil is found.[11, 12]

It is launched from the MODU the riser, which is the element that allows the connection between the outside and the bottom of the sea. It is through this element that all fluids move and also the drilling strings, used to drill to the desired reservoir.[11, 12]

On the surface there is the Blowout Preventer (BOP), which allows to control the entire system in case of imminent increase of abnormal pressure that could lead to an uncontrolled explosion.[11, 12]

When the MODU hits the inside of the tank, engineers must seal the well to prepare it for the production phase. Sorts of caps are used to seal the well and is used mud or seawater to provide the pressure to insure the stability of the structure. Upon reaching the predetermined depth, the well is coated with cement, to prevent it from collapsing on it. Then the well is ready for the extraction phase.[11, 12]

Infrastructure, Production and Maintenance

The extraction of products is made through a suction process which is powered by an electrical system that feeds the extraction pumps. In cases where oil is heavy it is necessary to create a second hole for the injection of water, so as to increase the pressure in the reservoir. The latter process is called Enhanced Oil Recovery [11, 12]. The next subsection will show the main equipments used in this phase.

Deactivation

After an analysis of the sustainability of the reservoir, and then concluded the impracticality of it,

is conducted a process of plugging the reservoir. In addition to this is also made a clean sweep of the area, treatment of various natural surroundings and removal of infrastructures. It is required by law to keep a check and monitoring of the field in post abandonment of the well.[11, 12]

1.3.3 Technological Overview

All the above phases include a wide range of technologies. For this work one will focus mainly on the production and support related equipments, essentially regarding the deep-sea production equipments like ROVs and subsea structures.

The new challenges for the exploration of deep-sea reservoirs (Brazilian pre-salt), lead to a new offshore technological paradigm (seabed to shore).[2]

Subsea Production System

A typical subsea production system is generally composed of the submerged well, including the wellhead, the ”christmas tree” underwater, interfaces connecting the drain system, the drain pipelines and risers (flowlines) and also the control systems and operation of the well, including umbilicals that are part of the sub-distribution system.[11, 12]

To the components outlined above one should still add the power supply function, essential for the functioning of the system. The components of the subsea production system are:

- subsea drilling systems (drilling);
- subsea christmas trees and wellhead;
- umbilicals and risers (communication interfaces and subsea flow - topside);
- subsea manifolds and subsea connection systems;
- tie-in and disposal systems;
- control Systems.

It may coexist in the same field several wells. These may be integrated into a structure designated by aggregating physical template or alternatively, forming a cluster and lying individually connected through flow lines to a common structure (the manifold). In both cases, transport of raw materials to the surface is performed by larger flowlines (risers) discharging into the floating platforms Floating, Storage and Offloading (FSO) or Floating, Production, Storage and Offloading (FPSO). These floating structures may have additional capacity for processing hydrocarbons. Disposal of products can also be made directly to onshore facilities (seabed to beach logic).

This new paradigm of subsea development brings three main technological trajectories [2]: continuity, characterized by the use of wet completion system, flexible risers and FPSO or semisubmersibles platforms; intermediary, to start the use of platforms operated with dry completion, such as tension-leg platforms using rigid risers; and subsea to beach, radical innovations, such as multiphase pumping and laser drilling that would enable the elimination of platforms.

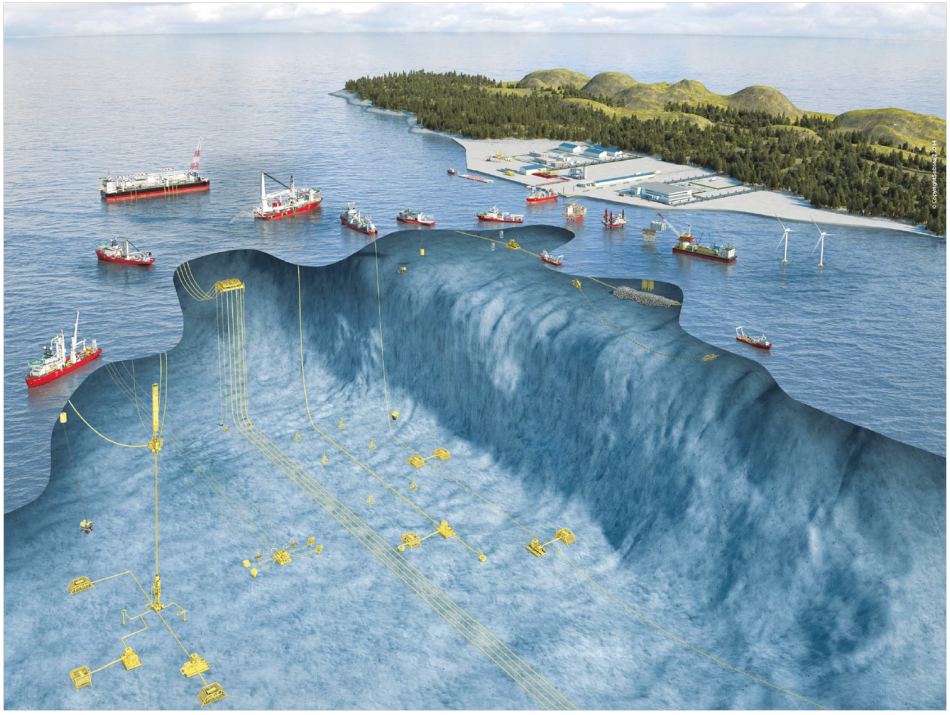

Figure 1.2: Composition of a Subsea Field and all the support logistics and naval equipments (Source: www.subsea7.com/en/what-we-do/explore-subsea-7.html - 25th November 2014)

1.4 Research Problem and Thesis's Outline

This thesis aims to identify two specific aerospace technologies, acoustical communications and composite materials, gather knowledge on concepts and limits of operations in order to understand how they are helping the deep-sea offshore oil and gas industry in this new paradigm of challenges.

The thesis is elaborated in a case study basis. After presenting the context, motivation and an introduction to the offshore oil and gas sector - value chain and technology overview - one decided to select two specific case studies, from aerospace technology already in use in the deep-sea offshore oil and gas industry, for a technological review and understanding of applicability limits: acoustic communications and composite materials under severe conditions.

For the underwater acoustics one decided to focus on the ranges of applicability and operation of underwater positioning systems and communications. For materials are specified characteristics like ageing and design approach under extreme conditions, presenting also the limits of applicability of such materials to the deep sea. For both cases are also appointed applications and possible further connections to the aeronautical sector.

The two case studies were studied with an extensive literature review on the topic and a careful analysis to the potential, risks and connection to the aerospace industry. Some recommendations will be drawn in order to develop those technologies following and integrative design approach.

The field work, presented in the last chapter, integrates the knowledge gathered in the other chapters and makes possible to understand the challenges pointed out in both cases and the limitations of these technologies with the help of the ROV Luso, along with the discussion and further work.

2

Research Methodology

Contents

2.1 Case Study Definition

The case studies' analysed in the next chapters follow an extensive literature review and interviews to experts in academia, scientific institutions and industry. The conversations with the experts followed a guideline presented in the annexes (along with the list of interviewed personalities A).

The selection of the case studies and the process of inducting theory using these cases follows a framework already tested and validated [13, 14].

The process for working case studies has several steps: defining the research questions, specify the population in case, select more than one data collection methods, have multiple investigators to combine different data, overlap data and opportunistic data collection, analysing data, comparison with conflicting literature and reaching closure.[13]

Case studies may involve multiple cases and numerous levels of analysis, for example literature review, interviews and field work. [15, 16]

This technique of creating new theories with case study basis has a great success on generating novel theory by juxtaposition and by reconciliation of different types of data [13]. Though many say that this technique is tendentiously to corroborate with the investigator's preconceptions, it is just the opposite. The only negative possibility comes from the staggering volume of rich data that can lead the investigator to try to "capture everything" [13].

This theory is applied to science when there is enough data to overlap and to get to real conclusions. All the theory must then be evaluated, parsimonious, testable and logically coherent [17].

After the selection of the case studies and the gathering of extensive data from literature and interviews one entered a phase of conclusions, following a framework of risk governance that consists on the selection of the major benefits, risks and principal recommendations (benefits/risks analysis).

Technology foresight analysis has no direct effect on the methodology of this thesis but is worth mentioning as the criteria to choose future options for the deep-sea offshore oil and gas industry, and also aeronautical, regarding the information already available, must follow a correct thought methodology. The term "foresight" has been used to describe how to deal with long-term issues essentially in new policy tools to deal with problems in science, technology and/or innovation systems. While a few tools and techniques have been developed, they represent an unprecedented diffusion of forecasting, planning and participatory approaches to long-term issues.[18]

The strategic importance of technology is to deliver value and competitive advantages to the companies and to the industrial networks in which they operate. These issues are becoming more critical as the cost, complexity and rate of technology change increases, and competition and sources of technology globalize. The management of technology must ensure that exists technological potential to solve the needs, now and in the future of a company and sector, in addition, the impact of changes in technology needs to be assessed, in terms of potential threats and opportunities, including disruptive technologies.[19]

In order to survive in a disruptive market, with an increasing need to develop disruptive technologies to overcome the challenges, there is a need to see the technology as a set of several subsystems,

each of them has its own path of innovation.[19]

There are several ways to evaluate whether a technology may or may not have a positive impact to solve the existing challenges, like technology roadmapping, which represents a powerful technique for supporting technology management and planning, especially for exploring and communicating the dynamic linkages between technological resources, organizational objectives and the changing environment [19]. The work here presented tries to be a part of that process on both case studies as one evaluates the limitations and risks of use of such technology in the exploration of deep sea. Essentially, the governance of risks and the benefits/risks analysis here performed for each case study, will allow to support a technological trajectory that has as focus innovation.

2.2 Risk Governance

2.2.1 Introduction

The aim of a risk governance analysis and framework is to help experts and academia, in various countries and different context conditions, to design policies, regulatory frameworks and industrial strategies to maximize the benefits of a technology improvement and a new design approach to the deep-sea offshore oil and gas industry, regarding the know-how provided by the evolution in the aerospace sector and the development of disruptive technology with an aeronautical insight basis.

2.2.2 Definitions

To analyse the risks of projecting totally different technologies for the deep off-shore oil and gas industry and adapting the know-how gained in the aerospace industry, not only in the mentioned areas, but also as an integrative research approach on engineering design under uncertainty and development of disruptive technology that may help to overcome the new challenges, it is important to acknowledge the existence of risks and so work on measures to understand, prevent and solve them. For this, each case study on this thesis, concludes with a very focused observation on the limitations and risks for each technology.

Before starting to explain the framework used in this work let one just clarify some of the definitions and key-words used throughout this next chapter:

Risk is an uncertain (generally adverse) consequence of an event or activity with respect to something that humans value. Risks are often accompanied by opportunities.[20]

Systemic Risks are embedded in the larger context of societal, financial and economic consequences and are the intersection between natural events, economic, social and technological developments e policy-driven actions. Such risks are not confined to national borders; they cannot be managed through the actions of a single sector; they require a robust governance approach if they are to be adequately managed. The governance of systemic risks requires cohesion between countries and the inclusion within the process of governments, industry, academia and civil society.[21]

Governance refers to the actions, processes, traditions and institutions by which authority is exercised and decisions are taken and implemented.[20]

Risk Governance is defined as the identification, assessment, management and communication of risks. Deals with the identification, assessment, management and communication of risks in a broad context. It includes the totality of actors, rules, conventions, processes and mechanisms and is concerned with how relevant risk information is collected, analysed and communicated, and how management decisions are taken. It applies the principles of good governance that include transparency, effectiveness and efficiency, accountability, strategic focus, sustainability, equity and fairness, respect for the rule of law and the need for the chosen solution to be politically and legally feasible as well as ethically and publicly acceptable. Risk accompanies change. It is a permanent and important part of life and the willingness and capacity to take and accept risk is crucial for achieving economic development and introducing new technologies. Many risks, and in particular those arising from emerging technologies, are accompanied by potential benefits and opportunities.[20]

Complexity refers to difficulties in identifying and quantifying casual links between a multitude of potential causal agents and specific observed effects. Complex Systems are by definition composed of many parts that interact with and adapt to each other.[20]

Uncertainty refers to a lack of clarity or quality of the scientific or technical data. Ambiguity results from divergent or contested perspectives on the justification, severity or wider meanings associated with a given threat.[20]

2.2.3 International Risk Governance Council Framework

In the attempt to prevent inequitable distribution of risks and benefits between countries, organisations and social groups, differing approaches to assessing and managing the same risk, excessive focus on high profile risks, to the neglect of higher probability but lower profile risks, inadequate consideration of risk trade-offs, failure to understand secondary effects and linkages between issues, cost inefficient regulations, decisions that take inappropriate account of public perception and loss of public trust, risk governance must ensure a comprehensive approach comprising:

- Pre-assessment;
- Appraisal;
- Characterisation and evaluation;
- Management;
- Communication.

These general categories, when interconnected and correctly applied to the different problems, provide a thorough understanding of a risk and options to deal with them.

The main challenge on managing risks, apart from adequate and adapt the existing frameworks, is that even in knowledge deficit situations, decisions must be made and action may be needed. In today's complex, uncertain and ambiguous scenarios the main way for action depends on the early detection and evaluation of potential risks.

Risk handling is not just about risk management. Earlier phases of pre-assessment can emerge essential aspects of the coming risks, particularly in assessing the systems that make up or surround the complex schemes one is dealing with.

This early stage cannot be started without a careful characterisation of risks, whether they arise from natural, technological, environmental or economic causes, in terms of their simplicity, complexity, uncertainty and/or ambiguity. Also other aspects are: the degree of novelty, the scope, the range, the time horizon, the type of hazard, the delay and the possible rapidity of introduction. [20, 22]

Another necessary aspect before entering in the problem solving reality is the awareness about if the risks will be or won't be accepted by all stakeholders (by evaluating their reactions as for example in interviews). This topic relates to the risk culture presented in people's minds and may influence the use of different methods, essentially in management and communication stages.

The risk appraisal develops and synthesis the knowledge base for the decision on whether or not the risk should be taken and, if so, how can it be reduced or contained. This stage is the most significant for all the technology related risks, as scientific risk assessment and concern assessment are accounted. Scientific risk assessment constituents [20, 22]:

- What are the potential damages or adverse effects?
- What is the probability of occurrence?
- How ubiquitous could the damage be? How persistent? Can it be reversed?
- How clearly can cause-effect relationships be established?
- What scientific, technical and analytical approaches, knowledge and expertise should be used to better assess these impacts?
- What are the primary and secondary benefits, opportunities and potential adverse effects?

Concern assessment constituents [20, 22]:

- What are the public's concerns and perceptions?
- What is the social response to the risk? Is there the possibility of political mobilisation or potential conflict?
- What role are existing institutions, governance structures and the media playing in defining public concerns?
- Are risk managers likely to face controversial responses arising from differences in stakeholders objectives and values, or from inequities in the distributions of benefits and risks?

The need to justify the options taken throughout the management of risks makes the characterization and evaluation an essential step to deal with. Combine scientific and societal facts is of great importance when judgemental decisions are made, like when considering a risk as acceptable, tolerable or intolerable.

The forth step is the management of risks itself. After the definition of risks as tolerable and acceptable, appropriate and adequate risk management must be made. This phase is defined by questions like [20, 22]:

- Who is, or should be, responsible for decisions within the context of the risk and its management?
- Have they accepted this responsibility?
- What management options could be chosen (technological, regulatory, institutional, educational, compensation, etc.)?
- How are these options evaluated and prioritised?
- Is there an appropriate level of international cooperation and harmonisation for global or transboundary risks?
- What are the secondary impacts of particular risk reduction options?
- What potential trade-offs between risks, benefits and risk reduction measures may arise?
- What measures are needed to ensure effectiveness in the long term?

At last the communication is of utmost importance. Here one can entirely comprehend the extension of risks and the roles of each figurine in the environment. This step is the one that creates and establishes trust in risk management, as it allows people to make informed choices and stimulates their own responsibilities.

In a conclusion basis, the presented framework sets as the most important factor the existence and quality of knowledge. The appearance of more complex, uncertain and/or ambiguous systems requires, as said, different approaches to risk evaluation.[22–25]

The approach here presented allows the emphasis on conveying systematic knowledge, assuring transparency and thinking in complex systems and collecting relevant experiential and practical knowledge. The integration among and between several risk domains (natural hazards, technological risks, chemical and biological risks), among different actor groups (academia and industry) and of theory and practice, permits an integrated and interdisciplinary approach to the sectors and themes ensuring quality on identifying and managing the risks.[22]

The framework stresses the broader social, institutional, political and economic contexts that must be taken into account in risk-related decision-making. The figure 2.1 shows the connections between all the mentioned categories and enhances the need to pay attention to all phases in a risk analysis study.

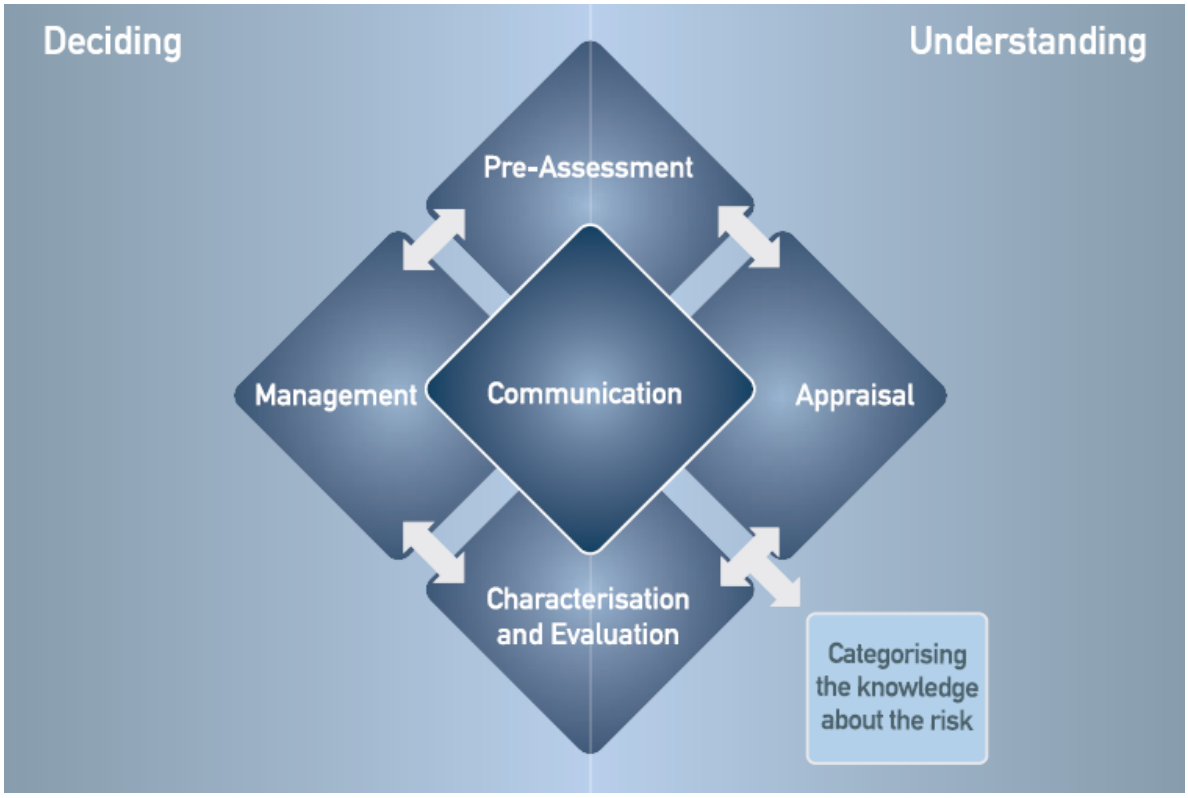

Figure 2.1: IRGC Framework considering the five areas of action in risk governance (source: [20])

When referring to technology-related risks one must understand the existence of three major categories of that are worth mention [20, 22]:

- Risks with Uncertain Impacts - uncertainty associated with technology and science innovation;
- Risks with Systemic Impacts;
- Risks with Unexpected Impacts

Complexity of the new technological systems can encompass and/or influence many of the International Risk Governance Council (IRGC) risk factors as: scientific unknowns, loss of safety margins, positive feedback, varying susceptibilities to risk, conflicts of interests, values and science, social dynamics, technological advances, temporal complications, communication, information asymmetries, perverse incentives, malicious motives and acts. [20, 22]

2.3 Risks in the Deep-sea Offshore Oil & Gas Industry

Before continuing for the two case studies that were taken into account let one just start by evaluating the global risks in the deep-sea offshore oil and gas sector. As in any other assessment the pros and cons of the entire situation must be taken into account.

The analysis to the risks and the major concerns of the industry, experts and academics is of great importance. This is an essential part of the development of state of the art areas, as the industry must be continually changing and adapting to new and demanding challenges with disruptive technology.

The methodology by the IRGC is then important to gather vital information to overcome, analyse, govern and manage all the possible events, creating some knowledge on the uncertainty.

This framework, and the questions written above, are going to be applied to each case study. This section is just an example in order to frame the rest of analysis that is going to be formulated ahead (next two chapters).

2.3.1 Benefits

The energy sector is under major transformations meaning that this industry must develop itself in order to correspond to the energy demand of the world and to be within the strict ambient regulations. Also, higher energetic standards mean better performances, not only for the deep-sea offshore oil and gas sector but also to several others.

Multiple benefits from an agenda of R&D for the deep-sea offshore oil and gas sector can be seen as for example:

- Provide affordable energy to businesses and consumers in the industrial, residential and transportation sectors;
- Create direct and indirect employment and economic prosperity;
- Contribute to a country's energy security by lowering dependence on imported energy;
- Provide a basis for a new export industry;
- Provide a backup energy source to solar and wind renewable;
- Enhance the competitiveness of a country's manufacturing sector, especially subsectors (e.g. chemicals, steel, plastic and forest products);
- Provide a development of R&D agendas in other industries (by using a majority of the state of the art technology and modular technology which decreases the costs of maintenance);
- Attract new players and so more investments;
- Development the scientific community by creating relations and partnerships between industries and academia, in order to further develop new technologies and better frameworks and methodologies;
- Reduction of the Capital Expenditure (CAPEX) and the Operational Expenditure (OPEX);
- Increase production from wells (by the proximity of equipments);
- Reduction of harmful emissions;
- Temperature stability;
- The possibility to control all the production system from the coast, reducing costs.

These benefits are just some examples of the results of an agenda for the technological and industrial development that can result from an investment in new ways and different techniques to explore the offshore oil and gas reserves, essentially in under-development countries (Brazil, Angola and Mozambique) that may create bases for a solid development and solution of existent problems. These benefits are a sum of what experts pointed for several other sectors, technologies and situations in general, but that are applicable to this context [26, 27].

2.3.2 Risks

The need to develop new technology, that will allow the reduction of risks, must be followed by the detection of actual risk situations. Also the development of these new technologies will bring to the equation several new other risks and variables that must be added to the actual panorama.

External Risks:

- Pirate actions;
- Ciber-attacks;
- Natural catastrophes - Katrina; Fukushima nuclear accident;

Production Risks:

- Detection of dangerous situations in the operations - industry catastrophic accidents (e.g. offshore oil spills) and public image;
- Geologic instabilities;
- Control with deep waters systems;
- Reduction of costs;
- Communications;

Regulatory and other Risks:

- New regulations and goals set for the emission of harming elements;
- Strict regulations in the admission of new technology and safety guidelines;
- Corruption in countries with lower education levels.
- Degradation of local air quality and water resources;
- Consumption of potentially scarce water supplies;
- Ecosystem damage;
- Community stress and economic instability;
- Induced seismic events;

- Exacerbation of global climate change by triggering more emissions;
- Slowing the rate of investment in more sustainable energy systems.

The risks presented were divided in different groups so that one can understand that the responsibilities vary from player to player: companies, governments, public society, regulatory agencies, international agencies and safety and security agencies (national and international).

2.3.3 Managing Risks and Recommendations

In order to prevent these great majority of risks the most important aspect to have into account is that this industry must set high levels of research and development. This will allow the industry to have a positive contribute to different others sectors and be always ahead of the challenges.

1. Countries considering developing technology and exploration at very deep waters should establish estimates of their technically and economically recoverable reserves and revise such estimates.

2. Policies to expand exploration to different locations should be implemented in ways that are consistent with global and national environmental goals (e.g. climate protection policies designed to slow the pace of climate change).

3. If a country envisions a major commitment to oil and gas exploration, government and industry should expect to make a sustained investment in the associated capabilities (e.g. workforce, technology, infrastructure and communications) that are required for success.

4. A regulatory system to effectively govern the new changes in production, including necessary permitting fees to support required regulatory activities, should be established, with meticulous attention to the principles of sound science, data quality, transparency and opportunity for local community and stakeholder participation.

5. Baseline conditions of some critical metrics should be measured and monitored to detect any adverse changes (e.g. changes to water supply and quality) resulting from development.

6. Since effective risk management at sites is feasible, companies should adhere to best industry practices and strive to develop a strong safety culture, which includes sustained commitment to worker safety, community health and environmental protection.[22–27]

The next table makes a small comparative study between three cases. Two of them already analysed by an IRGC report and the ”New Challenges Deep-sea Off-shore Oil and Gas” case study follows the result of the interviews with specialists and compares the risks with the other two cases. For the third case study one adapts some of the risks and benefits from the other two cases attending the results from the interviews and the literature review.

The main conclusion of this analysis is that without a high level of development and research the risks found will not be overcome, specially for the third case study.

Some of those new challenges will be addressed in the next two chapters presenting technological and future applications that may help the development of the deep-sea offshore industry in terms of acoustics and composites.

Unconventional Gas Development [26]	Maritime Global Critical Infraestructure [28]	New Challenges Deep-sea Off-shore Oil and Gas
Degradation of local air quality and water resources;	An explosion in an industrial area of refineries and petrochemical facilities in the Singapore Strait;	New regulations and goals set for the emission of harming elements;
Consumption of potentially scarce water supplies;	A cyber-attack on marine electronic systems in the Straits;	Cyber-attacks;
Habitat fragmentation and ecosystem damage;	Collisions in the Singapore Strait and in the Port of Singapore.	Natural catastrophes;
Community stress and economic instability;		Detection of dangerous situations in the operations - industry catastrophic accidents (e.g. offshore oil spills) and public image;
Induced seismic events;		Geologic instabilities;
Exacerbation of global climate change by triggering more emissions of methane, which is a potent, climate-changing gas;		Exacerbation of global climate change by triggering more emissions;
Slowing the rate of investment in more sustainable energy systems.		Reduction of costs;
		Communications;
		Pirate actions;
		Strict regulations in the admission of new technology and safety guidelines;
		Corruption in countries with lower education levels;
		Degradation of local air quality and water resources;
		Consumption of potentially scarce water supplies;
		Ecosystem damage;
		Induced seismic events;
		Control with deep waters systems;
		Slowing the rate of investment in more sustainable energy systems.

Table 2.1: Summary of Deep-sea Off-shore Oil and Gas risks compared to two different case studies

3

Underwater Acoustics

Contents

3.1 Introduction

As field developments move into deep water, numerous subsea intervention tasks have been assumed by non-human resources. Complemented by the new developments in the aerial autonomous vehicles industry (Unmanned Air Vehicle (UAV)s) and autonomous maritime vehicles (ROVs and Unmanned Maritime Vehicle (UMV)s), the new offshore oil and gas industry has at its disposal several new opportunities to solve emerging challenges.

There are several aspects to discuss in order to understand the use, the implications and the limitations of these technologies. The main focus of this chapter is to explain the underwater acoustical systems, understand their limits of operability and present some applications. The intend is also to grow a connection between the use of aeronautical systems to continue helping to solve some of the challenges and existing risks.

There are several autonomous vehicles, and others of support (buoys and platforms), that can be programmed to create "human-free" environments. The next figure 3.1 shows a possible combination of several elements (UAVs, AUVs, sensors and buoys) that communicate between them and may be used for different applications (from [29]).

The next section will address an explanation on how these communications are made and applications and limitations of operability and range. After that one will present briefly the ROV, concluding with a risk/benefit analysis.

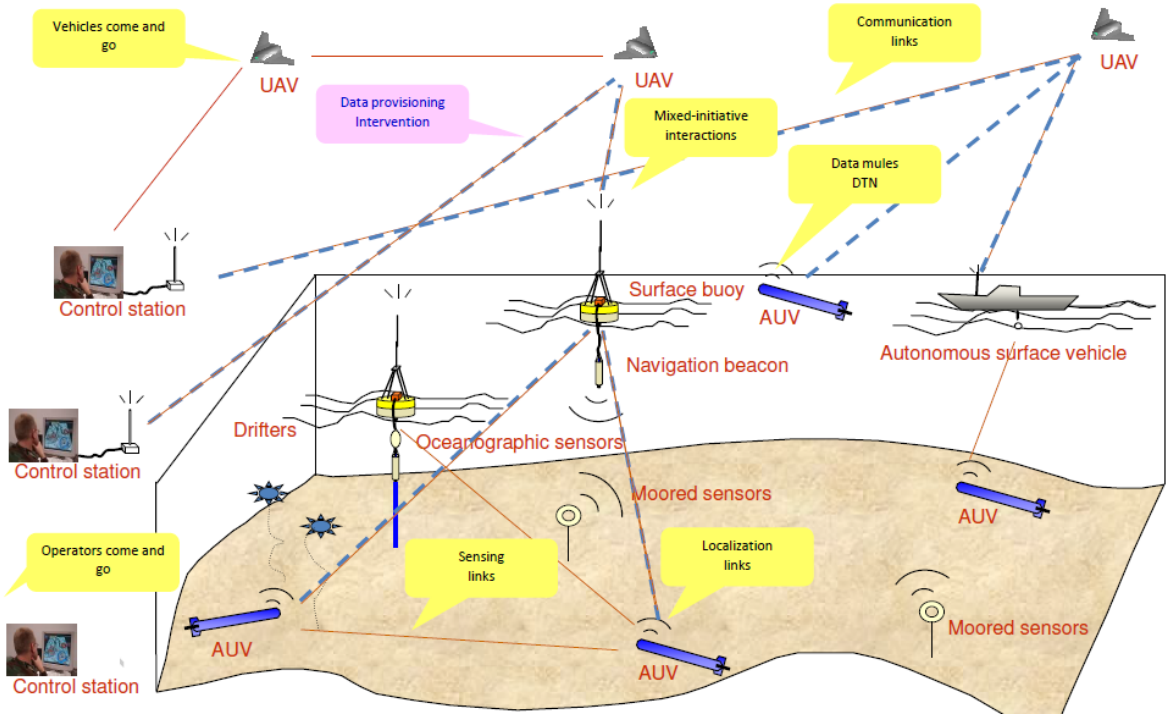

Figure 3.1: Network Vehicle System Concept - integration of multiple autonomous systems in marine environments (source: [29])

3.2 Underwater Acoustical Systems

3.2.1 Introduction

A large portion of Earth is inaccessible to electromagnetic waves, the underwater is one of the environments where that is true. Water, especially salt water, exhibits strong conductivity, meaning a higher degree of dissipation. This dissipation translates in an attenuation of the electromagnetic waves rapidly, limiting their use and range.[30] Acoustic waves are the most used way to transport information and data in the underwater environment.

The acoustic waves are mechanical vibrations of the medium and can propagate very easily in sea water, which makes them the only available option to communicate in this medium, contrarily to electromagnetic and light waves.

The aeronautical sector uses this mean of communication for years (sonar per example) and proved the quality and effectiveness of this technology, though is not responsible for the greatest technological jump in this area so far. The need to overcome the challenges of deep waters exploration leads to the need of developing a technological trajectory that will allow the offshore oil and gas sector to use this mean of communication in this new high demanding environment.

The propagation speed, less attenuation and better ranges (as one can see that underwater the ranges go up to thousands of kilometres against a few in aerial conditions) are some of the examples in which this mean of communication is proved to be the best solution for communication in deep-sea water, though the limitations one will refer after in this chapter.

There are available several solutions and applications that utilize the acoustic waves:

- Detect and locate obstacles and targets;
- Measure different characteristics;
- Transmit signals.

These systems may be considered active or passive, according to the need to transmit a characteristic signal or only intercept and receive sounds, respectively.[31]

3.2.2 Acoustic Wave Propagation

The acoustic wave is the propagation of mechanical perturbations. Compressions and dilations of the air are passed from point to point in space due to the elastic properties of air.

An acoustic wave needs an elastic mean to propagate, for example a gas, liquid or solid environment. The properties of the medium influence the properties of the waves, essentially their velocity.

The acoustic wave is mostly characterised by its amplitude, particle velocity (not the wave propagation velocity) and its acoustic pressure. The last is the essential characteristic of sound and is the property most used when studying and/or applying sound to technology.

Before presenting the applications, one is going to expose the fundamental properties and characteristics of acoustic waves (velocity, frequency and wavelength, wave equation, intensity and power).

The velocity of the sound wave depends on the medium properties: density (ρ) and elasticity modulus (E):

$$c = \sqrt{\frac{E}{\rho}} \tag{3.1}$$

It is important to mention that the velocity of sound in sea water varies between 1.450 m/s and 1.550 m/s depending on the pressure, salinity and temperature. These constraints are of extreme importance when referred to the deep-sea offshore oil and gas sector, as the new challenges account for different pressures, temperatures and salinity of water.[31–33]

Acoustic signals maintain a vibration mode that can be characterised by its frequency, f (and period, T, the inverse). The wavelength is the spatial interval between two points in the same vibration (phase shift equal to 2π).

$$\lambda = cT = \frac{c}{f} \tag{3.2}$$

The values for both frequency and wavelength can vary a lot and it depends on the characteristics of the medium, which influence the different physical processes behind the acoustic wave properties. The main constraints on the frequencies are:

- Dampening of sound waves in water (effect increases with frequency);
- Size of sound sources (increases with lower frequencies);
- Difficult selection of directivity of the acoustic sources and receivers (improving with frequency);
- Acoustic response of the target (comparison between the target size with the wavelength).

All these last mentioned situations must be carefully thought when selecting the appropriate frequency for each application.

Application	**Frequency (kHz)**	**Maximum Range (km)**
Multibeam sounders	10 to ≈ 200	10 to ≈ 0,8
Sidescan sonars	≈ 8 to ≈ 800	≈ 20 to ≈ 0,5
Transmission and positioning	10 to ≈ 80	10 to ≈ 2
Active military sonars	≈ 0,8 to ≈ 20 and 100 to 1000	≈ 200 to ≈ 8 and 1 to 0,1
Passive military sonars	Very low (≈ 0) to 10	10 to very high (over 1000)
Fishery echo sounders and sonars	≈ 20 to ≈ 200	≈ 8 to ≈ 0,8
Acoustic Doppler current profilers	≈ 0,05 to ≈ 0,8	≈ 3000 to ≈ 200
Sediment profilers	1 to 10	100 to 10
Seismics	Very low (≈ 0) to 1	Very high (over 1000) to 100

Table 3.1: Frequency ranges of main underwater acoustic systems and magnitude of maximum usable ranges [31]

The propagation of acoustic waves follows Helmholtz equation:

$$\Delta p = \frac{\delta^2 p}{\delta x^2} + \frac{\delta^2 p}{\delta y^2} + \frac{\delta^2 p}{\delta z^2} = \frac{1}{c^2(x,y,z)} \cdot \frac{\delta^2 p}{\delta t^2} \tag{3.3}$$

The last equation considers p, the pressure of the wave; (x,y,z), the space where it propagates; t, time; c(x,y,z), the velocity of the wave. (Just to clarify, Δ, is the Laplacian operator).

From this equation several solutions may be seen. Plane waves, associated to a single Cartesian space coordinate, are the most commonly used in order to simplify the solution. The next equation shows the solution for a plane wave propagating in the x direction, in which $\omega = 2\pi f_0$:

$$\frac{\delta p}{\delta x} = -\rho \frac{\delta v}{\delta t} \rightarrow p_0 = \rho c v_0 = \rho c \omega a_0 \tag{3.4}$$

The product of ρc is known as the characteristic impedance of the medium. It has as unit the Rayleigh and for a medium like water the value for this property is around 1.5 x 10^6 rayl, high-impedance thus a high acoustic pressure level.[31]

The sound wave transports acoustic energy, which can be divided into the kinetic part, movement, and the potential part, work done by the elastic pressure forces. The intensity of these waves, I, represents the mean value of the energy flux by unit of surface and time (for a wave with amplitude of p_0.):

$$I = \frac{p_0^2}{2\rho c}(Watt/m^2) \tag{3.5}$$

The power of a same wave, P, results from the last equation multiplied by the surface, S:

$$P = I \times S = \frac{p_0^2 S}{2\rho c}(Watt) \tag{3.6}$$

The intensity and power of an acoustic wave may vary a lot. Depending on the application and/or medium one can observe acoustics' power ranging from kilowatts to milliwatts.

Acoustic waves when propagating, lose intensity due to the divergence effect (geometric related) and absorption of the acoustic energy. This loss is a major factor when selecting the amplitude of the signals and constraints the receiver performance.[31–33]

The divergence effect can be explained like this: a sound source will spread the transmitted energy on larger and larger surfaces, hence with the conservation of energy, the intensity will decrease proportionally do the inverse of the surface:

$$\frac{I_2}{I_1} = \frac{S_1}{S_2} = \left(\frac{4\pi R_1}{4\pi R_2}\right)^2 = \left(\frac{R_1}{R_2}\right)^2 \tag{3.7}$$

The relation between the intensity of two points in a sphere, with two different radiuses, is proportional to the inverse of the ratio between the surfaces of the spheres at that radius.

In the case of propagation of acoustic waves in sea water one must add the dissipative action of the salt. Part of the energy is absorbed and dissipated through viscosity and chemical reactions. The acoustic pressure decreases with the distance adding more spreading losses:

$$p(R,t) = p_0 \exp(-\gamma R) = \frac{\exp(2j\pi f_0(t - \frac{R}{c}))}{R} \tag{3.8}$$

The attenuation is quantified by the parameter γ (Neper/m). This parameter is usually inserted in another one called the attenuation coefficient, α:

$$\alpha = 20\gamma log(e) \approx 8,686\gamma \tag{3.9}$$

The attenuation is the most limiting factor in acoustic propagation and, in sea water, it essentially comes from the viscosity of pure water, the relaxation of magnesium sulphate molecules above 100 kHz and the relaxation of boric acid molecules above 1 kHz.[31]

There are several models to deal with the absorption coefficient but the most recent ones are under the following form:

$$\alpha = C_1 \frac{f_1 f^2}{f_1^2 + f^2} + C_2 \frac{f_2 f^2}{f_2^2 + f^2} + C_3 f^2 \tag{3.10}$$

The most used model is the Francois-Garrison in which α is estimated regarding the depth, z, salinity, S, temperature, T, and the frequency, f:

$$\alpha = A_1 P_1 \frac{f_1 f^2}{f_1^2 + f^2} + A_2 P_2 \frac{f_2 f^2}{f_2^2 + f^2} + A_3 P_3 f^2 \tag{3.11}$$

In which the contribution of boric acid is accounted in A_1, P_1 and f_1; the contribution of magnesium sulphate is accounted in A_2, P_2 and f_2; and the contribution of pure water viscosity, depending on temperature is expressed in the variable P_3 and A_3.

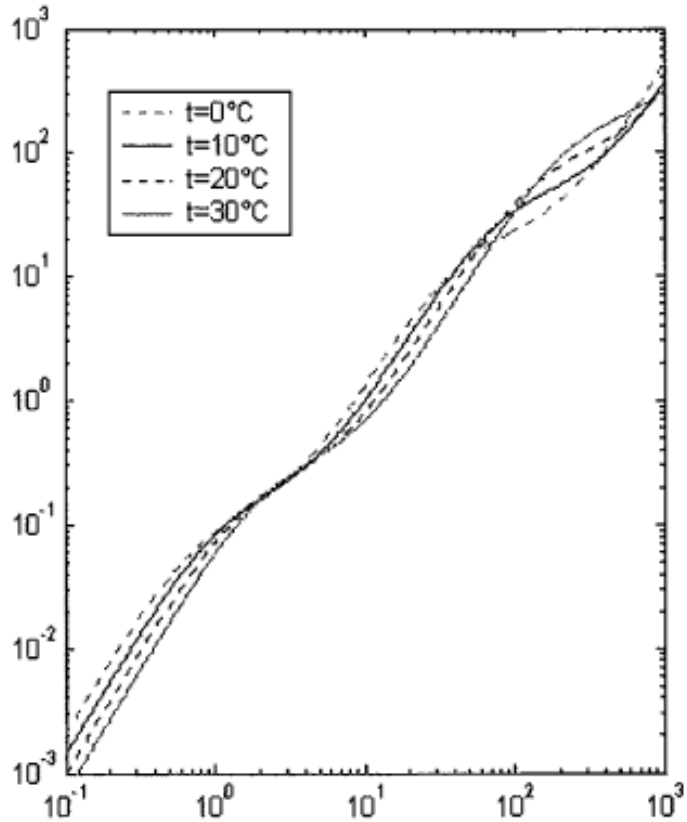

Figure 3.2: Sound absorption coefficient in sea water, as a function of frequency (salinity=35 p.s.u.; depth=0m; different temperatures) (source: [31])

Very low frequencies have an absorption coefficient extremely low, which implies that underwater systems are required to use frequencies around few kHz in order to achieve reasonable ranges.

Depth is another important factor in attenuation. Essentially for applications like data transmission, depth can highly influence the capability to transmit signals. For simple studies the model of Francois-Garrison may be used (not explained in this work) but it is important to use more models accurate and do not neglect the influence of salinity and temperature profiles. [31]

As a first approach to propagation losses spherical spreading can be modelled in dB as this:

$$TL = 20log(R) + \alpha R \tag{3.12}$$

This doubles for outgoing and returning paths for all systems that use echo-like systems. The simplicity of this formula is often sufficient but other models are more likely to be used when one enters high performance industries and their one applications.

Effect from air bubbles is other important aspect when considering very low depths (until 10 or 20 meters). The effects of this phenomenon are then extremely small for the applications regarding the oil & gas industry but one can exemplify some of them:

- Additional attenuation;
- Local modification of sound speed;
- Small and not real backscattering in records.

There are several others limitations and physical phenomena but for this thesis one is going to refer only one more, the Doppler Effect. This effect can be explained as an apparent change in the frequency of waves caused by the change in the source-receivers paths due to the relative velocity of the receiver, source or target.

Considering a pulse with period T, and distance between the source and target equal to D, in which D decreases with time (due to the relative speed of the target), the time of arrival of the signal sent at $t = 0$, is:$t_1 = \frac{D(t_1)}{c}$, where c is the speed of sound in the environment. The second pulse transmitted at t = T arrives at:

$$t_2 = T + \frac{D(t_2)}{c} = T + \frac{D(t_1) - v_r T}{c} \tag{3.13}$$

The Doppler Effect is thus a variation of frequency in the time lag between the two successive receptions:

$$t_2 - t_1 = T - \frac{v_r T}{c} = T(1 - \frac{v_r}{c}) \tag{3.14}$$

$$f = \frac{1}{T(1 - \frac{v_r}{c})} = \frac{f_0}{(1 - \frac{v_r}{c})} \approx f_0(1 + \frac{v_r}{c}) \tag{3.15}$$

$$\delta f = \frac{f_0 v_r}{c} \tag{3.16}$$

Where v_r is positive when moving closer and negative when moving away (remember always that for two travel ways one must multiply the former equation by 2). This phenomenon is hard to handle in applications like communications and transmission applications, but can also be used in several other ones (that use this phenomenon for effective measurements).

Before mentioning the most common applications of underwater acoustics it is important to understand that the speed of sound varies with water density, compressibility and the ratio of specific heat, which are all influenced by: temperature, salinity and pressure.[34]

$$U = 1449 + 4,6T - 0,055T^2 + 0,0003T^3 + 1,39(S - 35) + 0.017D(m/s) \tag{3.17}$$

In which T is the temperature in degrees Celsius, S the salinity in PSU and D the depth in meters.

3.2.3 Applications

Now that some considerations were made concerning the acoustic behaviour and the limitations in water, comparing with air, one will now present some of the applications that can be seen in some water-like industries or activities.

The applications can be divided into six main categories: navigation (of extreme importance for the ROV study), military (important in the aspect of understanding the ultimate technology available and possible future applications), fisheries acoustics, marine geology and seafloor mapping, physical oceanography and underwater intervention.

The first topic considered is the navigation, which groups these different applications:

- Acoustic beacons
- Echo-sounding
- Speed measurements
- Obstacle avoidance

The initial developments in underwater and air acoustics were in terms of navigation: sounding, speed measurements, obstacles avoidance, etc. This topic is of great importance when one talks about the essential technologies for any system.

Acoustic beacons transmit acoustic signals and optical or radio signals simultaneously, and used the delay between two times of arrival, mainly due to the different propagation velocities, to enable the observation and measure distances from equipments that had installed ad hoc receivers. It is possible to see now autonomous acoustic beacons (pingers) that are used to locate submerged obstacles or to help in the positioning of a submerged system. They can be used also as safety devices, on costly loads, for example, or systems going to sea and to facilitate future retrieval. This application is also used, and with extremely good results, for operations at sea like measure depth. [31]

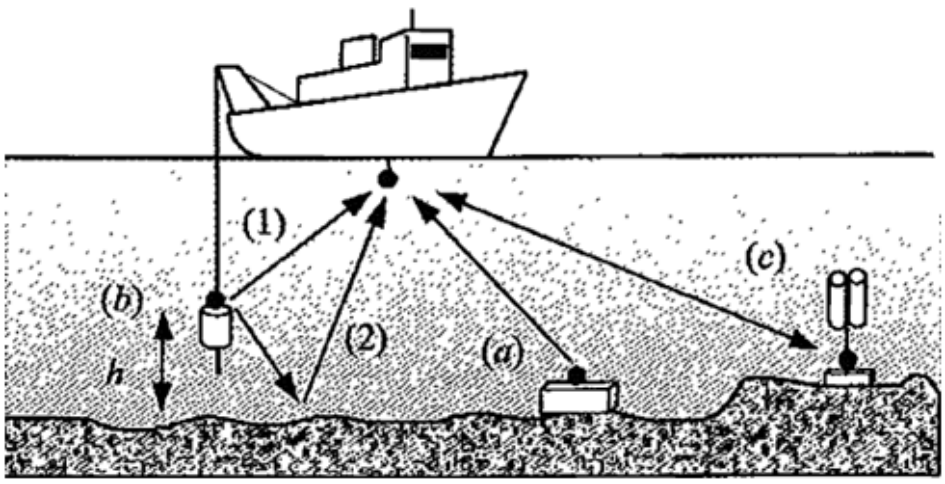

Figure 3.3: Acoustic beaconing configurations: (a) marking; (b) measure height;(c) locate remotely equipment (source: [31])

Single-beam bathymetric sounders are built so that they are used in navigation and mapping as these systems measure the instantaneous water depth. This technology is most common in every naval equipment and the ranges of frequencies used depend a lot in the depth: high frequency in shallow waters and low frequencies (10 kHz) in mapping surveys and oceanography. The sounders can also be used to target objects above, in cases where for example ice may be formed and so create difficulties in operations. [31]

Other sub-application is the estimation of related velocities with the Doppler logs, essentially for submersibles vehicles, as illustrated in the next figure.

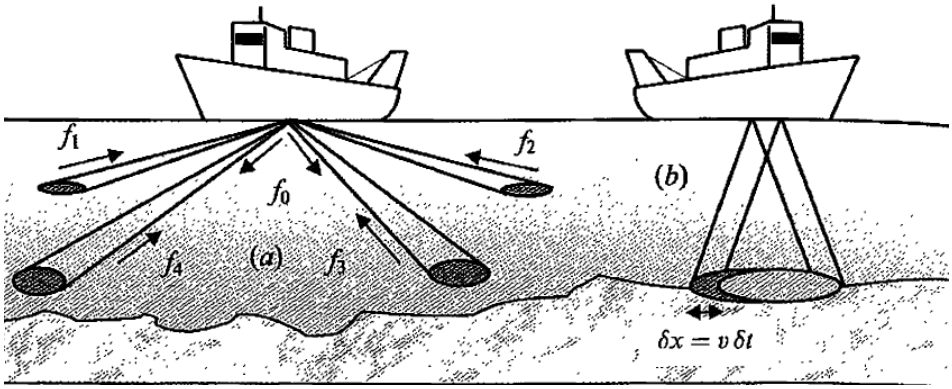

Figure 3.4: (a) Doppler log: with different beams on can calculate the velocity. (b) Correlation log: to correct the value by adding the distance covered by the ship (source: [31])

The equation exemplifies a way to calculate the velocity of the beams (p beams) using as reference the initial velocity of the beam and the final velocities of the ”p” beams. After that a correlation is made to consider the velocity of the ship.

$$v_n = \frac{c(f_n - f_0)}{2f_0}, n = 1, 2, ..., p \tag{3.18}$$

The obstacle avoidance system scan horizontally over a large angular sector (at very high frequencies) and are used to detect, locate and identify close by obstacles. Nowadays one may have a single beam rotating mechanically or a modern multibeam system.

Military applications of acoustic waves are the most modern naval systems, essentially detection ones. Some of the applications are divided in passive sonars (designed for detection, tracking and identification and work at very low frequencies) and active sonars (used for surveillance, tracking and identification; the frequencies used have decreased over the years from tens of kHz to a few kHz):

- The Passive sonars:

  Tracking

  Spectrum analysis and identification

  Interceptors

  Surveillance networks

  Airborne systems

Mines and torpedos

- Active sonar

  Variable depth sonars

  Low-frequency active sonars

  Sonars dipped from helicopters

  Buoys, torpedoes and submarines may carry also sonars

Fisheries acoustics, marine fisheries, use underwater acoustic techniques as sounders and sonars to detect and locate fish schools and to capture them. There are other scientific applications that seek to evaluate the presence of biomass. Several specific techniques can be used but none of them is of great importance to this work.

Marine geology and seafloor mapping is other important scientific and area that uses acoustic technologies to aid its investigation. In order to provide images of the seafloor or other parameters like impedance contrast between the water and the bottom, topography at various scales ranging from large geophysical structures to microscale textures, presence and structure of sub-bottom layers. Though these techniques do not replace the methods used by geologists they give a first good wide observation in the morphology between the water and seabed interface and sedimentary layers.

These applications use several techniques like sidescan sonars, multibeam sounders (image below) and sediment profilers. Techniques that help in seismic measurements are also used by geologists.

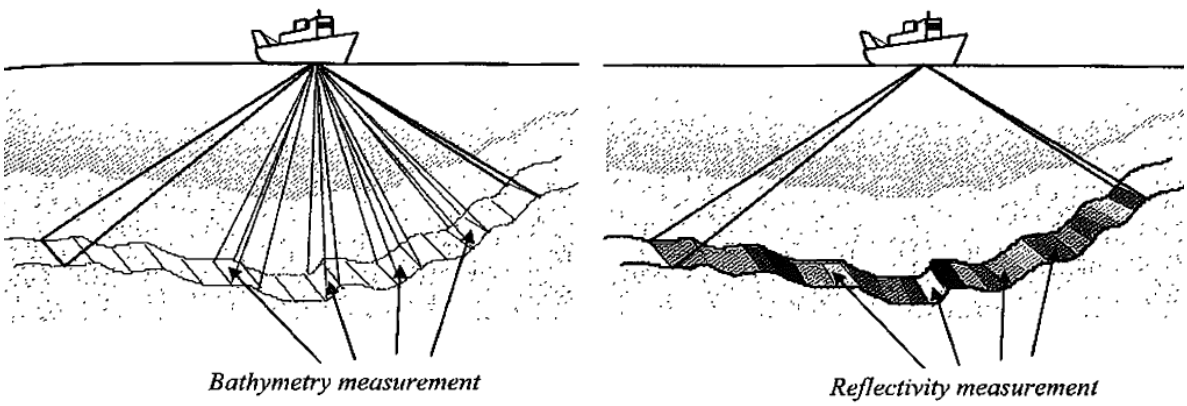

Figure 3.5: Multibeam sounders: bathymetry sounding and sonar imagery (left to right) (source: [31])

Other application is related to physical oceanography, to measure characteristics of water masses at medium scale (Ocean Acoustic Tomography) and the use of the Sound Fixing And Ranging (SOFAR) channel and its opportunities for long-distanced sound propagation at very low frequencies (transmitting acoustic signals over thousands of kilometres).

The technologies for intervention in deeper waters have developed for the last years. There is a need for dedicated instrumentation that could be used at depths of several kilometres and the development of appropriate deployment tools (oil and gas sector profits with the developments in all these areas).

Acoustic positioning, as referred before, is dealt with three main systems: [31, 34, 35]

- Long baseline (LBL) systems use a network of acoustic beacons, widely spaced over the area to be covered. Their position must be accurately determined prior to using the system. The position of the moving object that needs to be located is deduced from the travel times of the signals received from each beacon. Measurement of the absolute durations requires the use of clocks that are synchronous with the moving object and the beacons, or a system of interrogation of the beacons (transponders) by the moving object. After calibration, long-baseline systems can yield localisation accuracies of around a meter. A recent interesting variant consists in installing the acoustic beacons below drifting buoys whose positions can be tracked by GPS.

- Short baseline (SBL) systems use a single transmitter and a series of receivers placed close to each other. The relative position is determined by time differences between the paths received at different points on the antenna. They are easier to use than long-baseline systems, but accuracies are not as good.

- Conceptually similar to SBLs, Ultra Short Baseline (USBL) systems use a single receiver featuring a small array. Measuring the phase differences between the different points on the array determines the direction of arrival of the acoustic waves from the transmitter placed on the moving object. Depth can be measured using a pressure sensor, and transmitted acoustically; alternatively, it can be assessed acoustically if the receiver has access to absolute travel times. The most modern USBLs have positioning accuracies of around 10 meters in deep water.

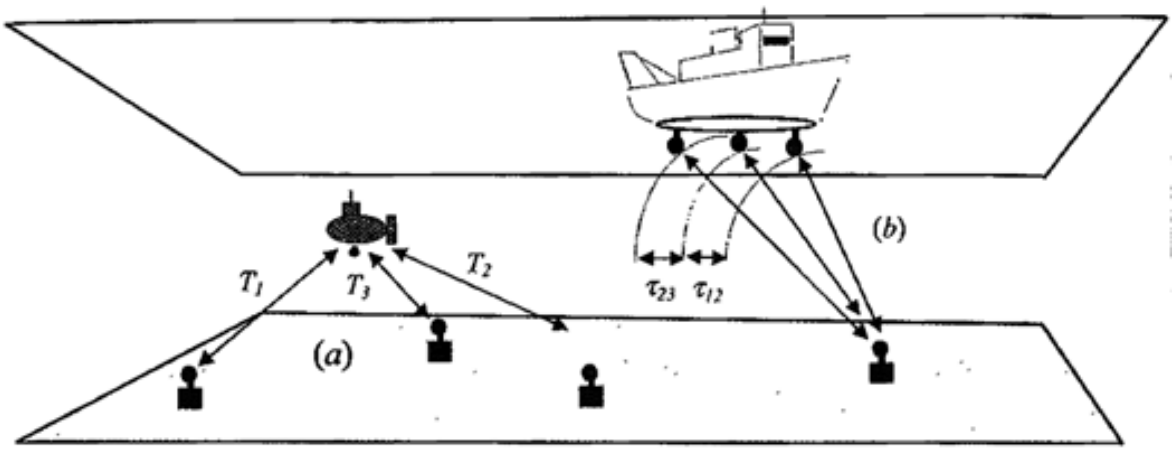

Figure 3.6: Acoustic positioning systems: (a) LBL and (b) SBL (source: [31])

Acoustic Positioning	**Ranges**
SBL	Baseline Length: 20m to 50m
USBL	Baseline Length: <10cm
LBL	Baseline Length: 100m to 6000m (or plus)
Frequency Bands	**Ranges of Frequency - Depth - Accuracy**
Low Frequency	8kHz to 16kHz - >10km - 2m to 5m
Medium Frequency	18kHz to 36kHz - 2km to 3.5km - 0.25m to 1m
High Frequency	30kHz to 60kHz - up to 1.500m - 0.15m to 0.25m
Extra High Frequency	50kHz to 110kHz - <1.000m - <0.05m
Very High Frequency	200kHz to 300kHz - <100m - <0.01m

Table 3.2: Limitations of acoustic positioning [35]

One of the most important applications of acoustic technology is data transmission which, similarly to other modern transmission systems, underwater acoustic data transmission is performed using digital signals. The data are coded as binary symbols, each type of symbol being transmitted with different acoustic signals. The design of acoustic digital data transmission systems can therefore benefit from the powerful techniques developed in telecommunications. However, today's international standard for underwater telephones uses an analogue modulation around an 8-kHz carrier frequency (poor quality).

Underwater acoustic data transmission presents some problems that are difficult to avoid. The first is the achievable data rate: the frequencies usable are a few tens of kHz at most, to get acceptable ranges. The available bandwidths are thus reduced, and therefore the amount of information that can be transmitted. And the vagaries of propagation strongly degrade the quality of the signals transmitted, in particular through multiple paths and reverberation, as well as rapid amplitude fluctuations due to interference and scattering. The performance of a given system will therefore depend a lot on its conditions of use.

To counter propagation effects, one uses directive antennas, decreasing the effects of multiple paths and reverberation. The signals transmitted must be optimised to counter certain processes; the same signal can be transmitted at different frequencies to decrease the risks of fading; successive signals can be transmitted at time intervals in excess of expected spread of multiple paths, etc. It is also possible to code digital signals, in order to detect and correct a posterior some transmission errors. Finally, there are many techniques of signal processing that can be applied at reception.

The performance and degree of sophistication of each system is highly variable, depending on the application and the techniques used. Data transmission towards automated systems (UMVs) requires total reliability, despite an often complex acoustic environment, but it does not require high transmission rates. In favourable conditions of propagation, such as vertical transmission at large depths, it is possible to reach rates of 10kbits/s at depths of 5.000m. [36]

Characteristics	Limitations
Constraints on the frequencies	Dampening of sound waves in water (effect increases with frequency); Size of sound sources (increases with lower frequencies); Difficult selection of directivity of the acoustic sources and receivers (improving with frequency); Acoustic response of the target (comparison between the target size with the wavelength).
Propagation losses	Attenuation of the signals transmitted (absorption is the principal cause); Small propagation speed compared to radar waves in space; Perturbations of propagation by different seeps of sound; Deformation of the signals transmitted (example, Doppler effect); Ambient noise in ocean essentially.
Data Transmission (maximum obtained)	Favourable conditions + Vertical transmission - 10kbits/s at 5.000m

Table 3.3: Summary of the acoustics limitations in water

3.3 Remotely Operated Vehicles

3.3.1 Introduction

The underwater communication is of great importance in several areas of the sea exploration. Mainly with the use of ROVs and UMVs, that are capable to overcome obstacles that humans cannot even reach with the help of acoustical equipments as one will see in the last chapter (ROV Luso).

Currently, underwater vehicles fall into two basic categories: manned underwater vehicles and unmanned underwater vehicles (UUVs). It is of great interest to present this small introduction to these vehicles that are of great importance not only for the O&G industry but also for several other tasks in the exploration of the subsea and use acoustical applications in their operations.

A ROV is a free-swimming submersible craft used to perform subsea tasks such as valve operations, hydraulic functions, and other general tasks.[34]

The difference between the Autonomous underwater vehicle (AUV) and the ROV is the presence (or absence) of a direct hardwire (for communication and/or power) between the vehicle and the surface. However, AUVs can also be (figuratively) linked to the surface for direct communication through an acoustic modem, or (while on the surface) via an RF (radio frequency) and/or an optical link.[34]

The ROV and the UAV falls within a broad range of mobile robotic vehicles generally termed ”remotely controlled mobile robots.” The motion of the vehicle can be via autonomous logic direction or remote operator control depending upon the vehicle’s capability and the operator’s degree of input.

The modern ROV is a mature technology with established standards of operator qualifications, safe operations, and a proven history of getting work done in the ”dull, dirty and dangerous” work

environments of the world's waters.[37]

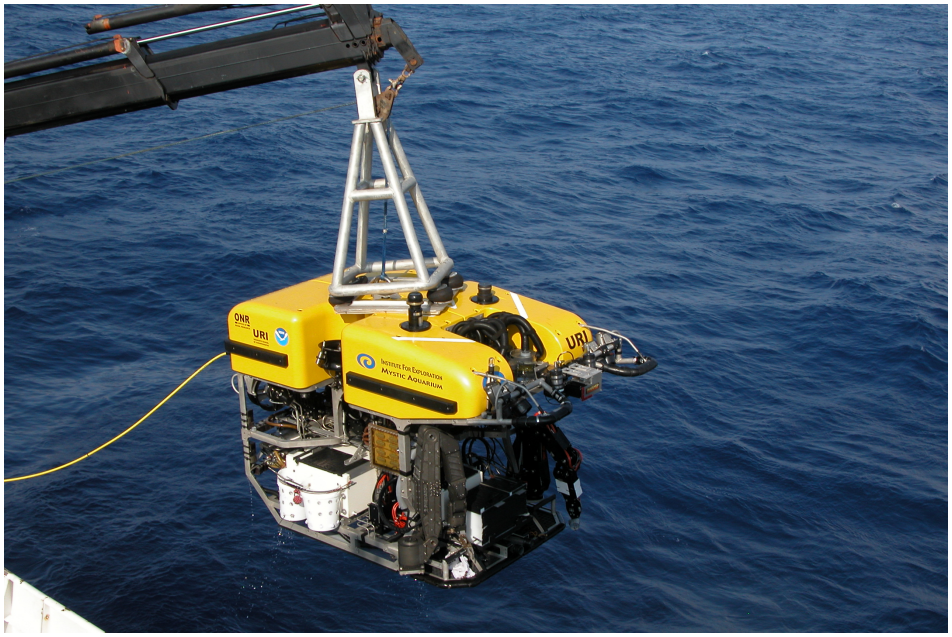

Figure 3.7: Hercules ROV by SubSea7 (source: www.bioscienceresearchcenter.it/servizi/noleggio-strumentazione-scientifica - 24th November 2014)

3.3.2 ROV Classification

ROV are used in a variety of applications from diver support to heavy marine subsea construction. The market is substantially segmented into four broad categories based upon vehicle size and capabilities [34]:

Observation class ROV (OCROV): These vehicles go from the smallest micro- ROV to a vehicle weight of 100 kg. They are generally smaller, DC-powered, inexpensive electrical vehicles used as either backup to divers or as a diver substitution for general shallow water inspection tasks. Vehicles in this classification are generally limited to depth ratings of less than 300 m of seawater due to the weight of the power delivery components and one atmosphere pressure housings-which imposes limitations upon the vehicle size (i.e., neutral buoyancy must be maintained if the vehicle is to have the ability to swim).[34]

Mid-sized ROVs (MSROV): These vehicles weigh from 100 kg to up to 1000 kg. They are generally a deeper-rated version of the OCROVs with sufficient AC power delivery components and pressure housings capable of achieving deeper depths over longer tether/umbilical lengths. These also are generally all-electric vehicles (powering prime movers (thrusters) and camera movement controls) with some hydraulic power for the operation of manipulators and small tooling package options. The vehicle electrical power is stepped down to a manageable voltage for operation of the various components and can be either AC or DC power.[34]

Work class ROVs (WCROV): Vehicles in this category are generally heavy electromechanical vehicles running on high-voltage AC circuits from the surface to the vehicle. The power delivered to the vehicle generally is changed immediately to mechanical (hydraulic) power at the vehicle for locomotion

as well as all manipulation and tooling functions.[34]

Special-use vehicles: Vehicles not falling under the main categories of ROVs due to their non-swimming nature such as crawling underwater vehicles, towed vehicles, or structurally compliant vehicles (i.e., non-free-swimming). One can add a fifth category were the prototypes are included.[34]

3.3.3 ROV Intervention

The ROVs may have multiple intervention tasks, in the deep-sea offshore oil and gas sector one may select these main interventions:

- Site survey;
- Drilling assistance;
- Installation assistance;
- Operation assistance;
- Inspection;
- Maintenance and repair.

Site Survey

A site survey has to be carried out before offshore activities such as drilling and installation to obtain the seabed's precise bathymetry and properties. Detailed seabed mapping through precise bathymetry may be performed by a seabed reference system with differential pressure sensors and acoustic data transmission, which may be deployed and retrieved by an ROV . Seabed mapping can also be performed by a ROV carrying a multibeam echo sounder (MBE) or a side-scan sonar (SSS). A sub-bottom profiler (SBP) for sub-bottom profiling may be used to assess the quality of seabed properties for offshore installation foundation. [34]

Drilling Assistance

Drilling activities for production drilling and completion normally include [34]:

- Deployment of acoustic units such as transponders or beacons by a ROV for surface or subsea positioning;
- Bottom survey by visual observation from a ROV with video and still cameras;
- Structure setting and testing (if needed) of permanent guide base (PGB), temporary guide base (TGB), Xmas tree, BOP, etc;
- As-built (bottom) survey by ROV visual observation with supplemental equipment.

During the entire process, the observation tasks with video cameras (often with scanning sonar as supplemental "acoustic observation") make up the majority of ROV drilling assistance. Tasks include

conducting the bottom survey, monitoring the lowering of the structure and touching down, checking the structure's orientation and level with a gyrocompass and bull's-eye, respectively, and performing an as-built survey. Some necessary intervention work may have to be done with ROVs or ROTs during structure setting and testing like acoustic transponder or beacon deployment and recovery, debris positioning and removal from seabed, including dropped objects and others [34].

Installation Assistance

The installation of a subsea production system from the water surface to the seabed can be divided into two parts [34]:

- Subsea equipment installation (e.g., manifold deployment, landing);
- Pipeline/umbilical installation (e.g., initiation, normal lay and laydown).

The installation methods for subsea equipment may be divided into two groups. Large subsea hardware with weights over 300 tonne (metric ton) can be installed by a heavy lift vessel where the crane wire is long enough to reach the seabed and the crane is used to both put the equipment overboard and lower it. A soft landing to the seabed may be required using an active heave compensation system with the crane. Alternatively, it may be installed with a drilling tower on a drilling rig, which can have a lifting capacity up to about 600 tonne. For smaller subsea hardware (maximum approximately 250 tonne), a normal vessel equipped with a suitable crane for overboarding the hardware may be used. The vessel normally would not have a long enough crane wire to the seabed, so the hardware is transferred from the crane wire to a winch with a high capacity and a long enough wire for lowering the equipment to the seabed once the hardware passes through the splash zone. In both installation groups, ROVs are used for observation and verification and for engagement and release of guide wires and hooks.

Subsea structures are widely positioned underwater using the LBL method in which transducers used for position measuring, a gyrocompass for orientation measuring, a depth sensor for depth measuring may be mounted onto structure by package(s) that will be retrieved by the ROV. The orientation control may be assisted by the ROV, and the ROV has to verify via camera that the structure is aligned and level before the structure's final setdown.

Operation Assistance

Main production activities normally include:

- Flow control by chokes and valves operated by hydraulic actuators through control pods and umbilicals or externally by ROV or Remote operated tool (ROT) intervention;
- Monitoring of flow temperature and pressure by relevant measurement meters;
- Chemical and inhibitor injection for corrosion, waxing, and hydrate formation resistance;
- Flow separation of liquids, gases, and solids (filtering);

- Flow boosting by pumping;
- Flow heating or cooling.

During the operation phase, ROVs are normally not required except for noncritical valve actuation and possibly intermittent status checks, taking samples, etc.

Inspection

Inspection may be needed on a routine basis for the structures expected to deteriorate due to flowline vibration, internal erosion, corrosion and others. Inspection includes:

- General visual inspection, including cathodic measurements and marine growth measurements;
- Close visual inspection additionally requiring physical cleaning for close visual inspection, Cathodic protection (CP) measurements, and crack detection by means of Nondestructive testing (NDT);
- Detailed inspection including close visual inspection, crack detection, wall thickness measurements, and flooded member detection;
- Routine pipeline inspection including tracking and measurement of depth of cover for buried pipelines, which is also applicable for control umbilicals and power/control cables.
- CP potential measurements may be completed by CP probe.
- Crack detection may be performed by an ROV with Magnetic particle inspection (MPI), eddy current, alternating current field measurement Alternating current field measurement (ACFM) methods, etc.

Maintenance and Repair

Maintenance activities include repair or replacement of modules subject to wear. Maintenance is normally performed by retrieving the module to the surface and subsequently replacing it with a new or other substitute module.

Retrieval and replacement have to be anticipated during subsea equipment design. Some modules such as multimeters, chokes, and control pods are subject to removal and replacement. A completed replacement may have to be carried out due to the significant wear on or damage to non-retrievable parts of subsea equipment.

Due to the difficulty and expense of maintenance and repair, the operation may be continued with regular monitoring if the damaged module is not readily replaced and does not prevent production.

3.3.4 ROV System

A ROV system used in subsea engineering can be divided into the following subsystems [34]:

- Control room on deck for controlling the ROV subsea;

- Workover room on deck for ROV maintenance and repair;
- Deck handling and deployment equipment, such as A-frame or crane/winch;
- Umbilical to power ROV subsea and launch or recover ROV;
- Tether management system to reduce the effect of umbilical movement on the ROV;

Umbilicals are one characteristic difference between a ROV and an AUV, is that the ROV has an umbilical that runs between the support vessel and the ROV to transport hydraulic/electronic power from the vessel to the ROV and information gathered from the ROV to the surface. The AUV, on the other hands, is a robot that travels underwater without tethering to the surface vessel/platform. An ROV is usually armored with an external layer of steel and has torque balance capacity. The diameter and weight of the umbilical should be minimized to reduce the drag force due to waves and currents as well as lifting requirements during launch and recovery of the ROV from the water to the surface. Normally the umbilical has a negative buoyancy, and the umbilical may be attached with buoyancy to avoid entanglements between the umbilical and subsea equipment or the ROV itself during shallow-water operation.[34]

This introduction to the ROV is of great importance in order to understand the object of the final practical case study. Vehicles like this are equipped with several systems, specially acoustical ones (positioning systems, altimeters and DVL, for example), making them a good case study to understand the limitations of operability and also what the future can bring in order to developed a new generation of these so important exploration vehicles.

3.4 Risk Analysis

Acoustic communications under water have been used for years. Solutions for present challenges are already in place. There are still difficulties to achieve reasonable accuracies for some operations in under water positioning and also good rates for data transference, but new solutions are being considered by the industry.

In this section one will discuss the benefits and risks of acoustical communications on deep waters and of the innovative solutions found by industry - UAVs and multi-vehicles systems.

3.4.1 Benefits

The benefits that can be seen from the application of these technologies is such environments are:

- Only way of communications ”allowed” underwater;
- Access to places that human cannot;
- Gather information not possible otherwise, reducing costs and preventing investments that may not have the expected outcome;

- Perform tasks impossible in another way.

The acoustics underwater allows the control of robots that may perform tasks impossible for humans. Not only due to water depths and conditions, but also autonomous operations like maintenance.

The next subsection will focus on the risks and debilities of such type of communications, but one must understand that subaquatic activities make impossible the use of any other alternative.

3.4.2 Risks

The existence of risks and limitations, already mentioned, must be evaluated. The analysis of risks must be essentially driven for the new solutions for the deep-sea offshore oil and gas industry, hence the limitations refer mainly to the acoustic systems utilized.

Acoustical systems:

- Low rates of communications;
- Lack of knowledge in extreme depths, though deeper the sound reaches, less he accuracy on positioning;

Future solutions:

- Errors in the control may lead to catastrophic situations - collisions;
- Lack of legislation and the existing is extremely conservative;
- Endurance perspectives are considered an obstacle that must be overcome rapidly;
- Cyber-attacks (as mentioned in [28])

In terms of acoustic communications is important to refer that low rates for data transfer make impossible the use of fully autonomous operations without the application of ”aid systems” like arrays or multi-vehicles systems.

The main issue on using all autonomous vehicles, and even some of the remotely operated vehicles, is the lack of legislation and certification on these systems. Other important situation is the vulnerability of the control systems to cyber-attacks and so the concern to have major catastrophes, like collisions, that may lead to spills, deaths and destruction of the ocean environment.

3.4.3 Managing Risks and Recommendations

Acoustic communications present limitations when operated underwater. The selection of which system to use depends highly on the range and accuracy intended and also on the desired application.

The main constraints found are related with the dampening of sound waves in water, attenuation of the signals transmitted, small propagation speed compared to aerial applications, perturbations of propagation due to different speeds of sound in water, deformation of transmitted signals and low rates of data transmission.

The creation of multi-systems architectures, using autonomous systems, has been proved possible and efficient [29] to overcome some of these limitations yet other risks arise, for example the lack of security on the networks, the delays on the means of communications and the testability of the robustness of the systems.

The capability to have a connection of different elements may lead to diminish the constraints on communications and lower rates of data transference underwater. The use of UAVs and buoys to connect to the ROVs is part of the technological roadmap in development, which includes the creation of complex control systems not only for fleets of UMVs but also integrating different technologies and systems.[29]

Another solution currently underdevelopment is the use of arrays to potentiate the sources of acoustical signal underwater and so diminish the losses [38].

Though there are several solutions, one must understand the limitations referred also in terms of legislation. ROVs are under the same legislation as ships and AUVs, on the other hand, are considered as separate entities as they are autonomous, however they create a gap in the legislation. An AUV is not considered a vessel per definition but existing domestic laws and international treaties are limited to vessels, and therefore not these vehicles.

It is then of great importance that the AUV operator is aware of the associated risks and how to manage them. The main focus is the risk associated with collision. Even though the risk of collision is small, the damage could be very high due to loss of the AUV or damage to other structures or ships. The operators need to be aware of their obligations with regard to avoidance of collision and how to minimize the risks of collision.

Technology	Type of Communication	Limitations	Risks
ROVs	Use of umbillicals or use of acoustical systems on board	Umbillicals restrict area of action Increase costs (need to have a human operator)	Low rates of communication Lack of legislation on ROVs
UMVs	Acoustic communication plus use of acoustical systems on board	Rate of data transmission very low Depending on environment conditions Endurance	Low rates of communication Possible cyber-attacks Small endurance and lack of legislation and certification on UMVs
UAVs	Electromagnetic communications	Endurance	Endurance Lack of legislation on UAVs

Table 3.4: Summary of risks and limitations of autonomous and remotely operated vehicles for deep-sea operations

Following the IRGC methodology for technology related risks one will check if all the pre-assessment

question are answered. The potential damages and adverse effects have been highlighted with reference to the communications limitations and control debilities that may create uncomfortable situations to users and operations. The probability of occurrence is high, as the limitations are presented in all the environments and conditions. These limitations may only be reversed with further scientific and technological research, and with the creation of robust systems that can overcome the existent limitations. The benefits, opportunities and potential of these applications are referred.

Concluding this first case study the main limitations concern to the range of operability and accuracy of some equipments. The acoustical positioning systems present a large scope of operability, starting with a few centimetres (less than 10cm) to several kilometres (up to 6km). The frequency bands used can also vary from a few kHz to hundreds kHz though the deeper the frequency can reach, the less accurate the measure is.

There are demanding limitations on acoustic communications that do not allow the rapid expansion of autonomous vehicles underwater, leading the technological industry to adapt solutions.

Integration of multiple sensors is therefore essential to surpass the limitations of individual equipments. The risks on the legislation and the capability to deal with cyber-attacks [28] must also be governed and new disruptive solutions for the deep sea exploration are essential to overcome these new challenges.

4

Materials Under Severe Conditions

Contents

4.1 Introduction

Offshore oil production has become more complex. The main challenge is to provide technical solutions, reliable and safe, for the new oil field discoveries presented before (deep-sea offshore - pre-salt).

One can gain insight from other industries that now utilise composites in primary structure and critical applications. Two main industries are the aerospace industry and the chemical processing industry.

The aerospace industry, both military and commercial, moved to composite materials due to the low specific stiffness and strength offered by carbon reinforced epoxy. This resulted in such significant savings of fuel and increased aerodynamic agility that became the only material that would achieve the ever-increasing performance envelopes.

In the chemical processing industry the extremely high corrosive nature of many fluids meant that glass reinforced vinylester was the only economically viable material for storage and transport of these fluids.

As the offshore oil and gas industry begins looking to new horizons beyond current resources, and towards exploiting reserves that are less easy to produce, it too will face situations where composite materials may be the only economically viable material available. The main attributes of composites - corrosion resistance, high stiffness and strength and lower weight - will give them an edge over carbon steel.

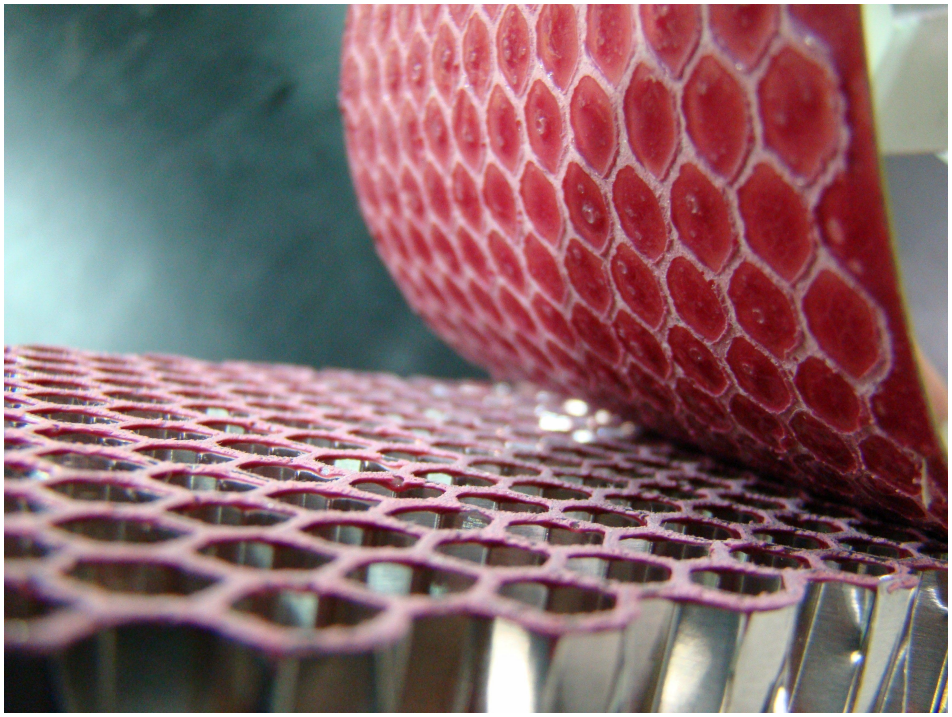

Figure 4.1: Example of a composite material used in Aeronautics - sandwich panel with honeycomb internal structure (source: news.sherrylabs.com/laboratory-news-article.php - 24th November 2014)

There are several potential uses of composite materials in the deep-sea offshore oil and gas sector and for the past few years the development and use of components fabricated with these materials

have grown, but only in lower risk situations. There are several barriers to the exploration of these materials, curiously the same has happened in the aeronautical industry, essentially concerning the certification.

The search for new wells, at depths of 1500m to 3000m, the so called ”hard to reach” reserves, bring along several challenges one must face [39, 40]:

- Temperatures in excess of 200^0C;
- Pressures over the 138Mpa;
- Highly sour reservoirs which include the presence of H_2S.

High specific strength and stiffness are of great importance to solve some of the technical challenges and to obtain extreme high performances in the deepwater fields. Some composite materials can be created in order to not to corrode so easily, which is of supreme importance for the offshore oil and gas industry. The only problem is to create means to understand the rate of degradation, which implies a search for new technologies to comprehend the long term degradation and/or ageing of these materials in the deep-sea offshore oil and gas environments. [39–42]

The O&G industry follows several limitative regulations, concerning the security, testability and efficiency of the several systems and sub-systems. This aspect reduces the willingness to accept components fabricated with composite materials as they are considered to have low levels of testability and proves of security.

It is the significant increase in operating conditions discussed above along with new types of composite materials that require a more in depth knowledge of the use of composite materials to enable their reliability to be assured for these new challenges particularly in their long term evaluation. This knowledge needs to be developed in parallel with the new applications and pieces of equipment fabricated from composite materials such as spoolable thermoplastic tubular and reinforcement in unbounded flexible pipes (which will be explained later).

However, and as one goes into deeper waters, the sheer weight of the equipment pose problems for installation. The struggle with installations when one has passed 1000 m water depth, and now even more when going towards 4000 m offshore, like in Mozambique.

Subsea technology in use has a main preference for steel as the main material choice for systems that contain the flow pressure like pipes and valves, for structural elements including trawl protection, etc. Is now time to change this paradigm.

4.1.1 Challenges

While the industry is gaining experience at the drilling at great water depths the critical factor in increasing depth is the drilling raiser. The riser must be made lighter to avoid excessive tension levels in its upper part. This may be achieved by replacing sections of the steel riser with composite material risers. Additionally, removing substantial weight from the riser, by fabricating them from composites, will proportionally reduce the topside counter balancing weight and allow current handling capacities

of rigs and derricks to be used. The density of steel is 8 in air and composites are approximately 2. However in water, the densities are reduced to 7 for steel and 1 for composites. Thus composites offer a seven-fold weight reduction which reduces the capacity of handling equipment or allows larger parts when using composites. The same principle must apply to cabling, wire lines and choke and kill lines that run from the surface to the well-head. A composite riser solution is still under development and is discussed below. Additional challenges for drilling in ultra-deep water include weakness of the surface formations and the range of temperatures and pressures encountered which may vary from near 0^0C at the seabed to 150^0C (or more) in the formation at pressures in excess of 400 bar.[39–42]

For production, the seafloor-to-surface mooring systems, umbilicals and risers have additional challenges to that of weight as described for drilling risers.

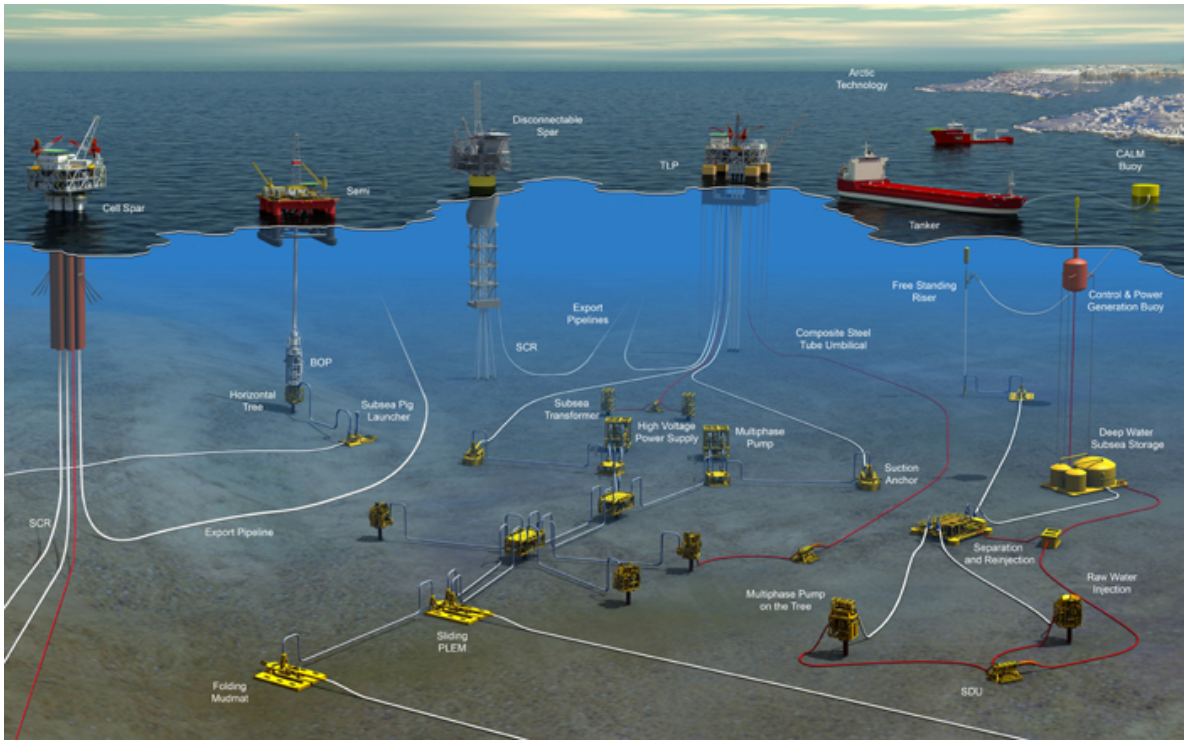

Figure 4.2: Big Picture of the subsea technologies with the subsea production systems and naval support equipments (Source: www.genesisoilandgas.com/our-business/subsea/Pages/default.aspx - 24th November 2014)

4.2 Technical Characteristics in Extreme Conditions

To meet some of these challenges, the industry is beginning to look at new types of composite materials moving on from the established glass reinforced epoxies, used in piping, to carbon reinforced thermoplastics that offer high temperature capability, and high load capacity and stiffness. The use of unreinforced thermoplastics within the industry is not new with PVDF, PEEK, Polyamide and others being used widely for back-up rings and fluid barriers. However, the use of these thermoplastics as composites (i.e. reinforced with continuous glass or carbon fibres) requires identifying which of these materials should be used for specific operating conditions.

4.2.1 Ageing Performance

Materials behave differently when in constant contact with high temperatures and corrosive means. Hence, it is important to understand the different aspects of long term ageing and how this can be applied to a composite material in service in deep sea exploration.

It is known that the environment can have a great influence on materials resulting in degradation. For metals, corrosion literature is in abundance, explaining the creation and propagation of these effects. In composite materials and in general polymers, the environment can cause irreversible changes to the original properties, analogous to corrosion. However, there is far less literature available.

The process of change in properties of polymers or the fibres, or the bond between the polymer and the fibre is termed ”ageing”, replacing the word corrosion. For composite materials ageing can be categorized by three different primary mechanisms: physical, chemical and mechanical. These mechanisms depend on the material characteristics, for example: thickness, density, matrix; as well the type of application, environment and time of exposure.

Physical ageing will occur in polymers at temperatures below the glass transition temperature (T_g) and is based on fluid absorption. Initially, the fluid absorbs into the composite material surface and then, as time progress, a fluid content concentration gradient develops through the thickness of the material by diffusion. It is generally the first effect of ageing in non-extreme environments (i.e. concentrated acids) and can be reversible in amorphous polymers by heating it above its T_g. For composites these effects are complicated by different concentrations along continuous fibres. [39]

Chemical ageing is an irreversible procedure and generally happens after physical ageing. It is irreversible because it affects the polymer chains through mechanisms such as cross-link creation, hydrolysis and chain scission (loss of molecular weight). It may also permanently damage the fibre or the bond with the resin. Similarly to physical ageing, it starts at the surface and continues inward. It can be characterized by changes in the T_g and mechanical properties. [39]

Another stage of ageing is mechanical ageing when the pipes are under load, for example. This is also irreversible and affects the bulk material. It includes matrix cracking, delamination, interface degradation and all processes that are observable on the macroscopic scale. A well known type of ageing is the termed environmental stress cracking. [39]

Many of the composite pipes will utilize polymer liner to prevent the transport fluid contacting the structural walls of the pipe. These may be dealt with in two ways. If they are considered part of the structural design of the pipe, then they can be evaluated for ageing and treated in the same way as a single ply (of a different material). If they are considered as fluid barrier alone, then they can be excluded from the structural analysis, but the time for the transport fluid to permeate to the composite must be added to the analysis. As with liners in flexible pipes, liner collapse and other issues such as rapid gas decompression should be considered.

Ideal Fickian behaviour moisture absorption increases linearly with the square root of time for values of $M_t/M_{\text{inf}} < 0.5$ (where M_t is the total amount of moisture absorbed at time t, and M_{inf} is the total amount absorbed at equilibrium). Diffusion can be accelerated by increasing the temperature

and follows the Arrhenius relationship [39]:

$$D = D_0 \left(e^{-\frac{E_a}{RT}} \right) \tag{4.1}$$

Where E_a is the activation energy of the diffusion rate, R is the universal gas constant and T is the absolute temperature of the exposure in degrees Kelvin. Time thickness scaling allows the long-term prediction of absorption in thick laminates from thin sample measurement. When Fick's law applies, the rate of depth of the moisture content x can be characterised by [39]:

$$\bar{x} = \sqrt{aDt} \tag{4.2}$$

This equation allows calculating the distance of ageing effects from the inner surface related to each individual ply thickness.

Knowing the individual ply thickness and using suitable analysis, the overall effect on the performance of the pipe, or other component, may be determined. The effects physical and chemical ageing have on the mechanical properties of individual plies needs to be established and requires relevant mechanical tests. This requires specimens for compression, shear and fracture properties. In reality it may also require micro-mechanics evaluation of the fibre and matrix specifically. These properties give indications of ageing but not the consequence of that ageing.

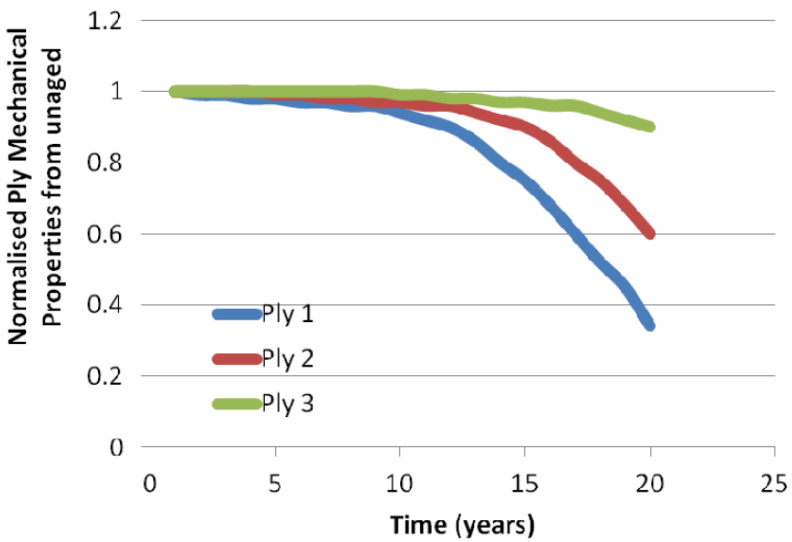

Figure 4.3: Illustration of the ageing process of several plies (source: [39])

The approaches used in the aerospace industry such as A and B basis allowable along with limit load approaches may serve as a starting point for the new offshore oil and gas industry.

4.2.2 Design Approaches

For future design steps to be developed, using ISO14692 [43], one can detail the design steps for composite piping systems to be designed and installed safely. The effect of ageing is added to one of the design parameters, external pressure collapse [39]:

$$P_c = 2(\frac{1}{F})E_h(\frac{t}{D})^3 \tag{4.3}$$

Where P_c is the collapse pressure, F is a safety factor, E_h is the hoop modulus of the pipe, t is the average wall thickness and D is the pipe diameter.

Except for E_h, no parameters in this equation are affected by ageing (assuming no material loss). The hoop modulus is a function of the material, the lay-up and the number of plies. Knowing these variables, the hoop modulus can be calculated by the Classical Laminate Theory (CLT). [39]

With composite materials, each ply or lamina has a modulus in the fibre and transverse directions and has a shear modulus. By conducting ageing tests, or using equations, an understanding of the changes in properties with time can be established such that at any time during service, the properties of the plies are known.

The use of CLT is suitable for regular geometries such as pipes. For more complex geometries the use of finite element analysis must be used where the model must incorporate the individual properties, on a ply-by-ply level.

The most used materials in pipes and offshore equipments are the Fibre Reinforced Plastic (FRP) materials, that due to their nature of anisotropy and performance degradation the structural design makes them an unique case study. The structural design typically includes the design for internal pressure, external pressure, axial strength, bending strength, and buckling strength. Testing based methods are required in most cases in order to establish the long-term performance limits of FRP piping components, whilst the design strain based calculation may also be used along with short-term verification tests.[44]

Different safety factors are defined to give the credit to the long-term pressure testing. Design strain method is also allowed as an alternative for internal pressure design. Since FRP is a non-isotropic material, there is often more than one allowable stress. As a minimum, there are three long-term allowable stresses that need to be defined: allowable axial stress, allowable hoop stress, and allowable bending stress. The allowable hoop stress σ_h is determined by long-term hydrostatic pressure test and the following equations:

$$\sigma_h = \frac{\sigma_{qs}}{\eta} \tag{4.4}$$

Where,

$$\sigma_{qs} = \frac{f_1 P_{LTHP} D}{2t_r} \tag{4.5}$$

In which σ_{qs} is typically called the qualified stress; P_{LTHP} denotes the long-term hydrostatic pressure obtained following [45]; f_1 is a factor to represent the 97.5% Lower Confidence Limit (LCL) of P_{LTHP} based on a design life of 20 years(account for ageing processes); t_r is the average reinforced thickness of the wall (i.e., excluding the thickness of linear and added thickness for fire protection); D is the mean pipe structural diameter calculated by $D = D_i + 2t - t_r$ where D_i and t denote the inside diameter and total wall thickness, respectively.[44]

It is also important to define the long-term and short-term axial stress in order to develop the failure

envelope.[1]. The long-term allowable axial stress with bi-axial stress ratio hoop/axial=0/1 is:

$$\sigma_a = \frac{0.5r\sigma qs}{\eta} \tag{4.6}$$

$$r = \frac{2\sigma sa}{\sigma_{sh}} \tag{4.7}$$

where σ_a is the long-term allowable axial stress with bi-axial stress ratio hoop/axial=0/1; σ_{sa} is the axial strength or design strain based axial strength (short-term) for pure axial strength; σ_{sh} is short-term hoop strength due to internal pressure; η is the safety factor with default value of 1.5 for normal operation; r is bi-axial failure stress ratio.[44, 46]

The long-term allowable axial stress with bi-axial stress ratio hoop/axial=2/1 is determined by:

$$\sigma_{a1h2} = 0.5\sigma_{qs}/\eta when r \leq 1.0 \tag{4.8}$$

$$\sigma_{a1h2} = 0.5r\sigma_{qs}/\eta when r > 1.0 \tag{4.9}$$

where σ_{a1h2} is the long-term allowable axial stress with bi-axial stress ratio hoop/axial=2/1; σ_{qs}, r and η are as defined above.

Determination of the long-term allowable bending stress is not as straightforward as that of hoop and axial allowables. There is also no reliable testing method that can directly evaluate the long-term bending behaviour of FRP pipes. The ABS [46] guidance provides a combination of short-term tests and design strain based calculations as follows:

$$\sigma_b = \frac{0.5r_b\sigma qs}{\eta} \tag{4.10}$$

$$r_b = \frac{2\sigma sb}{\sigma_{sh}} \tag{4.11}$$

where σ_b is the allowable bending stress; σ_{sb} is the short-term bending strength; σ_{sh} is the short-term hoop strength; r_b is the bi-axial bending failure stress ratio; η denotes the safety factor with default value of 1.5 for normal operations; σ_{qs} is the qualified stress as defined above.

With the long-term allowable axial stresses determined above a failure envelope can be established. A long-term allowable (design) envelope for FRP pipes is obtained after applying the safety factor η. The sum of the axial stresses due to pressure, weight, expansion and other dynamic and sustained loads should not fall outside this allowable envelope. Similar allowable envelope can also be established for other FRP piping components such as fittings and joints. Different bi-axial failure stress ratio r should be used to define the mechanical properties of non-isotropic materials.

As noted in the definition of long-term allowable stresses, the safety factor η has default value of 1.5 for normal operations under sustained loads. Sustained loads generally include internal pressure, external pressure, vacuum, piping weight, insulation/fire protection weight, fluid weight, inertia loads due to motion during operation (e.g., daily wave action), and sustained environmental loads (such as ice and snow). In the case of sustained thermal expansion induced stresses, which is self-balance

[1]This is performed by simplifying the structure to bi-axial (hoop-axial) motions, which will be considered when analysing the risks of this technology and the respectively testing and design methodology

loading, the default safety factor can be reduced to 1.2. When considering the stresses due to occasional loads, the default safety factor is 1.12. Occasional loads include, for example, internal pressure from hydro-testing, pressure surges from water hammer, pressure surges from safety valve releases, transient equipment vibrations, impact, inertia loads from motion during transportation, occasional environmental loads (such as wind from storms), and overpressures from blasts and other occasional loads. It should be noted that certain design conditions such as severe internal or external corrosive conditions, elevated temperatures, and cyclic loading (more than 7000 cycles), may necessitate a reduction in the allowable stress values.[43]

The next table reflects the bi-axial stress ratios categorized for several applications when the impossibility to calculate the real ones:

Component	**Default Bi-axial Stress Ratio**, r
55-degree Filament Wound Pipe	0.5
Filament Wound Fittings (primarily hoop wound)	0.45
Laminated Fittings (bi-directional reinforced)	1.9
Adhesive Bonded Joints	1.0
Laminated Joints (bi-directional reinforced)	2.0

Table 4.1: Bi-Axial Stress Ratios [46]

4.2.3 Conditions vs. Materials - Example of a test methodology

The absorption of water in composite materials can be found out by a gravimetric analysis. That is to say by the measurement of the relative weight uptake of the aged specimens in accordance with the exposure time. [47] To test the phenomenon of ageing on materials by influence of water one may emerge specimens in a water bath, during the pretended time to evaluate. The surface of these specimens must be meticulously dried and weighed immediately to determine the weight of wet specimen so one may observe and study the water absorption characteristics of the composites taking into account the relative uptake of weight defined as M_t:

$$M_t = \frac{W_t - W_0}{W_0} \times 100(\%) \tag{4.12}$$

Where W_0 is the weight of dry specimen and W_t is the weight of wet specimen at time t. Different models have been developed in order to describe the moisture absorption behaviour of composite materials. For a plane sheet of thickness h with uniform initial distribution and equal initial surface concentration, Fick's laws lead to the following equation [44]:

$$\frac{M_t}{M_m} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\inf} \frac{1}{(2n+1)^2} \exp\left(\frac{-(2n+1)^2 \pi^2 D t}{h^2}\right) \tag{4.13}$$

where M_t is the moisture uptake at time t, M_m is its maximum moisture uptake, at equilibrium state, D is the diffusivity and h is the thickness of the specimen. As long as the concentration in water remains zero in the middle off the plate, the absorbed water mass varies linearly according to the

square root of immersion time. For values M_t/M_m lower than 0.6 approximately, the initial part of the curve can be correlated by[44]:

$$\frac{M_t}{M_m} = \frac{4}{h}\sqrt{\frac{Dt}{\pi}} \tag{4.14}$$

For the second half-absorption, M_t/M_m upper than 0.6 a proposed approximation [47] may be driven from [44]:

$$\frac{M_t}{M_m} = 1 - \exp\left[-7,3\left(\frac{Dt}{h^2}\right)^{0,75}\right] \tag{4.15}$$

The diffusion coefficient D, which is an important parameter in Fick's law in the case of the values of M_t are less than 60% of the equilibrium value M_m [44]:

$$D = \frac{\pi}{(4M_m)^2}\left(\frac{M_t h}{\sqrt{t}}\right)^2 = \pi\left(\frac{k}{4M_m}\right)^2 \tag{4.16}$$

Where the coefficient k is the slope of the linear part of the curve $M_t = f(\sqrt{t}/h)$.

However, a correction factor is needed to take into account the finite dimensions of the rectangular specimens [44]:

$$D_c = D(1 + \frac{h}{L} + \frac{h}{w})^{-2} \tag{4.17}$$

where D_c is the corrected diffusion coefficient, L and w are respectively specimen length and width.

The test here proposed may be adapted to other liquid environments after which on must test tensile and flexural properties in order to determine the influence of the water absorption on these mechanical properties.

From this and others experiments in industry and academia, some results are shown after in order to prove the change in properties of composite materials.

4.2.4 Conditions vs. Materials - Examples of results from industry

It is interesting to show some results, from the industry as there are no capacity to perform such tests, that evaluate the behaviour of some of these thermoplastic materials in extreme conditions: saltwater, hydrocarbon gas condensate and 30ppm H_2S. To refer that these studies were not performed during the preparation of this work but were gathered from the available literature.

Several configurations were studied by [48] with two different basis - glass and carbon - and application of different polymers depending on the environment in case.

The design of materials to subsea applications is not an easy task, the influence of severe conditions lead to uses of high values for safety factors, as in aeronautics. Though the safety margins are set to control eventual degradation of materials, is of great importance to observe the behaviour of materials in severe conditions (high temperatures, years of service and corrosive environments).

Saltwater

Different materials were studied by [48] in saltwater conditions. For example for the POM/Glass 4.4 the tensile and flexural property levels show an overall decrease on exposure at elevated temperatures. The tensile property levels gradually decrease with increasing temperature for maximum stress

and maximum strain whereas the modulus shows no change within the experimental error of the measurement. The flexural property levels differ in that the maximum stress decreases with increasing temperature and the flexural modulus drops by approximately 70% for all temperatures, conversely the maximum flexural strain increases above the initial value decreasing then with temperature.[48]

Also as an example, the CBT/Glass shows also degradation on the mechanical properties with increase temperature as the tensile maximum stress of PA11/Glass 4.5 shows a high degree of variability however there is an average property level loss of around 40%. There is no change in maximum strain, within the experimental error, and again the variability in the results is large. The tensile modulus shows a slight decrease with temperature. The change in flexural property levels is the same for each of the elevated temperatures with a 50% drop in maximum stress, 20% drop in modulus and no change in maximum strain.[48]

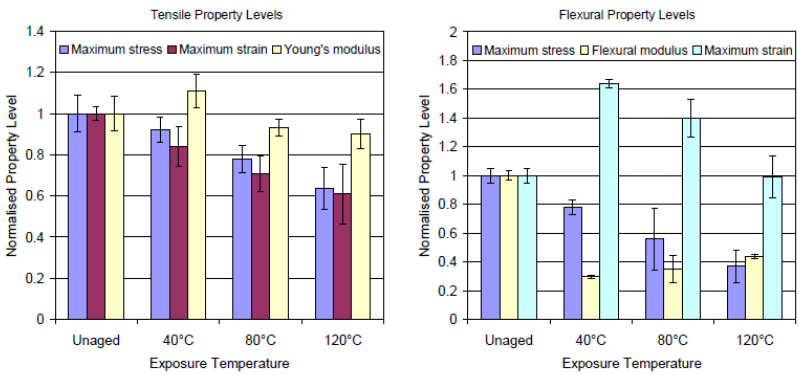

Figure 4.4: POM/Glass Results in Saltwater: Tensile and Flexural Properties (source:[48])

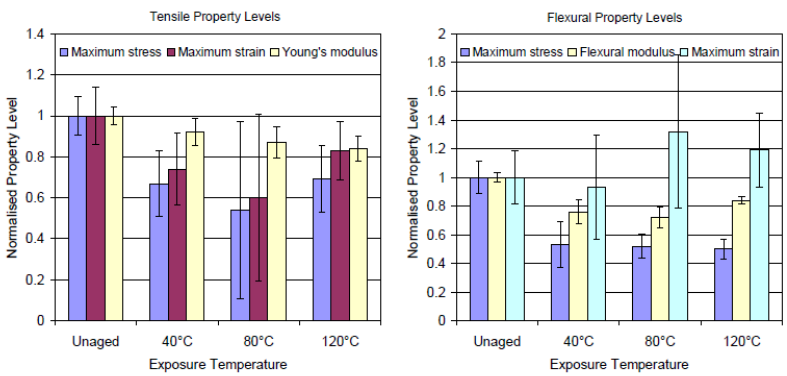

Figure 4.5: PA11/Glass Results in Saltwater: Tensile and Flexural Properties (source:[48])

All the materials experimented by [48] show evidence of ageing to some extent based on the overall decrease in tensile and flexural property levels after exposure to this environment. Water absorption in composites is more complex than in polymers alone [47]. In the case of these thermoplastic composites, the water diffuses into the polymeric matrix, with the extent of the absorption depending on the chemistry and morphology of the polymer as well as the volume fraction and configuration of the glass fibres. The combination of moisture absorption and elevated temperature can cause plasticisation of the thermoplastic matrix, which allows relaxation of the polymer chains below

the glass transition temperature. It also affects the residual stresses present within the composite and can allow micro-crack formation which may ultimately lead to increased water absorption, weakening of the fibre/matrix interface and development of micro-cracks. The effects of water absorption tend to become more apparent in higher temperatures. This is due to the fact that the higher the temperature the faster the rate of diffusion and ultimately the higher the level of water absorption. In aged materials the maximum strain values decrease but the failure is not brittle suggesting that the load is not being effectively transferred to the fibres indicating that the matrix/fibre interface has deteriorated.[47, 48]

Hydrocarbon Gas Condensate

For this condition the observation by Roseman [48] shows for example that the tensile maximum stress and modulus of CBT/Carbon 4.6 has an overall decrease with increasing temperature. The maximum tensile strain however is highly variable and does not show a relation with temperature. The flexural and interlaminar shear property levels show significant deterioration with increasing temperature.

All the materials studied showed evidence of ageing to some extent based on the overall decrease in tensile and flexural property levels after exposure to this environment. Hydrocarbon exposure has caused more severe ageing of some of the candidate materials than others. There are similarities here with the water. In some cases the evidence for chemical attack is clear. For other materials the change in material properties is likely to be due to a combination of chemical and physical ageing. As with the water exposure the mechanism of failure in all of the materials appears to be due to deterioration of the matrix/fibre interface based on the change in how the specimens fail when subjected to mechanical testing.

30ppm H2S

For this environment the tests on PPS/Carbon 4.7 show no correlation with temperature. The aged samples generally retain their tensile property levels to within the range of experimental error. The results of the flexural testing show an excellent retention of property levels for all temperatures. Similarly the interlaminar shear property level is unaffected at all temperatures. The same for was seen for the PEEK/Carbon, good retention of tensile property levels at all of the elevated temperatures and good retention of flexural and interlaminar shear property levels is also shown for all temperatures.

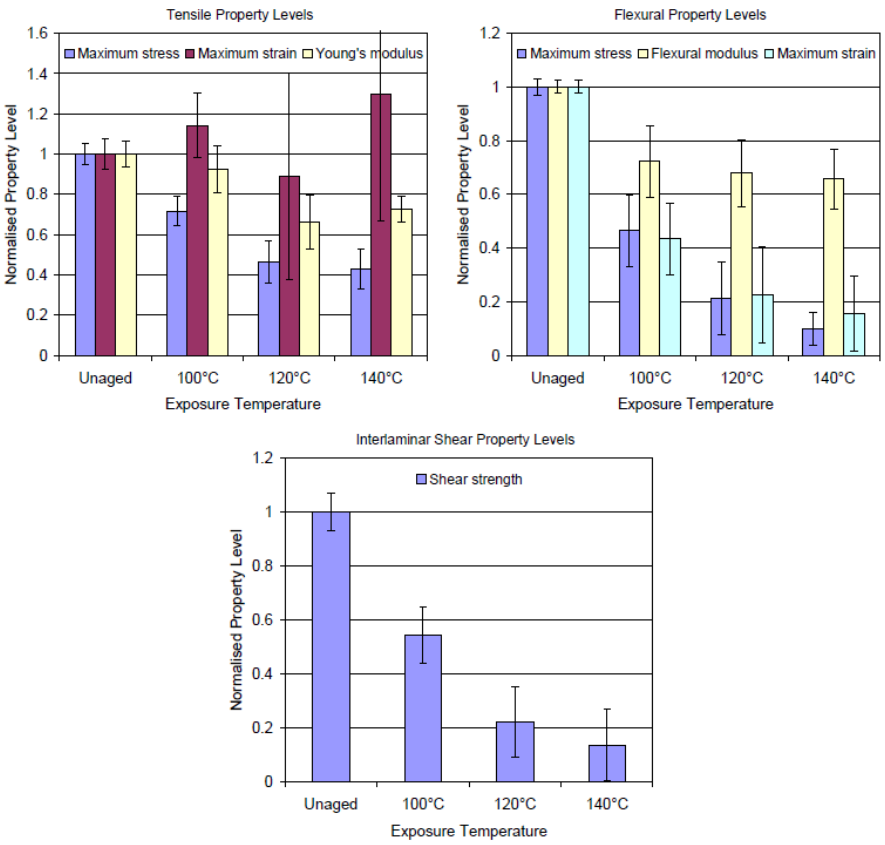

Figure 4.6: CBT/Carbon Results in Hydrocarbon Gas Condensate: Tensile, Flexural and Interlaminar Properties (source:[48])

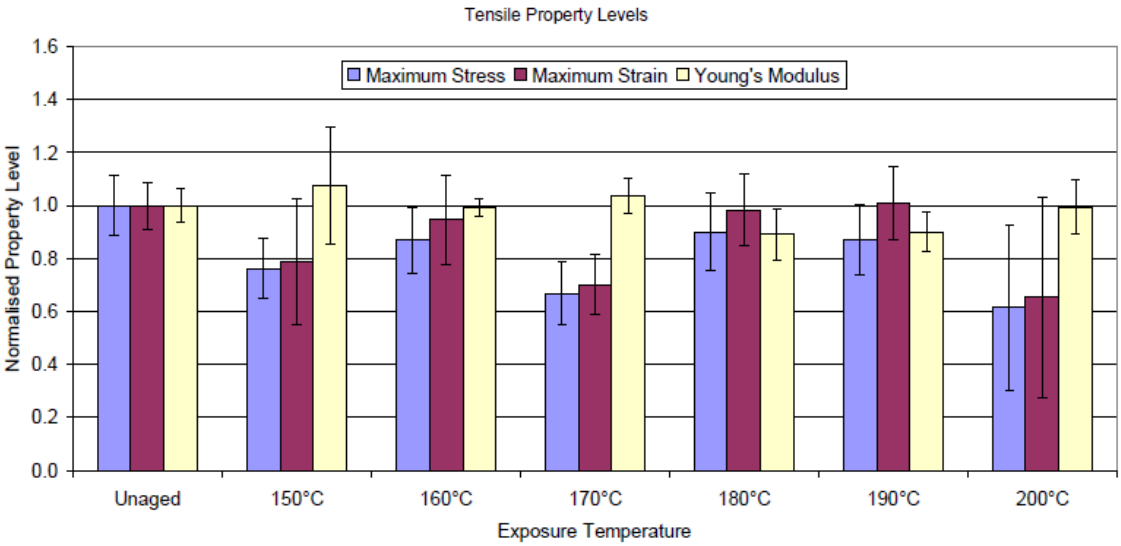

Figure 4.7: PPS/Carbon Results in 30ppm H2S, Tensile Properties (source:[48])

This section and after analysing the results from the graphics, drives to the understanding that, as already mentioned, the mechanical properties of composite materials change accordingly to the environment and the time of service. This is of great importance when one thinks of applying such

materials to offshore equipments, as the ones following.

The next chart sets a summary on some technical limitations and compares to one aeronautical case.

Phenomenon	Limitations
Ageing - salt water (Glass fibres with different matrices)	Materials show evidences of ageing to some extent (tensile and flexural properties) after 1 week at $\approx$ 350 bar [48]
Ageing - hydrocarbons gas (Glass and Carbon fibres with different matrices)	Materials show evidences of ageing to some extent (tensile and flexural properties) more than with salt water after also 1 week at $\approx$ 350 bar [48]
Ageing on water - (Epoxy + Glass-fibres)	Failure Stress decreases during the first 10 days of immersion (240 h) and Young Modulus also decreases with time of exposure Linear decrease of 10% is found for the glass-fibre composite aged between 10 and 30 days Failure stress reaches 25% after 40 days [47]
Ageing (Aeronautics)	20.000 cycles (80.000 h) of -55 to 120^{0}C for degradation of properties [54]

Table 4.2: Summary of limitations for composites

4.3 Applications

Pipework and Pipelines

The use of composite materials for rigid pipe work has potentially significant advantages over carbon steel. They have a lower specific weight, higher chemical resistance (i.e. they do not rust), and can be cheaper when fabricated from Glass Reinforced Plastic (GRP) materials. However, while composite pipes have been set widely in onshore facilities and in processing plants to transport crude oil, they have not been widely specified for offshore applications, and then only low to modest pressure and temperature service. Typical offshore applications include sea water cooling lines, air vent systems, drilling fluids, fire and deluge water mains systems, ballast and drinking water lines. [42]

These pipes are often filament wound GRP which made possible the creation of an ISO standard entitled *Specification and recommended practice for the use of GRP piping in the petroleum and natural gas industries* (ISO 14692 [43]). The *Guide for the Certification of FRP Hydrocarbon Production Piping Systems*[44] by the American Bureau of Shipping also covers all aspects from the manufacture to use of these pipes and have helped increase end-user confidence.

The main issue with such pipes remains the joining of the different lengths. To solve this question adhesive bonding, threaded joints and key-lock joint that utilise rubber seals are being used. For higher pressure applications one may use spigot/socket joint with machined or moulded threads. Heavy flanges are still the preferred method.

GRP pipes and tubes have other uses including sulphate reduction units, inner liners for drill bits to retain core, float shoe noses for assisting casing and cementing, and vent lines.

One composite product that has seen significant increased usage, particularly onshore, is spoolable Composite Coiled Tubing (CCT). This product comprises a thermoplastic liner for permeation an erosion protection over-wound by a filament wound composite for structural properties. An outer coating can be applied for additional protection from impact and adverse soil conditions. The spooling process introduces micro-cracks within the composite layer. These are believed to be advantageous as they allow gases which permeate the liner to leave the CCT, in effect acting as pressure relief.

Composite materials are being increasingly used to line steel pipes. The composite provides corrosion protection for the pipe bore by acting as a barrier to the passage of transported fluids. The composite lined pipe solution is in direct competition with conventional corrosion resistant alloys (CRA) systems for downhole and flowline/pipeline applications.

Statoil pioneered the use of downhole tubing with composite materials in the North Sea. A Duoline 20 liner was examined after five years of service at up to 110°C and was found to be in excellent condition. The technology has generally been confined to water injection service. [42]

Statoil has now developed internal specifications for the use of downhole tubing with composite material liners in the North Sea after an extensive test and pre-qualification program based on results from a well in the Norne field. [42]

Compared with other low cost alternatives such as fusion bonded epoxy (FBE) coatings and polyethylene liners, FRP liners provide a more robust corrosion protection system. While some resins

are not suitable for certain fluids, other fibre and resin systems such as carbon and phenolic, may well be able to survive under sustained High Temperature and High Pressure (HTHP) conditions.

Flexible Pipe with Carbon Fibre Armours

The conventional unbounded flexible pipe is based on independent layers of steels and thermoplastic polymers. This typical pipeline architecture has been used in offshore industry for 40 years.

The extremely severe conditions in terms of dynamic loading, high corrosive environments and temperatures, demands design innovation to extend he envelops of performance. In this situation, composite material will then contribute to improve the performances of flexible pipes when it is exposed to fatigue and corrosion. Nevertheless, design considerations have to be attended to the composite materials requirements, especially concerning criteria on ageing and fatigue behaviour as well. [42, 55]

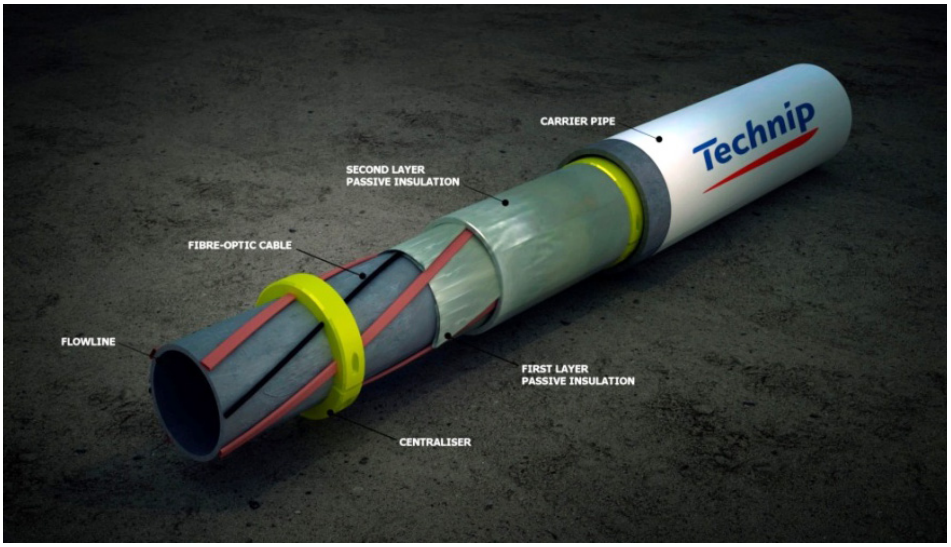

Figure 4.8: Example of a Flexible pipe with carbon applications by Technip (source: www.offshore-mag.com/articles/print/volume-73/issue-4/pipelines-flowlines/electrically-trace-heated-pip-system-advances-subsea-development.html)

Composites to Repair Corroded Steelwork

The use of composite materials for repair and rehabilitation of corroded steelwork, including pipes, decks, structural members and caissons, is now established practice. The approach is to wrap a fibre mat of glass or carbon, depending on the pressure requirements. The resin, often a polyester, vinylester or epoxy, is usually applied as a vacuum infusion and cured using a heat source such as a thermal blanket. Using the laminate in a multi-directional orientation allows the rehabilitation to repair potential leaks and restore axial and hoop strength capability. A document published by the HSE gives a guide to the use of composite repair where there is: [42]

- External corrosion where there is no leakage and structural integrity needs to be restored and deterioration halted;
- External damage where structural integrity needs to be restored;

- Internal metal loss through corrosion or erosion that may or may not be leaking but structural integrity needs to be restored.

Gratings, Handrails and Stairways

Gratings are not only an accepted product but also a commercial competitive one. The advantages offshore are obvious in the improved resistance to corrosion in a sea water environment and their durability and light weight, compared to metallic options. The products are generally pultruned glass reinforced, offering a cost effective manufacturing method. The use of phenolic resins allow the parts to meet fire resistance requirements offshore. An important driver for GRP gratings has been the ease of installation compared to steel. [42]

Blast and Firewall panels

Panels and three dimensional mouldings comprising sandwich structures of composite materials with a thermal insulating core are used for passive fire and blast restraint systems for jet fire and blast protection in the offshore oil and gas industry. These blast panels require approval from bodies such as Loyd's Register and DNV for protection against hydrocarbon jet fire, pool fire and gas cloud explosion blast conditions. [42]

Subsea Equipment Protection Structures and Thermal Insulation

Composites are also being increasingly used to protect subsea structures such as wellheads, and flowlines, protecting them from impact events such as dropped objects and commercial fishing operations. This is an accepted area of use where perceived risks of adoption are outweighed by the benefits in performance and corrosion resistance. Other examples of such equipment include subsea shutdown valve and actuator enclosure. Composites are also used extensively for thermal insulation where phenolic resin composite materials are used for subsea flowline insulation and doghouse assemblies where resistance to increasingly stringent HTHP conditions is necessary. The doghouse provides a shell around a flowline to manifold connector and are designed to be positioned by ROVs at depths of 1700m operating at over 110^0C. [42] In the last chapter one will discuss further the application of composite materials to ROVs, using the Luso ROV as a case study.

Aplications	Conditions
Pipework and Pipelines	Tests in the North Sea: 5 years at 110^oC (water injection) [42]
Subsea Equipment Protections	Used at 1700m of depth at 110^oC (water) [42]
Flexible Pipes (Carbon Fiber Armors)	Ageing performance validation for 30 years, at 110^oC, in water + CO_2 + H_2S [41]

Table 4.3: Summary of composite materials in use in the deep-sea offshore oil and gas industry and their operation conditions

4.4 State of the Art and Future Perspectives

The implementation of composite materials and the qualifications of these components for the use in the deep-sea off-shore oil & gas are some of the most important steps for the next few years. The introduction of this technology and its applications to deep-sea off-shore exploration is clearly incorporated in the technological trajectory for the industry, as referred by *Oliveira et al.* [2], in the radical innovative solutions. The other two main trajectories, continuity and intermediary (see [2]), may also gain with the application of such technology, though the propose of those trajectories sets limits to the use of innovative and disruptive technology.

Over the past decades, carbon fibres have found wide applications in numerous industries. As described, it is now also beginning to find innovative applications in the deep-sea offshore oil and gas and subsea industry.

With the expansion of the industry, new applications and studies are being performed. Composites have been studied for drill pipes and risers primarily because they will weigh less than half that of a similar steel components. This not only has advantages for deepwater uses and extended lateral drilling, but also has potential cost savings for on-board ship deployment because more sections can be shipped at one time. Another advantage is the development of smart drill pipes with the composite carrying cabling for real time signal and power transmission within the pipe walls. With suitable fatigue designs, a tighter drilling radius can be incorporated. [42]

There have been several projects investigating the use of carbon reinforced composites for risers where one of the prime motives is for lighter string in deep water applications. Composite risers may see more applications with the increase in deep water exploration.

While CCT has seen significant service on land, its use offshore under significant HTHP conditions is still growing. Spoolable composite pipe has been used in several offshore locations particularly in steel pipe repairs, where the CCT is pulled through the pipe to form the new line. The steel pipe protects the CCT and avoids buoyancy issues and the need for weighting solutions. [42]

Composite TLP tether, under investigation also, can be fabricated to be virtually neutrally buoyant, reducing the tensioning requirement. Also, the tethers are largely unidirectional carbon composites, they have excellent fatigue strength against the pitch and roll of the TLP.

Composite materials also offer advantages as the principal material for the body of valves and pumps, They have a proven track record in other industries where hostile fluids are handled and can be used for Acid Transfer, Brine, Chemical Processing, Corrosive Services, Water Treatment, etc. While GRP pumps and valves have better corrosion resistance compared to more expensive and highly-alloyed metals, use of carbon fibre composite further increases the durability for use with downhole and production chemicals. [42]

One of the next steps for composite material pipework is to manufacture solid composite flowlines that can resist HTHP and other hostile conditions. Composite pipelines are currently limited to use primarily in the water and sewer industries. However, in the offshore oil and gas sector, composite pipelines are used to transport hydrocarbons at temperatures above 90^0C. [42]

In drilling, completion and workover operations many tools, such as packers and bridge plugs are milled or drilled out when they need to be removed for stimulation and workovers. When multiple bridge plugs are used, this drilling becomes a time consuming process. This is an easier lower cost exercise with composites. Composite drillable plugs continue to be the material of choice for several companies in these applications. Other components fabricated from composites used in cementing operations, include squeeze packers, landing collars and liner wiper plugs and pack off inserts. While these parts tend to be glass or carbon epoxy, thermoplastic resins such as PEEK and PPS are also being considered for their better environmental resistance.

Intelligent composite material wire line concepts are being investigated using carbon PEEK braided and pultruded around a copper, another application in study. [42]

Rather like the aerospace industry, composite materials are becoming an enabling materials to solve some of the technical challenges faced by the offshore oil and gas industry in accessing ”hard to reach” oil and gas reserves with priority on deep water production. Like in the aerospace industry, the high specific strength and stiffness are paramount to obtaining the performance for the deep water fields. However there is another significant advantage of composite materials and that is that they do not corrode. This is not entirely accurate because in the long term, composites to degrade in hostile environments and the rate of degradation needs to be understood.

While the design and engineering of composite material components for the offshore industry can learn from and use the tools in the aerospace industry, the evaluation of long term degradation or ageing in the deep-sea offshore oil and gas environments requires new technologies to be developed as the ones developed for the aerospace industry (see table 4.4).

Ultra-Light Composites used in Advanced Aeronautics may also be used in the deep-sea offshore oil and gas industry. For example the TeXtreme® [56] technology can be manufactured using many different materials but are mainly produced using HS, IM and HM type carbon fibre:

- High Strength (HS) carbon fibre
- Intermediate Modulus (IM) carbon fibre
- High Modulus (HM) carbon fibre

The Spread Tow UD (Uni-Directional) tapes produced are much thinner than conventional carbon fibre tapes and have more material packed in the same area which gives better mechanical performance. [56]

- Light weight
- Thin plies
- Manoeuvrability
- Impacts reaction improved

The Spread Tow structure makes possible the creation of thinner laminates, the straighter fibres with reduced crimp optimize and strengthen the composite and lower crimp reduce the excess of plastic, minimizing weight. [56]

Adding other fibres such as Innegra®, Twaron®, Kevlar®, Dyneema® or Zylon® in order to improve impact tolerance, varying the modulus within the fabric, and changing tape orientation are just a few of the ways to achieve the maximum benefits derived from TeXtreme®. [56]

These are just some examples of what may be used and tested in the near future for the deep-sea offshore oil and gas industry, others alternatives and projects were also presented in the last Offshore Technology Conference (OTC) conference (2014): [57–59].

The aeronautical industry, with the vast knowledge on this field of expertise, is of extreme importance for the evolution and development of the composite materials industry with applications in the O&G and subsea exploration sector.

This sector has already results in place for the behaviour of several materials like for carbon-epoxy composites. The certification for the use of composites in aeronautics obligates to identify possible occurrence of degradation by ageing, essentially regarding the thermal ageing process that affects the weight (weight loss) and a significant loss of mechanical strength and ultimate strain. [54].

The results for aeronautics, plus the existence of models to correlate the loss of mechanical characteristics of composite materials, are of great importance for the development of applications with composite materials for the offshore oil and gas and deep sea exploration sector.

Limitations	Aerospace	Deep-sea Offshore Oil and Gas
Ageing Performance	Loss of weight and of mechanical strength and ultimate strain due to chemical degradation on environments rich in oxygen [54]	Degradation of materials - loss of weight and change in mechanical properties - due to the severe environment: sealtwater and chemical products like hydrocarbon condensate and H2S
Design Approach	Bi-axial approximations to motion and high values for safety factors (flight envelopes)	materials under complex three-dimensional stress states [60] and design of equipments (pipes) must take into account the change of mechanical properties

Table 4.4: Summary of the technical comparison between Aerospace and Deep-sea Offshore Oil and Gas - composite materials: ageing and design approach

4.5 Risk Analysis

To conclude the discussion on if composite materials are capable to offer solutions for the deep-sea offshore oil and gas industry one will now follow the framework by IRGC to analyse the benefits and risks of their application.

The analyses are performed with data from interviews (industry mainly), literature review and comparison with similar studies by IRGC.

4.5.1 Benefits

The use of composite materials, as seen, is capable of offering numerous advantages for overcoming the new challenges.

- Resistance to corrosion and other environments (all references);
- Lighter applications (all references);

After the extensive literature review and interviews with the industry, is evident that the composite materials are one of the main developments in the technological industry with applications in this sector. [41]

The benefits go further with the possibility for faster installations of risers (Technip in [41]) to higher safety margins in the fatigue performance and corrosion resistance.

Though these benefits are essential for the development of the deep-sea offshore oil and gas industry one has also to look for the main assessed risks.

4.5.2 Risks

Materials address some risks, essentially on the topic of the testability and reliability of these materials when compared to others that are used for far more years (metals and plastics).

The risks on the materials derive mainly from technological aspects but also from regulations and certifications:

- Technical issues like ageing essentially concerning elevated temperatures (accelerates degradation) [41];
- The increase on pressure invalidates the design simplifications (three dimensional failure criteria [60]);
- Standards still not adapted to all geometries [41].

Essentially the risks come from scientific and technical issues. The lack of knowledge on the behaviour of some materials is still the greatest risk with the composite applications.

Certification guidelines like [61] have still some limitations on procedures for different geometries though ASTM [45] and ISO [43] guidelines already recommend specific tests.

4.5.3 Managing Risks and Recommendations

The use of composite materials is of great interest for the deep-sea offshore oil and gas industry. The information gathered in the interviews to the industry and literature show that several projects of R&D are underdevelopment and that the industry is extremely interested as can be seen in the OTC of 2014 and 2013. [39–41, 57–59]

The investigation of the physical characteristics and behaviours of materials and the reactions to external conditions is an opportunity for the Portuguese universities to enter in this demanding sector. The opportunity that may be of more significant interest is the development on the extremely light composites, as mentioned.

Following the IRGC methodology for technology related risks, one has to check if all the pre-assessment question are answered, essentially regarding the scientific risks. The potential damages and adverse effects have been highlighted with reference to the degradation of materials. The probability of occurrence is high, as the limitations are presented in all the environments and conditions, but the problem is that may just appear after several years of operation (life cycles of around 30 years). These limitations may only be reversed with further scientific and technological research in order to understand the performance and evolution of the materials in these environments. The benefits, opportunities and potential of these applications and solutions are also referred.

Concluding, the application of composite materials is of great interest for the deep-sea offshore oil and gas industry. Research is needed in terms of the evaluation of the behaviour of materials in extreme conditions. After such a thorough investigation, that has already started, major benefits may be gain with the introduction of this type of technology (table 4.5). The opportunities that arise from the use of composites for deep-sea environments may be categorized as radical and innovative solutions ([2]) which bring some more challenges that the industry has already proven to risk, as the potential benefits are extremely valuable.

Limitations	Risks	Solutions
Ageing Performance	Materials, as the examples show, change abruptly their physical characteristics with time under severe conditions of temperature and in corrosive environments (saltwater, hydrocarbon gas condensate and 30ppm H2S)	Deeper knowledge on the matter urges, using for example the approaches used in the aerospace industry such as A and B basis allowable along with limit load approaches tests
Design Approach	The design approach must care for these changes in performance of composite materials (fibre carbon and fibre glass). Other important issue on the design approach is the simplification into a bi-axial state which is not a valid simplification when referring to the new challenges of deep sea exploration	Also deeper knowledge urges but for this case one may use safety factors that may help prevent possible situations. The use of different types of materials already used in aeronautics may serve as a solution to prevent some issues

Table 4.5: Summary of Materials - risks and recommendations

5

Discussion and Summary

Contents

5.1 Introduction

Presented the two technological case studies, underwater acoustics and composite materials, one is now going to integrate the limitations and operability ranges to a specific case study, the ROV Luso. The acoustic systems and the composite materials on board are studied and an analysis to their limitations and ranges is presented with the operational data received from the EMEPC.

The practical case study has as main objective to make a contact with specialists in deep-sea operations in order to add more value to this work and so understand the robustness of the work here presented. The work with the EMEPC was developed at their headquarters, Paço de Arcos, and was helped by the use of data from the dives since 2008.

The discussion and the presentation of further work and limitations conclude this last chapter.

5.2 The ROV Luso - An application case study

To integrate the research one will present the case of the ROV Luso, the only ROV operating in Portugal, bought in 2008, by the EMEPC, and only one of eight in Europe (for the same purposes).

The ROV Luso has the capability to dive until 6000 m of depth and has as main goals the gathering of samples from the deep subsea and constitutes an advantage when accessing European and other funds in the areas of deep sea exploration.[62]

This machine has several equipments, mainly robot arms, video camera, Doppler velocity logger (DVL), CTD (conductivity, temperature, and depth sensor) for measuring oceanic properties, altimeter and acoustical positioning systems.[62] The structure of the equipment is mainly constituted by aluminium and titanium alloys (T6082 for example).

For the study of this ROV, field work and interviews are performed to members of the EMEPC (A).

The interest in this case study is that the technology on board, not only acoustical systems (positioning systems) but has also composite protection structures, makes it an ideal case for applying and understanding the behaviour of the last mentioned phenomena, limitations and risks.

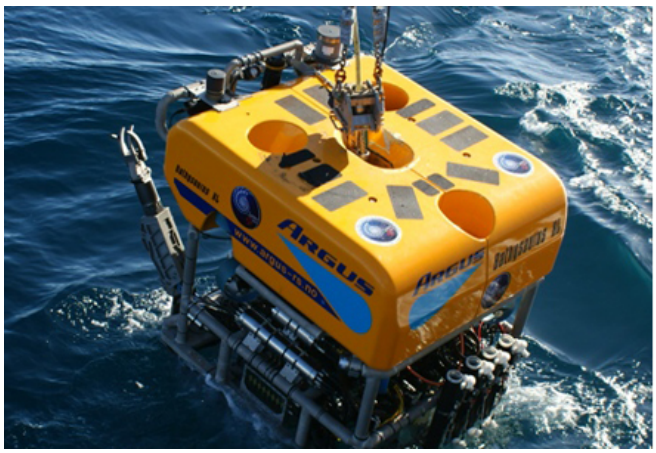

Figure 5.1: Photo of the launch of Luso in 2012, Azores (Source: www.rtp.pt/acores/index.php?t=Missao-cientifica-recolhe-nos-mares-dos-Acores-novos-dados-para-alargamento-da-Zona-Economica-Exclusiva-som.rtp&article=28390&visual=3&layout=10&tm=10)

The field work and interviews are expected to allow to understand these next issues:

- Understand the projects in which the Luso ROV is involved;
- Technical definitions and characteristics of the operations of Luso;
- Understand the acoustical systems of the ROV:

  Limitations of use;

  Used ranges;
- Understand the composite materials of the ROV:

  Materials;

  Limitations of use;

5.2.1 Technology on board

In order to study the capacity of the ROV Luso to overcome the challenges of the operations in deep-sea, and following the topics discussed above, the following vehicle's instruments were chosen for study:

	Equipments
Acoustic Systems	Acoustic Positioning - USBL
	DVL (Doppler Velocity Log)
	Altimeter
Composite Materials	Buoyancy - Sintactic Foam
	Umbilical - Kevlar

Table 5.1: Equipments to test on the ROV Luso

Having defined in previous chapters the challenges in terms of depths, high corrosion and wide temperature ranges, all this combined with highly demanding cycles of utilization of the equipment, is important to start to identify and check the conditions of operation.

It is also essential to understand that Luso is not associated with so demanding operations as the deep-sea oil and gas exploration but certain challenges are comparable to those, as illustrated below.

Operations of Luso

Luso was purchased in 2008 and since then has operated in several missions. Mainly from scientific nature, the ROV operates in conditions of high depths, for demanding cycles.

It is important to verify the temperature ranges and salinity, per dive, as it has been previously discussed that these variations are of limiting conditions for the proper functioning of the acoustic systems.

As a way of gathering all this information data from the CTD (figure 5.2), altimetry and positioning were requisitioned and are grouped in tables and graphs, shown below.

Figure 5.2: Photo of Luso's CTD sensor - instrument used to determine the conductivity, temperature, and depth of the ocean

The next graphic and table present the evolution of depths experimented by the ROV, per year and summarizes the number of dives and total hours of use:

Year	Data
2008	Number of Dives: 22
	Maximum Depth: 2656 m
	Total hours of use: 87:50:00
2009	Number of Dives: 23
	Maximum Depth: 3248 m
	Total hours of use: 88:57:00
2010	Number of Dives: 26
	Maximum Depth: 2407
	Total hours of use: 111:01:38
2012	Number of Dives: 20
	Maximum Depth: 2235 m
	Total hours of use: 77:03:00
2013	Number of Dives: 15
	Maximum Depth: 2150 m
	Total hours of use: 71:11:12

Table 5.2: Operations of the ROV Luso - Dives

From this last table one may observe that, per year, the ROV is in average around 87 hours in operation and does in average 21 dives (lacks data from 2011).

The maximum depth operated is of 3248 m (2009) and from the following graphic it is possible to

see that the ROV has operated in ultra-deep water conditions more than once (over 1500 m).

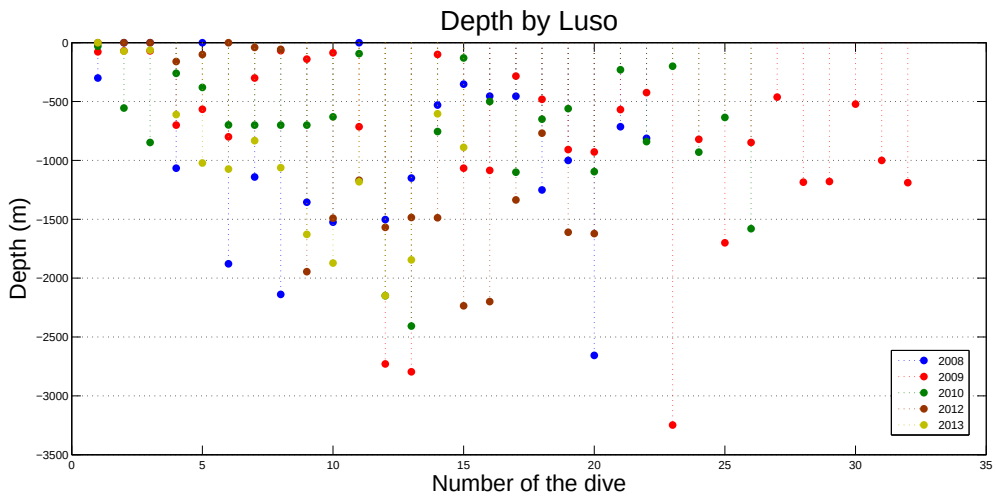

Figure 5.3: Depth of Luso's dives. Data from the EMEPC from 2008 to 2014, except 2011

This next chart, in addition to the table 5.3, shows the variation of temperatures Luso experiences in one dive, though higher temperatures may be seen when near thermal areas, around 300°C (this ROV has operated in such conditions but that information was not provided).

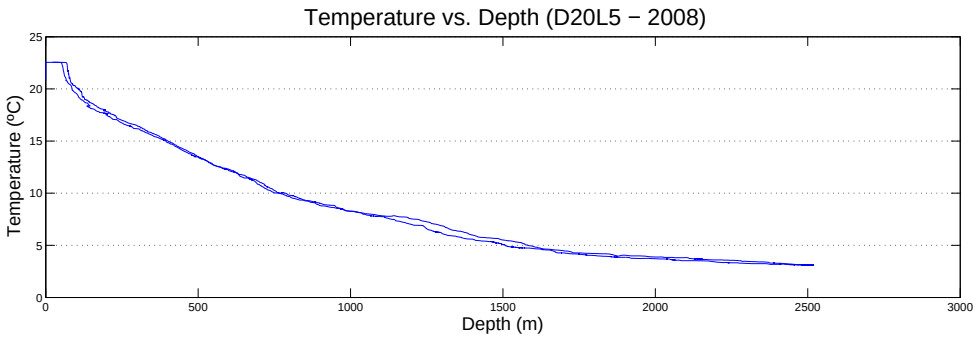

Figure 5.4: Temperature vs. Depth by Luso in the dive D20L5 of 2008. Data from the EMEPC

Other important factor is the salinity of the water, which interferes with the acoustic communications and also helps on the degradation of materials. In the next chart one may see the evolution of the salinity in one dive of the ROV Luso, this year.

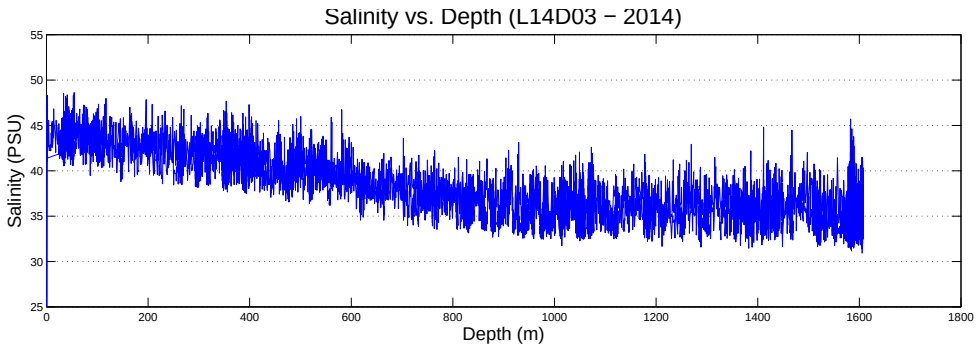

Figure 5.5: Salinity vs. Depth by Luso in the dive L14D03 of 2014. Data from the EMEPC

This next table resumes all the important values to retain in terms of the conditions to which the ROV experienced in this last 6 years (2011 has no data available):

Year	Data
2008	Temperatures range (^{o}C): from 22,559 to 3,087
	Salinity maximum (PSU): 40,68
2009	Temperatures range (^{o}C): from 25,561 to 2,912
	Salinity maximum (PSU): 35,29
2010	Temperatures range (^{o}C): from 22,845 to 3,288
	Salinity maximum (PSU): 38,66
2012	Temperatures range (^{o}C): from 25,771 to 3,924
	Salinity maximum (PSU): 39,65
2013	Temperatures range (^{o}C): from 21,778 to 3,244
	Salinity maximum (PSU): 37,39
2014 (Some data)	Temperatures range (^{o}C): from 14,629 to 3,437
	Salinity maximum (PSU): 53,36

Table 5.3: Operations of the ROV Luso - Maximum and minimum ranges of operation in terms of temperature and salinity

To resume the conditions to which Luso is subjected one may conclude that deep-sea operations bring enormous challenges for the equipments on board.

Depths of more than 1500 m, temperature ranges that are usually around 20°C and salinity maximums of 53.36 PSU are certainly extreme conditions to any system.

The variation of all these properties leads to the continuous change of sound velocity (graph 5.6), according to the equation 3.17, which constraints the use of the acoustic components of the ROV.

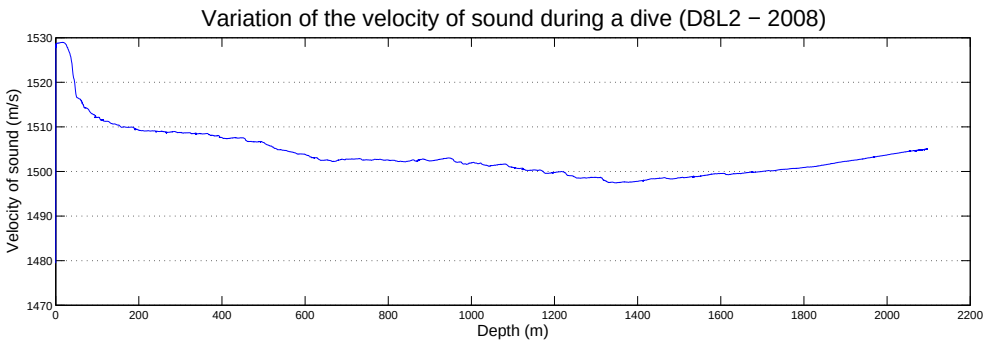

Figure 5.6: Variation of the sound velocity in deep waters - data from the dive D8L2 of 2008. Data from the EMEPC

The speed of sound in a dive changes significantly, in this case it is possible to observe a range of speeds from 1530 m/s to speeds lower than 1500 m/s. This variation is also confirmed by the literature though for this work the important is that the variation will be limiting for the acoustical signs.

High levels of salinity added to temperature ranges bigger than 20°C constrain not only the use of the acoustical sensors but also help to deteriorate the mechanical properties of the ROV's structure, essentially some specific equipments such as the umbilical.

Acoustic Systems

The Luso presents several acoustic systems on board: USBL, DVL and Altimeter (table 5.1). For each system one will present photographs and tables gathering all the information researched *in loco* at the EMEPC.

The acoustical equipments on board of Luso serve mainly to assess the ROV location when in operation. As this is the main aim of these equipments one will try to understand how the challenging conditions of deep-sea condition the use of such equipments and propose solutions for the limitations.

Firstly one must understand which equipments were reviewed:

Equipments	Data
Acoustic Positioning - USBL	Tracklink 10000
DVL (Doppler Velocity Log)	RD Instruments - Workhorse Navigator DVL
Altimeter	The Kongsberg SIMRAD Mesotech 1007-Series

Table 5.4: Acoustic equipments on the ROV Luso

The altimeter is a Mesotech 1007 and works only when the distance to the bottom of the ocean is smaller than 100m.[63] This sensor is extremely limited as during the majority of operations it is not delivering any real data, though it may have a major role when operations take place close to the ocean floor. The next photography shows this equipment:

Figure 5.7: Photo of Luso's altimeter (black instrument)

The Doppler Velocity Log (DVL) , showed in the next figure, has its operation ranges presented in the table 5.5. This system is essential to gather information on the positioning of the ROV and collect data from the currents (current's profiler).[64]

As shown in the next figure the DVL is located in the rear of the ROV:

Figure 5.8: Photo of Luso's DVL - Doppler Velocity Log - On the left the entire sensor and on the right a close photo of the sensor

The USBL is composed by two transponders and an array transceiver (with two heads). Works in two different modes: responder and transponder. Is the main acoustic equipment of Luso and is essential to gather information on its positioning.[65]

This equipment is the most required during operations. As explained later this equipment (Ultra Short Baseline) needs only one terminal on the ship in order to create a ”line of communication” (responder vs. transponder). This limits the operations with the ROV but at the same time it allows the vehicle to dive practically everywhere, as there is no need for extra receptors.

Figure 5.9: Photo of Luso’s USBL - positioning system - On the left one of the ”heads” and on the right the central core

The ranges of operation of all the systems mentioned are presented in the next table (following the information presented in [63–65]):

Equipments	Operation Ranges
Acoustic Positioning - USBL	-5 to 45°C and an accuracy range of 0.4m
DVL (Doppler Velocity Log)	-5 to 45°C and up to 6000m
Altimeter	Up to 6000m and starts working at 100m of the ocean floor

Table 5.5: Acoustic equipments on the ROV Luso

As one may see by comparing these ranges of operation and the conditions experienced by the ROV, Luso’s operations do not stress the use of such equipments, though some challenges have been point out by the EMEPC.

Composite Materials

The Luso presents two important composite materials structures: the buoyancy and the umbilical (table 5.1).

The majority of the structure of the ROV is in aluminium and titanium alloys. The composite materials serve mainly two functions: enhance the buoyancy of the structure and to protect the interior of the umbilical, serving mainly to hold the tensions in the cable.

Equipments	Data
Buoyancy	Sintactic Foam with glass reinforced spheres
Umbilical	Aramid (Kevlar) and thermoplastic polyester

Table 5.6: Composite materials on the ROV Luso

The umbilical has several layers but the most important for this case study is the Aramid reinforced one (the second layer starting from the outside 5.10).[66] This Kevlar layer of 21.7 mm (diameter), has several applications also in aeronautics, and shows good resistance to abrasion, good resistance to organic solvents, is non-conductive, degradation starts from 500°C, low flammability, presenting extraordinary mechanical properties such as: high Young's modulus, high tenacity and low creep.

The yellow and orange layers (in figure 5.10) are fabricated in thermoplastic polyester and have 25.7 mm and 17.2 mm of diameter, respectively.

Figure 5.10: Photo of Luso's umbilical - section of the umbilical with the protection layers and the interior cables (three of cooper for energy conduction and one fibre-optic cable)

The materials within the umbilical show some signs of degradation which can easily explain the rupture of the umbilical at least two times in the last six years.

The buoyancy is composed by a sintactic foam with glass reinforced spheres comprising glass microspheres and macrospheres held together within an epoxy resin system to create a homogenous matrix. Composite buoyancy systems comprise an integrated shell to ensure maximum protection of the core material in the event of accidental impact. The selection of a barrier coating on buoyancy modules of any type is a critical issue. These coatings provide impact and abrasion resistance.[67–69]

Figure 5.11: Photo of Luso's buoyancy system: top left and bottom with a general overview and top right a close photo of the interior (sintactic foam)

The materials on board of the ROV are subjected to extreme corrosive means (as seen in the salinity table) and to a high temperature amplitude which, as seen in the previous chapters, induce some degree of material degradation (specially in the area where the external coating has been lost).

The specifications of each materials allow these operation conditions but several issues were mentioned by the EMEPC ROV team, especially the setting of conditions for the fluctuation, which has already led to an improvement on the ROV Luso.

The limitations found for the ROV Luso are explained in the next subsection, and rely on the motivations of the ROV's coordination group and their vast experience.

Conclusions on the case study

The conditions found by the EMEPC in the Atlantic ocean are inside the ranges of operability of all Luso's equipments, as expected.

Though the requirements are met, several issues came up during the interviews. For the acoustical systems, noise and deficiencies in the transmission of signals, were the main difficulty presented as the noise from the propulsion system limited the use of the USBL. The use of individual sensors, i.e. not integrated, revealed several limitations in the operations.

For the composite materials the degradation of the umbilical led to the reduction of the tensile and flexural properties and the structural changes in the ROV imply the constant adaptation of buoyancy.

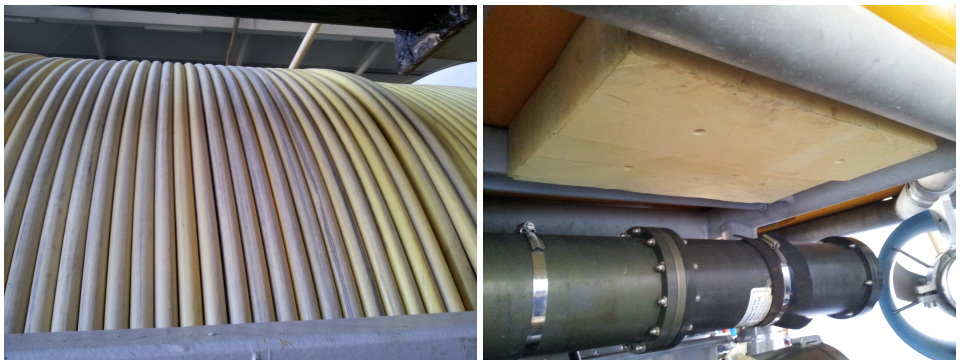

Figure 5.12: Photos of Luso's structural limitations - On the left the degradation of the umbilical and on the right the adaptation of extra buoyancy

The need to improve the ROV for different missions, and also to upgrade to a novel generation of remotely operated vehicles, makes the integration of new materials and structures that may accommodate this last challenges.

The work developed together with the EMEPC made possible to identify some projects that may be of great importance for the future of the deep sea exploration:

1. Structures in composite materials to upgrade current generation of ROVs;
2. Adapt existing sensors towards multi-sensor integrated systems, to avoid current limitations of positioning sensors;
3. SHM mechanisms, integrating acoustic sensors and composite materials;

In conclusion, this case study made possible to understand the limitations of the oceanic environment and the challenges in the deep sea exploration.

The ROV Luso may also be used as a test bed for the development and test of further technology for the deep sea essentially regarding the technological areas presented throughout this master thesis.

5.3 Summary

The new challenges for the deep-sea offshore oil and gas exploration, but also for the sustainable exploitation of the oceans (as both share similar challenges, as proved with the case study on the ROV Luso), are leading the technological trajectories to focus on innovative and radical solutions.

Therefore the main purpose of this thesis was to identify and understand the applications and limits/challenges of operation for two technologies (case studies), from the aeronautic sector, in this environment: composite materials and acoustic communications.

- The analysis - learning from aeronautics:

  Acoustic communications: towards multi-sensor integration in deep-sea robotics;

  Composite materials: towards future applications in deep sea robotics for better buoyancy control.

The research presented in this work shows several references to the aeronautical sector when referring to the deep-sea offshore oil and gas technological developments. Not only with possible new applications for technology already developed for the aeronautical industry but also the scientific knowledge, the know-how in working with state of the art technology, the certification and the testability procedures used in aeronautics. This information was gathered not only in the bibliographic review but also by specialists (FMC Technologies and LusoTechnip) and confirmed with the practical case study with the ROV Luso.

In terms of the first case study, the main limitations concern to the range of operability of some equipments. The acoustical positioning systems present a wide range of operability, starting with a few centimetres (less than 10cm) to several kilometres (up to 6km). The frequency bands used can also vary from a few kHz to hundreds kHz, though the deeper the frequency can reach the less accurate the measure can be.

The changing conditions on sea behaviour (temperature, salinity, currents and others - as seen in the last section) change abruptly the propagation of sound waves. The data transmission rate can, for example, reach 10kbits/s in extreme depths with favourable conditions. This vulnerability of the conditions may compromise all the acoustical communications.

The limitations found, and the new challenges ahead, are leading to the integration of equipments, multi-sensor integration, in order to prevent the constraints found in frequencies, propagation losses and also data transmission limitations.

The second case study emphasizes the need to evaluate two important aspects on the use of composite materials: the ageing of materials and the design approaches. The first phenomenon evaluates the behaviour of materials after cycles of service under extreme conditions. The second explains the main issues on designing components for the deep-sea offshore oil and gas industry, with composite materials.

Composite materials, such as fibre-glass and carbon-fibres, change their mechanical behaviour abruptly when subjected to extreme conditions. The literature shows changes in the Young modulus

and tensile and flexural properties after 1 week of exposure to salt water (fibre-glass at around 350 bar) and evidences of total degradation of materials (glass and carbon fibres) when exposed do hydrocarbons gases.

Both issues are related, as the process of ageing changes some critical characteristics of materials, changing parameters in the design of objects, mainly in the safety factor. The main solution is the continuation of research in this topic but different materials may now be used as, for example, the new tape-like composite materials. The research and testability of these materials may benefit from the use of knowledge of the aerospace industry, as stated in some literature.

The Luso case study helped to gather the insights of specialists and made possible to identify a test bed for future uses. The capacity of the Portuguese industry, mainly the aeronautical sector, to enter in this industry may gain an important view and chance of testing technology by resorting this equipment.

- Application - ROV Luso: a test bed for future exploitation;

The practical case study served to identify clearly the environmental conditions in the deep-sea and also to understand the practical limitations of the acoustical equipments and the degradation of the composite materials on board.

The work developed with the EMEPC enabled to identify specific technological areas that are essential for the future of the sustainable exploration of the deep-sea:

1. Structures in composite materials to upgrade current generation of ROVs;
2. Adaptation of existing sensors towards multi-sensor integrated systems, to avoid current limitations of positioning sensors;
3. Structural Health Monitoring mechanisms, integrating acoustic sensors and composite materials.

There is still a long path to follow in order to overcome the new challenges for the deep-sea offshore oil and gas industry. Though it is already possible to reach deep sea waters, better accuracy is still needed to perform all the necessary tasks. Also for the composite materials, there are plenty of applications and possibilities.

The next table summarizes some of the risks and challenges for both case-studies, accounting for the main risks found for the deep-sea offshore oil and gas industry in this new age of challenges:

Deep-sea Offshore Oil & Gas	Underwater Acoustics	Composite Materials
Pirate Actions in Offshore Locations	-	-
Ciber-Attacks	Control systems and Use for Malicious activities	-
Natural Catastrophes	-	-
Industrial Catastrophes - Spills	-	Reaction of Materials to Impacts
Control and Communications in Deep Water	Use of ROVs and UMVs present the limitations mentioned	-
Lack of Scientific Knowledge	Control systems for using multiple robots interactions	Behaviour of Materials (Long-term use - Ageing; Simplifications on Design Approaches)
Lack or Non-Existing Regulations - Testing, Certifications and/or Guidelines for Technology use	UAVs, ROVs and UMVs	Certification and testability of Materials
Environment's Degradation - Pollution, Degradation of local air quality and water sources, Ecosystem Damage	-	Degradation of Materials

Table 5.7: Summary of risks for each case-study

The risks here pointed out and the need to develop innovative solutions to overcome such challenges is the primary goal of the creation of the International Observatory of Global Policies for the Sustainable Exploration of Atlantic, which is an implication of this thesis. This platform will allow the opportunity to develop and further study all the sea related technologies, making possible to assess and explore new engineering for the deep-sea offshore oil field services for the South Atlantic, allowing the managing of the risks.

- Implications: The need for an Observatory, to assess and explore new engineering for the deep-sea offshore oil field services for the South Atlantic.

5.4 Limitations and Further Work

The methodology used was based on an extensive literature review, in an interview method and field work to cover the information on all topics.

The work presents three ways for gathering scientific knowledge and one may observe important results and conclusions from the investigation performed. After an extensive literature review on all topics, not only the two technological aspects but also the deep-sea offshore oil and gas industry, all the information was corroborated by a large spectrum of interviews. The application of this knowledge to the ROV Luso is the most important part of this work as it serves as a ”test bed” to validate all the research. This last part makes possible the observation *in loco* of part of the phenomena studied but also helps to systematize the information on Luso, creating a summary of some technical characteristics and operation's summary.

The most important barriers to this thesis were the little readiness of individuals and groups (interviews and also literature) to engage in systematic and interdisciplinary thinking and sharing valuable insights and time constraints to deal with all the three case studies.

In terms of further work all chapters may be further studied, not only in terms of interviews, but also in terms of literature review and experiments to further prove the phenomena here presented.

This thesis is a first approach on a comparative study between two technologies from the aerospace sector and their implications when applied to the deep-sea offshore oil and gas industry. In terms of scientific knowledge it is important to continue to gather more information on the topics and understand what are the main projects undergoing on both sectors.

After analysing the undergoing projects another interesting path for the following work is an investigation on the capacity of Portugal's industry to develop work on this field of expertise. The aerospace industry in Portugal is an example of a sector that shows capacity, motivation and interest in expanding their end-users. The evolution of our technological society must pass by the search for players that can develop value from technology and so diversify their areas of comfort, by introducing disruptive technologies, making the sustainable exploration of the deep-sea an interesting area to explore.

Other topic that is of great importance to address is the study of the new technology-related industrial paradigm. To set the integration of technology as the driver for companies to present innovation and added value to the products, integrating also different actors (from academia to industrial partners), should be studied as the new product development paradigm.

In order to achieve better results in this investigation the work developed by my supervisor and me is going to continue. A research grant is in place to investigate the capacity of the Portuguese industry to attend the needs of the deep-sea offshore oil and gas industry and also the sustainable exploration of the Atlantic. The investigation will continue as part of the creation of the OIPG.

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A

Interviews - Guide and Interviewed Specialists

This interview aims to gather more information on the case studies by some specialists from industry and academia.

Technological Aspects

Offshore Oil & Gas Sector and Deep-sea Exploration

- What are the main changes, nowadays, on the O&G sector worldwide (technologically and business related)?
- Is it possible to refer the major risks in the O&G sector?
- Are these risks being carefully governed? Care to explain? Strategies o solve them?
- Which are the main technical challenges for the next years?

Composite Materials/Acoustic Communications

- Which projects are being developed in this area?
- Which kind of projects one can think with the connection between these areas? Are there any other projects one can think for this area?
- What are the main advantages of using that kind of technology in the O&G sector?
- What are the main risks of using that kind of technology?
- Is there enough knowledge in the Portuguese industry to develop this technology?
- Which are the main technical challenges for the next years?

Final Part

Portuguese Industry

- Which are the main projects in the company (aerospace related)?
- Which are the main end-users the company have?
- Is there any interest in developing projects in the O&G sector for the company?
- Is there enough knowledge (technological capability and human resources) in the Portuguese aerospace industry to undertake the risk of entering in a new sector?

Interviewed Person	Company/ Institution
Eng. Artur Costa	CEiiA
Eng. Fernando Barata Alves	Partex Oil & Gas
Dr. Tor Berge S. Gjersvik	FMC Technologies
Eng. Emir Sirage	FCT
Eng. Luis Serina	FCT
Dra. Fernanda Povoleri	Technip
Eng. Cristiano Silva	Technip
Eng. Rui Pimentel Santos	IN+
Eng. Nuno Simoes	UAVision
Prof. Antonio Pascoal	ISR
Eng. Luis Sebastiao	ISR
Dr. Aldino Santos de Campos	EMEPC
Dr. Pedro Madureira	EMEPC
Eng. Antonio Calado	EMEPC
Dra. Andreia Afonso	EMEPC

Table A.1: List of specialists