FACULTY OF SCIENCE AND TECHNOLOGY

MASTER THESIS

Study programme / specialisation:
Marine and Offshore Technology

The spring semester, 2022

Open / ~~Confidential~~

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Thesis title:
Risk Assessment of Utilising an Extra-Large Autonomous Underwater Vehicle for Liquid CO2 Transportation
Credits (ECTS): 30

Keywords:
Subsea Technology
Shuttle Tanker
Submarine
Autonomous transportation
Risk assessment
Risk analysis

Pages: 55

\+ appendix: 59

Stavanger, 15th June 2022
date/year

Acknowledgements

This thesis concludes my master's studies in the University of Stavanger's Marine and Offshore Technology program. I would like to thank everyone who has assisted and supported me during this thesis project.

First and foremost, I would like to express my gratitude to Professor Yihan Xing for his guidance, vast knowledge, kindness, and encouragement during this work and my master's studies.

My heartfelt appreciation to Yucong Ma for his invaluable assistance in providing information and suggestions that aided in completing my thesis.

Egor Smirnov
June 2022
Stavanger, Norway

Abstract

The development of autonomous maritime systems has been proliferating in recent years. One of these systems is a subsea shuttle tanker (SST) concept proposed as a potential alternative to pipelines and tanker ships for liquid CO_2 transportation. The SST is an extra-large merchant autonomous underwater vehicle. It travels from onshore facilities, where CO_2 is captured and transiently stored, to subsea wells for permanent storage and enhanced oil recovery projects. It is believed that introducing such extra-large AUVs can reduce the occurrence frequency of human-induced accidents. However, the potential accidents related to these vessels are still not detailed identified. Therefore, this work presents the full risk assessment of the SST for liquid CO_2 transportation. This work aims to close the gap within the operative context and design characteristics of such autonomous underwater freight vehicles. To do so, a formal safety assessment is performed in accordance with International Maritime Organization standards. First, the most critical information about the SST regarding the risk assessment process is highlighted. Then, the preliminary hazard analysis is implemented to identify hazards and evaluate relevant risks based on the presented baseline SST. Subsequently, systematic hazard identification is used to find critical safety and security risks. Further, corresponding control safety options are addressed for risk mitigation. Finally, generic recommendations for the main design aspects of the SST are provided based on the work results. The presented assessment revealed 90 hazards and relevant scenarios, and the implemented analysis showed that the most prioritised risks are dedicated to human involvement at the stage of mission configuration. It is expected that the results of the performed assessment will be taken into account in further stages of the SST development and may be useful for future unmanned and autonomous marine transportation studies.

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1. Introduction and Background

The most convenient way of transportation offshore oil and gas is via pipeline transportation from floating production units (FPUs) to onshore facilities (IHS Global Inc., 2013). However, there are limitations to this mode of transportation due to technical and economic restrictions. One essential constraint is the deployment cost, which increases with pipeline length and water depths. Besides significant capital expenditures (CAPEX) considerations, deep-water installations require constant inspections and surveillance, which may be challenging and expensive. Furthermore, pipeline maintenance and repair operations imply a whole line or partial shutdown, which can be economically undesirable. Thus, utilisation of offshore pipelines is desirable for large and high marginal fields located not far from the shoreline (Wilson, 2008). If a single field is remotely located, it is simpler to employ a shuttle tanker (Vestereng, 2019). However, tankers are exposed to dynamic load effects from wind and waves. Further, tanker operations are vulnerable to weather and cannot be carried out in severe sea states. Subsea Shuttle Tanker (SST) (illustrated in Fig. 1.1) proposed by Xing et al. (Xing et al., 2021) can serve as a potential alternative to conventional tankers and subsea pipelines. Placing transportation underwater will allow overcome weather-related limitations described above (Ellingsen et al., 2020; Equinor Energy AS, 2019; Ma, Xing, Ong, et al., 2021).

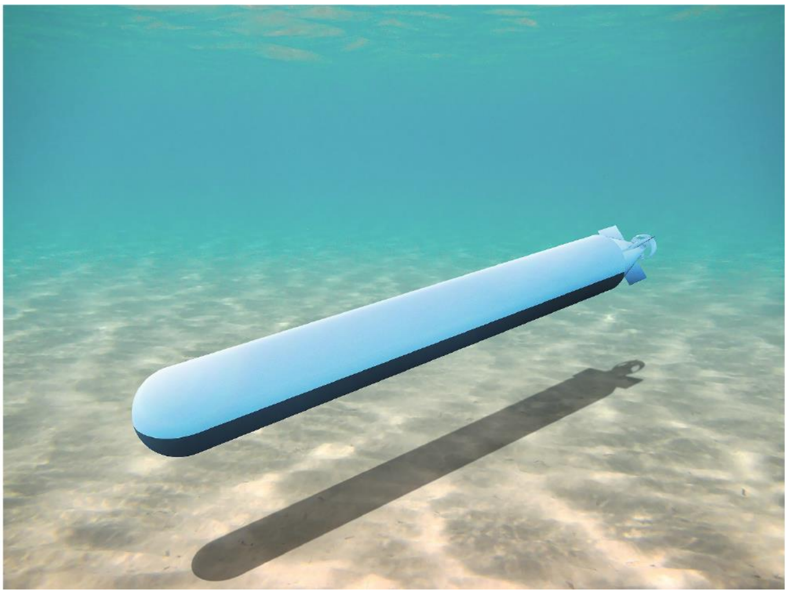

Fig. 1.1 Illustration of the subsea shuttle tanker.

1.1. Previous Research in Underwater Cargo Vessels

The idea of utilising underwater vehicles as means of transportation is not new and was proposed first in the 1970s by Jacobsen (Jacobsen, 1971) and Taylor et al. (Taylor & Montgomery, 1977), who presented the use of nuclear-powered submarines in a variety of sizes, 20,000 to 420,000 dead (DWT), to transport crude oil in the arctic region. Further, in the 1980s, Jacobsen et al. (Jacobsen et al., 1983; Jacobsen & Murphy, 1983) proposed two new submarines with higher capacities for LNG transportation: the first one was 660,000 DWT nuclear-powered vehicle, and the second one was a 727,400 DWT conventionally powered submarine. More recently, Ellingsen et al. (Ellingsen et al., 2020) published several underwater freight vehicles in a disclosure. One of these vehicles is an innovative vehicle, a 'cargo train' made up of interconnected subsea tanks with independent propulsion units located either at the bow or aft of the vessel. Another proposed vehicle is an ultra-efficient large glider vehicle. Based on that, Xing (Xing, 2021) came up with a 785 DWT subsea cargo glider that has a calculated power consumption below 10 kW. Furthermore, Ma et al. (Ma, Xing, Ong, et al., 2021) closed this knowledge gap by defining a baseline SST design and presenting the most critical design aspects, including weight distribution, structural capacities, cargo properties, and offloading methods. Defined baselined design can be used as the fundament for safety and risk assessment, which will allow to identify potential improvements and system safety in general.

1.2. Risk Assessment Towards Autonomous Maritime Industry

Due to recent technological advancement and experience gained in operations of unmanned systems, such as autonomous underwater vehicles and unmanned surface vessels, the interest in the projects such as SST has shown to be relevant (Banda et al., 2019; IHS Global Inc., 2013; Ma, Xing, Ong, et al., 2021; Ø. J. Rødseth & H. C. Burmeister, 2015; Wróbel et al., 2017). It is believed that the first unmanned sub-sea vessels will become available within the next 5-10 years (Kretschmann et al., 2015). Nevertheless, insurance companies are still sceptical about the concept of autonomous cargo vessels and unmanned vessels in general. This is because of the lack of legal framework for autonomous marine systems to operate in international waters. Existing regulations and conventions will need to be updated to account for their existence

(Hogg & Ghosh, 2016). So, it is vital to ensure that the utilisation of autonomous vessels would increase maritime safety or at least will maintain it at the same level as crewed vessels.

The first step to meeting the criterion described above is to conduct a safety and risk assessment on autonomous vessels. The present studies have been elaborated to establish the initial safety and risk management challenges that autonomous vessels will face. Wrobel et al. (Wróbel et al., 2016; Wróbel et al., 2017) analysed safety risks for the concept of an autonomous vessel, identifying the main challenges for the execution operations and prevention of accidents. Other studies have been aimed to assess the human role involved in the management of safety and during operations of autonomous vessels (Ahvenjärvi, 2016; Ramos et al., 2019; Wahlström et al., 2015). Further, more studies focused on the analysis, reviewing a semi-defined operative context and a determined escalation process for various degrees of autonomy (Burmeister et al., 2014a; Burmeister et al., 2014b; Ø. J. Rødseth & H.-C. Burmeister, 2015).

The previous studies have shown the need to consider the safety management of autonomous vessels from all possible perspectives for future successful operations. However, most of the presented studies were based on data lacking specific details about actual design characteristics, its operative context, and relative statistics used (Banda et al., 2019).

This work is aimed to close the gap within the operative context and design characteristics by implementing the full risk assessment for a novel SST vessel. The risk assessment would start by identifying operational scenarios and hazards in the different phases of operational activities. After, risk analysis will be implemented for each scenario based on evaluated probabilities and consequences. Furthermore, risk control options, cost-benefit assessment and general safety recommendations will be given following the overall structure of the IMO Formal Safety Assessment (FSA) (2018).

Risk assessment provides a structured basis for offshore operators to identify hazards and to ensure risks have been cost-effectively reduced to appropriate levels. It aims to identify risk at acceptable levels, point out potential improvements in an existing design, or choose between alternative design options (Rausand, 2020).

A significant number of studies have been elaborated on risk analysis of operational modes within marine traffic, including collision (Banda et al., 2016; Brown, 2002; Goerlandt & Montewka, 2015; Soares & Teixeira, 2001; Tam & Bucknall, 2010), grounding (Bakdi et al., 2020; Hong & Amdahl, 2012; Mazaheri et al., 2015; Mullai & Paulsson, 2011) and fire-related risks (Cicek & Celik, 2013; Soner et al., 2015; Vanem et al., 2008). Furthermore, studies in the domain of autonomous underwater vehicle safety have been elaborated recently (Brito & Griffiths, 2018; Brito et al., 2010; Griffiths & Trembanis, 2006). Despite the fact that the SST does not belong to the conventional class of tanker or AUV, these studies provide the basis to develop frameworks for the risk analysis of SST. These frameworks are considered for transferring the main components of safety assessment and hazard identification with the domain of underwater freight vessels. Further extensive description of tools and techniques applied during the evaluation will be specified in the upcoming section of methods.

According to the background above, the objective of this thesis work is to perform a risk assessment for the SST. The assessment will include hazard identification, risk analysis and evaluation; moreover, risk control options, cost-benefit assessment and general safety recommendations will be given. This will allow addressing the main safety consideration for the further development of the SST and its operations.

This thesis consists of seven chapters. **Chapter 2** describes the methodology of risk assessment, including the main definitions which will be used and information about Formal Safety Assessment and Preliminary Hazard Identification. **Chapter 3** presents the description of the SST system, which further be used as the baseline for assessment. **Chapter 4** contains an analysis of related hazard and threats studies; based on presented results, PHA is also performed in this chapter. **Chapter 5** shows the main finding of the cost-benefit assessment. **Chapters 6 and 7** summarise the results of assessments performed in this whole thesis work and present related recommendations. **Appendix A-F** present results of performed Preliminary Hazard Analysis for six operational phases of the SST. In **Appendix G** the draft paper on based work for journal publication is presented.

2. Methodology

This chapter will cover the methodology dedicated to the risk and safety assessment. The chapter contains two parts. Firstly, the terms and definitions used in the thesis will be presented. In the second part, methods used for risk assessment will be extensively described.

2.1. Definitions

2.1.1. Risk

A general definition of risk from ISO 31000 standard (2009):

> "Effect of uncertainty on objectives."

Here is another more specific definition, which is given by NORSOK Z-013 (2010):

> "Combination of the probability of occurrence of harm and the severity of that harm."

It can also be represented in the form of an equation:

$$\text{Risk} = \text{Probability} * \text{Consequences} \tag{1.1}$$

Rausand (2020) defined risk in another way, which is more suitable in terms of risk analysis:

"Risk is the combined answer to three questions: (1) What can go wrong? (2) What is likelihood of that happening? (3) What are the consequences?"

2.1.2. Hazard

A hazard can be defined as a "potential source of harm" (NORSOK Z-013, 2010). There harm may be "loss of life, damage to health, the environment, or assets, or a combination of these" (NORSOK Z-013, 2010). A hazardous event or scenario describes the event when a hazard is released (NORSOK Z-013, 2010).

2.1.3. Accident

An accident may be defined as:

"A sudden, unwanted, and unplanned event or event sequence that has led to harm to people, the environment, or other tangible assets."(Rausand, 2020)

There are several ways to categorise accidents, such as based on the type of accident, cause of the accident, and severity of the accident.

2.1.4. Failure and fault

NORSOK Z-016 (1998) defines the term failure as:

"Termination of the ability of an item to perform a required function."

From the definition, a failure is an event. When the item fails, it has a fault, which is its current state. However, a fault is often the result of a failure, it may exist without one (NORSOK Z-016, 1998). A fault can be used as:

"State of an item characterised by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources." (NORSOK Z-016, 1998)

2.1.5. Barriers

A barrier can be described as:

"Physical or engineered system or human action (based on specific procedures or administrative controls) that is implemented to prevent, control, or impede energy released from reaching the assets and causing harm." (Rausand, 2020)

Barriers may also be referred to as safeguards, risk control options or protective layers.

Barriers will be identified in relation to principles for safety engineering proposed by Möller and Hansson (2008). Safeguards can be divided into four major categories: inherently safe design, safety reserves, safe fail and procedural safeguards.

Inherently safe design measures aim to reduce inherent dangers as far as possible. This means hazards are rather to be excluded at all than just enclosed. Secondly, safety reserves imply establishing and including safety factors during calculation, for example, for loads. Safety reserves are used to make sure that loads applied would not exceed design values. A safe fail principle, in general, can be defined in the following way. When the failure occurs, it should fail "safely ", or then an internal component of the system fails, and the system as a whole should continue to work. Procedural safeguards can be presented in the form of applied standards and quality assurance for the technical aspect of the system, or also can be training and behaviour control of the staff.

Those four types of safety principles will be used to define barriers in the present work.

2.2. Risk and Formal Safety Assessment Process

In this study, a risk assessment, including hazard identification for Subsea Shuttle Tanker during transportation of CO2 in the Norwegian sector, is presented. The assessment aims to ensure acceptable safety and security levels for the SST and other vessels and the shipping community in general. Furthermore, the assessment points out potential improvements in an existing design or chooses between alternative design methods.

The application considers the outcomes of previous studies on maritime transportation and traffic risk, including those executed for the analysis of autonomous and unmanned vessels. The primary type of accidents and hazards in the operational context will be identified based on this information.

The SST operations can be associated with a number of hazardous outcomes. This involves damage or loss to the SST or its equipment, damage to 3rd parties and assets involved at any operational phases of the SST. Furthermore, consequences related to environmental and health damage can also be considered. These considerations may be very broad; thus, in this work, risks related to health and loss of life factors would not be considered since operations of SST do not contribute direct human involvement. The main scope will be aimed to describe risks involved in damage and loss of SST, mission disruption/abortion and also damage to equipment directly involved in an operation, such as thug boats or wellheads. However, risks excluded in the presented work should be considered in future.

The case study will consider the utilisation of the SST within the Norwegian sector's carbon capture and storage (CCS) programmes. For operational context, several phases of operation will be considered. The phases include underwater navigation, underwater-surface transition, surface navigation, loading and offloading, and preparation.

The analysis is limited at a high level, and functionally will be addressed to the major components of subsystems. Hardware damage can be assumed both from internal and external impacts. The main components subjected to external damage are the hull, propeller and bladders. The internal damage can affect hardware inside the SST, connections etc.

2.2.1. Formal Safety Assessment

The risk assessment used for the SST system is based on the Formal Safety Assessment (FSA) method from IMO guidelines. Formal Safety Assessment is a structured and systematic methodology aimed at enhancing maritime safety, including the protection of life, health, the marine environment, and property, by using risk analysis and cost-benefit assessment (Organisation I. M., 2018). This is an internationally accepted method for risk-based analysis. Thus, it is a reasonable baseline to use for a novel vessel such as SST. The Formal Safety Assessment methodology can be applied as a balanced view to identifying areas of concern and priorities at the phase of design. As defined, FSA includes a 5-step process, including hazard identification, risk assessment, development of risk control options, cost-benefit assessment, and making recommendations for decision making. The FSA process is depicted in Fig. 2.1.

The process of FSA starts with defining the objective of the study along with boundary conditions. The boundary conditions were identified in **Chapter 2.2,** and the SST description as a whole will be described in **Chapter 3 a**fter this information is used in the defined steps of the process.

All available and suitable data should be considered in the Formal Safety Assessment to provide sufficient results. To sustain data, expert judgement, simulations and analytical models may be used to achieve valuable results (Organisation I. M., 2018).

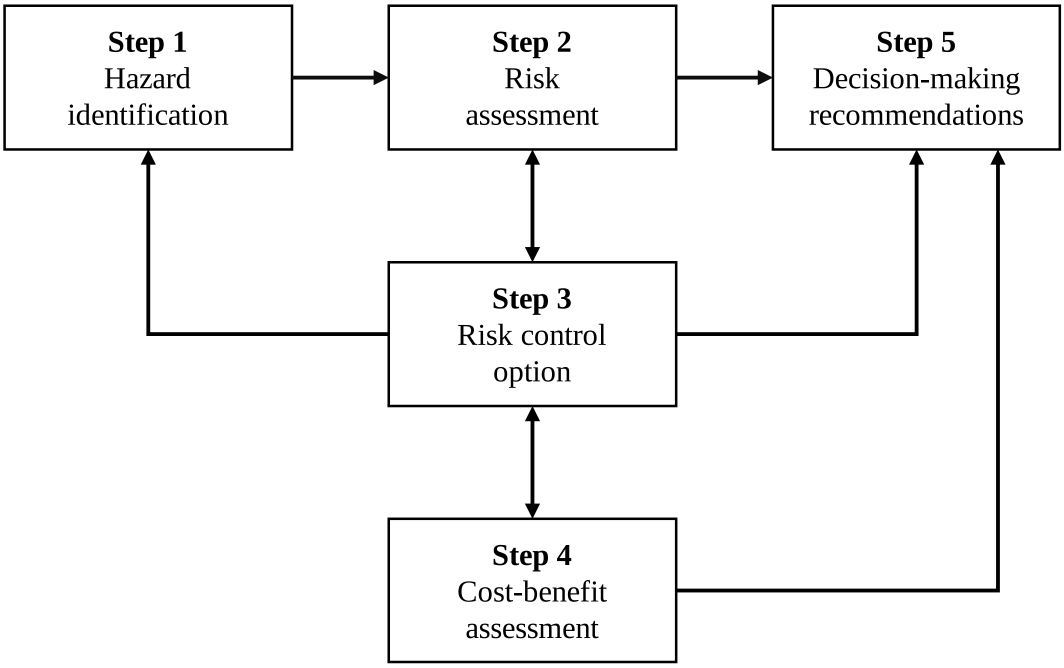

Fig. 2.1 FSA methodology (Organisation I. M., 2018).

The identification of hazards is the first step at FSA, and it is aimed to identify hazards and relevant associated scenarios specific to the operation of the SST in that case. The identification of hazards will be considered for different operational phases of the SST to provide an overall view.

In the second step, the risk analysis is meant to provide a detailed understanding of the causes and consequences of accident scenarios. Risks should be ranked accordingly to their probabilities and consequences. Probabilities and consequences should be evaluated considering historical data and previous studies. Once the risks have been assessed, they should be considered relative to their ranking, from highest to lowest.

In the third step, risk control options (RCO) will be discussed. Here the accidents with unacceptable risk levels have to become the primary focus.

The cost-benefit assessment focuses on identifying and comparing the costs of each risk control option with the purpose of identifying the best practices. However, the safety of the system and environment must be prioritised against any economic aspects.

The last step in FSA is decision-making recommendations; in the presented work, those recommendations will be addressed for improvement of the SST safety and its design.

However, FSA provides a structured and systematic methodology, but it does not regulate tools and methods. DNV guidelines on autonomous and remotely operated ships DNVGL-CG-0264 (DNV, 2018b) can be used here to choose a method of hazards identification and risk analysis.

DNVGL-CG-0264 (DNV, 2018b) guideline provides a framework for technical guidance for the safety assessment of autonomous and remotely operated vessels concepts and technologies. Presented guidelines cover safety considerations for the entire spectrum of functions intended for the autonomous system: Vessel engineering, Navigation, Remote control, and Communication. Furthermore, for autonomous type, enhanced assessment must be implemented for controlling vessel functions. This focus includes safe-state, failure mode, and fault robustness of the functions and systems.

Previous publications regarding autonomous and unmanned shipping safety utilised the following methods for risk assessment: HAZID (Ø. J. Rødseth & H.-C. Burmeister, 2015), BBN (Thieme & Utne, 2017; Wróbel et al., 2016), What If (Wróbel et al., 2017), and STPA (Wróbel et al., 2018). However, accordingly, DNVGL-CG-0264 suggests a preliminary hazard analysis (PHA) method as preferred for the technology qualification process at the stage of design.

The approach in this work will utilise Preliminary Hazard Analysis as the method of hazard identification and risk analysis. The utilisation of PHA will cover the first three steps of FSA, following which a cost-benefit assessment will

2.2.2. Preliminary Hazard Analysis

Hazards and potential accidents are identified with PHA during the early stages of the project. In addition to identifying hazards, PHAs are used to rank related risks according to their probability and consequences. The PHA technique was firstly developed by the US army (Deprtament of Defence, 2012), and has been used in a wide range of industries, including machinery, defence, process plants and etc.

The overall objective of a PHA is to reveal potential hazards, threats, and hazardous events early in the system development process, such that they can be removed, reduced, or controlled in the further development of the project. (Rausand, 2020) In addition, PHA identifies safety-critical functions and top-level mishaps to keep safety in focus during the design process. Furthermore, PHA allows to evaluate of relative risks by giving general characteristics of probability and consequences together with Initial Mishap Risk Index (IMRI) or Risk Priority Number (RPN).

The process of PHA consists of the following steps, those steps described below and represented in Fig. 2.2:

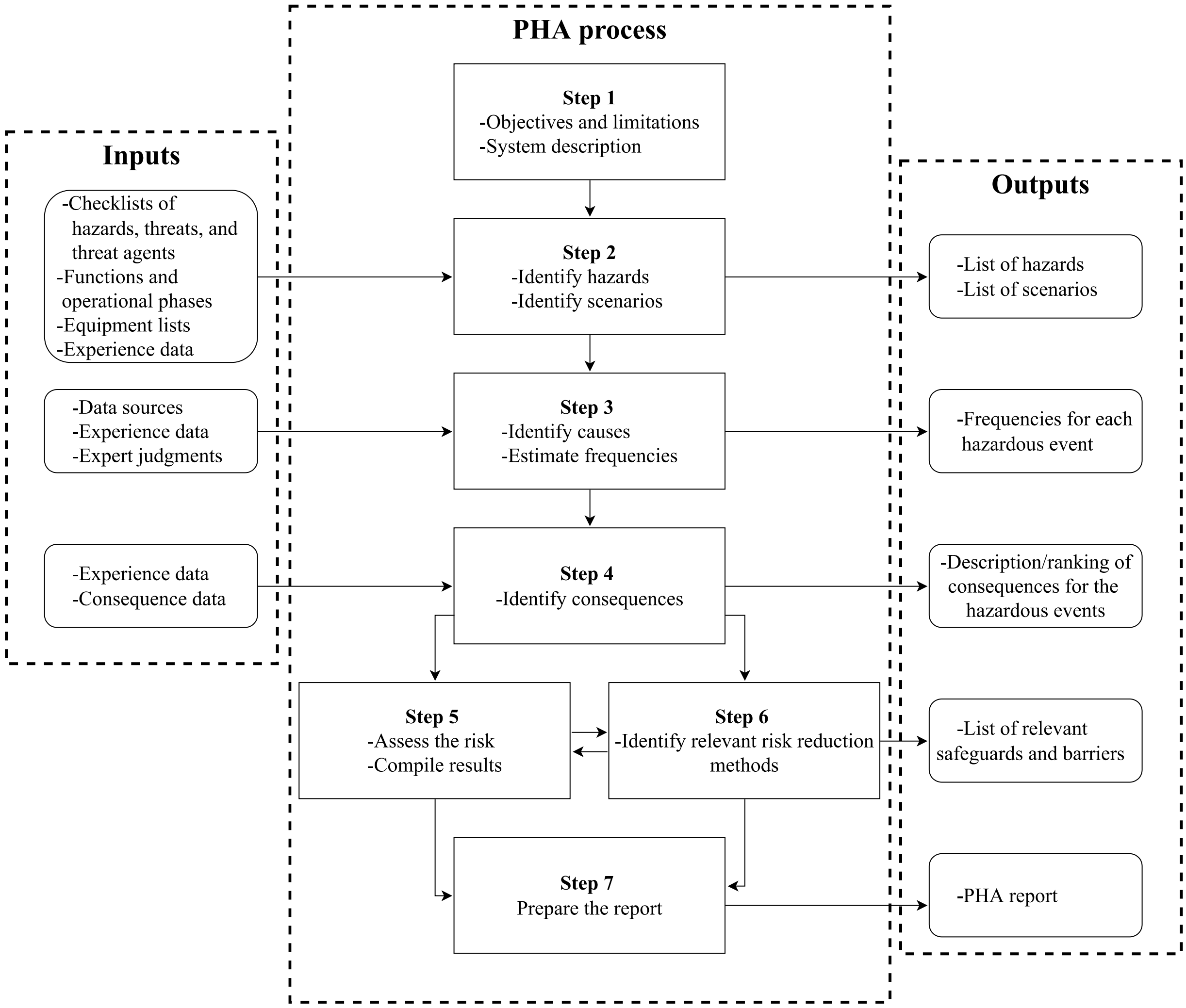

Fig. 2.2. PHA process.

<u>A. Plan and prepare</u>

The main aim is to assemble all known information, define time constraints and establish the list of participants to carry out the assessment.

Discuss main objectives and limitations. Define the mission, mission phases, and operational context. Acquire design, operational, and process data. Provide background data such as hazard checklist, failures and accidents, lessons learned and safety criteria.

B. Identify hazards and scenarios (hazardous events)

This step aims to establish a list of hazardous events. The identification of hazards takes place during the meetings of the expert group based on a generic checklist of hazards. In addition, participants contribute their knowledge and expertise, as well as experience from the study object (or a similar system). The main sources for judgment are reports from previous accidents and incidents, accident statistics, expert judgments, operational data, and checklists.

The outcome of this step is a list of hazards, causes, accident scenarios, and consequences. After that, a final list of hazardous events is established after structuring and filtering. It has the purpose of filtering out overlapping hazardous events and events with negligible probabilities and consequences.

C. Determine the frequency of hazardous events

In this step, the team discusses causes and evaluates the frequency of each event that was identified during step 2.

The frequency evaluation may be based on historical data, expert judgments, previous studies, and assumptions. The historical data usually comprise accident reports and statistics from similar accidents. Based on evaluated frequencies, the probabilities or likelihood of events are defined. Probabilities are sorted into categories, either based on qualitative or quantitative nature. In this study, we consider qualitative analysis, and probabilities categories are depicted in **Table 2.1**

Table 2.1 Probability categories used in the PHA.

Category	Rating	Description
Frequent	5	An event that is expected to occur frequently
Probable	4	An event that happens now and then and will normally be experienced
Occasional	3	An event is likely to occur in the lifetime of the system

Remote	2	A very rare event that is unlikely but possible to occur in the lifetime of the system
Improbable	1	The event, which is so unlikely. That it can be assumed not to be experienced

D. Determine the consequences of hazardous events

In this step, the potential consequences following each of the hazardous events in step 2 are identified and assessed. The scope covers consequences for different assets, such as people, equipment, and reputation. During estimations of consequences, assets are divided by their type, and estimation is performed for each. Afterwards, consequences are ranked by their severity and assigned with a corresponding value starting with 1 for least critical consequences and increasing as the severity escalates.

Consequence's categories are presented in Table 2.2 and can be assessed in relation to different values, such as life and health, environment, operations, economics and credibility. As the SST utilisation mainly implies autonomous operation without crew, life and health factor is not considered. Mainly consequences will be judged on operational consequences as the work aims to address adjustments and improvements to the SST design. However, risks related to environmental impact will be ranked accordingly to environmental categories of consequences.

Table 2.2 Consequence categories used in the PHA.

Consequences	**1**	**2**	**3**	**4**	**5**
	Not hazardous	**A certain hazard**	**Hazardous**	**Critical**	**Very critical**
Life and health	No physical or mental injuries.	Few or minor physical or mental injuries.	Serious physical or mental injury without permanent damage.	Serious physical or mental injury with permanent damage.	Death.
Environment	No measurable environmental damage.	Short-term reversible environmental damage or single emissions.	Long-term reversible environmental damage or recurring emissions.	Possible irreversible environmental damage.	Irreversible environmental damage.

Operation production and service	No impact on primary functions.	Minor reduction of primary functions that can be solved by simple means within a short time.	Primary activity is noticeably reduced but can be restored within a reasonable time.	Primary activities have been substantially reduced over a long period of time. Recovery will be demanding.	Primary functions are permanently impaired.
Economic and material values	No financial harm.	Minor financial loss that can be recovered.	Significant financial loss that can be recovered.	Irreparable financial loss.	Significant and irreparable financial loss.
Credibility and reputation	No impact on credibility. No reduced recruitment or funding	Impaired local cooperation and credibility. Somewhat reduced recruitment or funding.	Impaired regional cooperation and credibility. Reduced recruitment or funding.	Impaired national cooperation and credibility. Reduced recruitment and significant reduction in funding.	Impaired international and national cooperation and credibility. Significantly reduced recruitment and funding.

E. Assess the risk

Here, the risk is described as a list of all potential scenarios, together with their associated probabilities (frequencies) and consequences. Afterwards, to illustrate the risk all hazardous events are inserted into the risk matrix with the purpose to illustrate the risk. Risk acceptance criteria and corresponding risk control options are presented in Table 2.3.

Table 2.3 Risk acceptance criteria used in the PHA.

Category	Risk rating	Action
Unacceptable	17-25	Must implement cease in activities and endorse for immediate action
Tolerable	10-16	To implement improvement strategies, they must be reviewed on a regular basis
Adequate	5-9	Consideration may be given to the further analysis
Acceptable	1-4	It may not be necessary to take further action, and maintaining control measures is encouraged

F. Identify relevant risk reduction measures

After the risk has been identified, the team will provide new reduction measures wherever it's possible to maintain the risk within the limit of ALARP. After new/updated reduction measures have been represented, the risk is assessed again to demonstrate a reduction of it.

After completion of all steps, results will be presented in the form of PHA tables.

As it has been stated before, both Formal Safety Assessment and Preliminary Hazard Identification start with the description of the objective of the analysis, here SST.

3. SST baseline design / system

This section is intended to briefly summarise the design considerations for the Subsea Shuttle Tanker and the systems involved during offloading and loading. The presented design will be based on the work presented by Ma et al. (Ma, Xing, Ong, et al., 2021). The systems introduced here serve as a basis for the risk assessment in the following sections.

3.1. Overview

The main objective of the SST is to transport CO_2 in a liquid state autonomously underwater from land or offshore facilities to subsea wells for direct injection. The baseline SST is designed to be deployed in the Norwegian sector's carbon capture and storage (CCS) programmes. There are currently three ongoing projects: Sleipner, Utgard, and Snøhvit (Norwegian Petroleum Directorate (NPD), 2020). Furthermore, the Northern Lights project is set to start operation in 2024, where CO_2 generated from non-petroleum industrial activities will be transported and injected into the Troll field (Equinor ASA, 2020). The position of SST in the CCS supply chain is depicted in Fig. 3.1. Accordingly to the baseline SST (Ma, Xing, Ong, et al., 2021), the SST's cargo capacity is 15,000 tonnes to match the maximum annual carbon storage capacity of the CCS projects, i.e., 1.5 million tonnes annually. The locations of the above-mentioned projects are shown in Fig. 3.2.

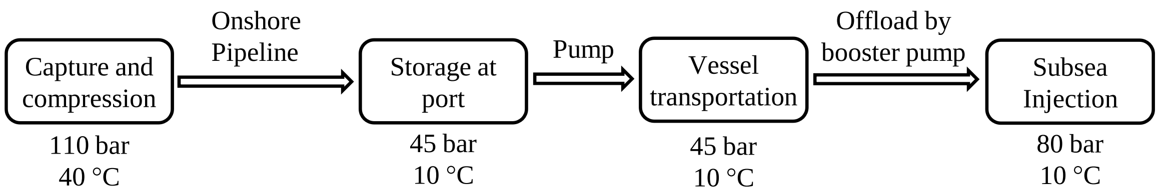

Fig. 3.1. CCS offshore storage process with SST transportation (Ma, Xing, & Hemmingsen, 2021).

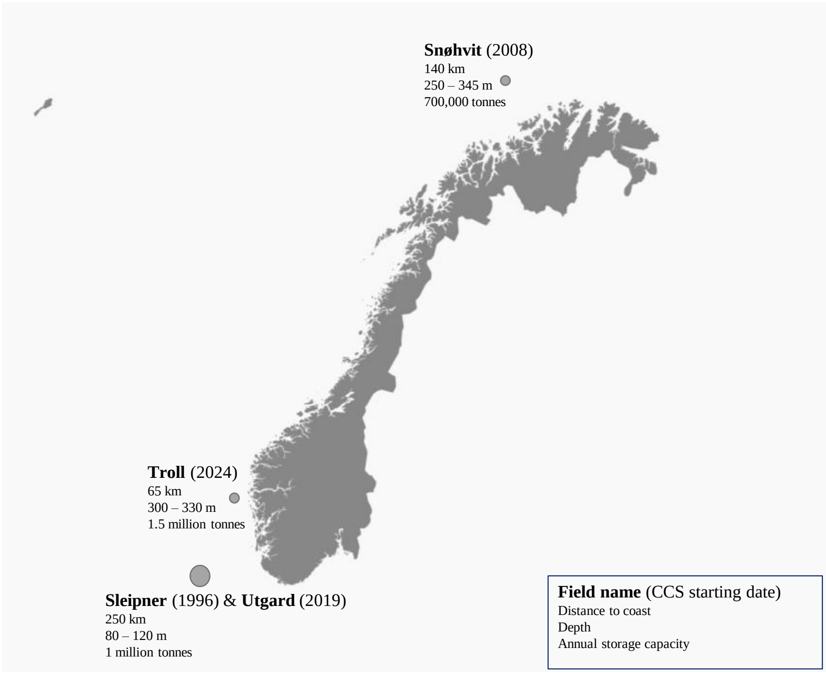

Fig. 3.2. Carbon storage sites in the Norwegian sector, current and planned (Ma, Xing, Ong, et al., 2021).

The SST can be designed to be utilised for the transportation of other types of cargo such as hydrocarbons, electrical power (through batteries), and subsea tools. Also, SST can contribute to the mitigation of global warming in a different manner. It is fully electrically powered and emission-free, which contributes to the sustainability of shipping. Approximately 3.3% of fossil-fuel-related CO_2 emissions currently contribute from shipping (Papanikolaou, 2014). On the other side, SST enables the flexibility to utilise marginal subsea fields as CO_2 storage sites without considering flow insurance problems relevant to pipeline transportation.

3.2. Mission requirements

The SST system by classification belongs to a cargo type of vessel. From the study proposed by Ma et al. (Ma, Xing, Ong, et al., 2021), SST is a submarine with 164 meters in length and 17 meters in beam, and calculated displacement constitutes 33,619 tonnes. The presented design is capable of carrying up to 16,362 m^3 of CO_2 for a range up to 400 km at a speed of 6 knots. The main design parameters are presented in Table 3.1.

<u>A. Operating depth range</u>

- The safety depth is set to be 40 meters. This is needed to avoid collision with surface ships or floating installations.

- The nominal diving depth is 70 meters. The SST is designed for operation at a constant 70 m depth. This depth is defined based on minimum recoverable depth from lost-control situations (Ma, Xing, Ong, et al., 2021).
- The test diving depth is 105 meters, and the collapse depth is 190 m. Those depths were established following DNVGL-RU-NAVAL-Pt4Ch1 (DNV, 2018c). The test diving depth is 1.5 times of nominal diving depth. Considering the collapse depth, the SST is designed not to collapse at a maximum 190 meters depth which is defended to be 2.7 times of nominal diving depth.

B. Range

The SST is designed to have a range of 400 km, which is sufficient to make a return trip to Snøhvit and Troll or a one-way trip to Sleipner and Utgard. Furthermore, the SST can be recharged using the existing offshore facilities in the latter case.

C. Environmental data

The SST will operate in the Norwegian Sea. In this region, the seawater temperature range is 2 °C –12 °C (Seidov et al., 2013). The temperature in seawater usually does not go below 0 °C, and for the summer months, 20 °C is the maximum temperature that can be reached.

The observed seasonal average current speed in the Norwegian Sea is 0.2 m/s, and the highest seasonal speed of the North Atlantic Current and Norwegian coastal current is 1 m/s (Mariano et al., 1995; Sætre, 2007). The latter is used as the SST designed current speed.

Table 3.1. Subsea shuttle tank main design parameters.

Parameter	Value	Unit
Length	164	[m]
Beam	17	[m]
Displacement	34,000	[tonnes]
Operating depth	70	[m]
Collapse depth	190	[m]
Operating speed	6	[knots]
Maximum range	400	[km]
Cargo volume	16,000	[m^3]

Cargo pressure	35-55	[bar]
Cargo temperature	0-20	[°C]
Design current speed	1	[m/s]

D. Carbon dioxide properties

Two methods are commonly utilised for the transportation of CO_2. First, CO_2 could be transported through the pipelines in the supercritical state and by using ships in the saturated liquid state. The utilisation of SST implies transportation in the saturated liquid state, in which the temperature and pressure are passively regulated by the environment, i.e., maintaining them at the defined setpoints requires no external energy. During transportation with SST, the pressure of liquid CO_2 will vary along the boiling line in the phase diagram as presented in Fig. 3.3. Furthermore, the liquid CO_2 at 45 bar can be directly pumped in to the reservoir using a single-stage booster pump, as opposed to gas carriers, where there are multiple booster pumps and interheaters required.

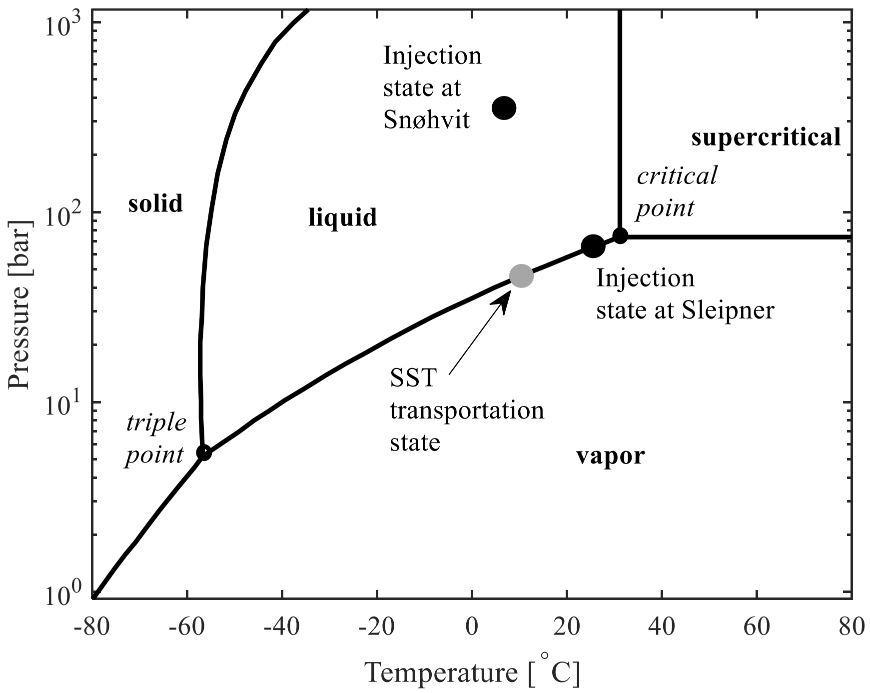

Fig. 3.3. CO_2 phase diagram with corresponding CO_2 states of transportation methods (data from (Ma, Xing, & Hemmingsen, 2021; Ma, Xing, Ong, et al., 2021)).

3.3. Systems and components

3.3.1. General arrangement

The SST is constructed with a torpedo-shaped hull that has a hemispherical bow, a 130.5 m long cylindrical mid-body section, and a 25 m long conical aft, the diameter is 17 m. To simplify geometry and reduce drag resistance, the torpedo shape was chosen. However, it is particularly challenging to design large submarines to resist collapse in deep waters. For the large diameter thin-walled structures, it is extremely costly to increase the collapse capacity (Xing et al., 2021).

A double hull design is utilised at the cylindrical mid-body to avoid the need for collapse pressure design. That means water can enter the internal space of the mid-body, as a result, internal and external pressures on the external hull cancel each other. In turn, cargo tanks and buoyancy tubes are designed to handle burst and collapse loads. The hemispherical bowl and conical aft are free flooding compartments; however, they a relatively smaller in size, allowing them to efficiently withstand pressure loads. All compartments are checked for collapse diving depth (19 bar). The steel VL D47 is chosen to be the material for all three compartments. The detailed characteristics of the material are presented in Table 3.2.

Table 3.2 SST external hull properties.

Parameter	Free flooding compartments	Flooded mid-body	Unit
Length	23.75	100.0	m
Thickness	0.041	0.025	m
Frame spacing	1.0	1.5	m
Steel weight	521	1374	tonnes
Material type	VL D47	VL D47	
Yield strength	460	460	MPa
Design pressure	20	7	Bar

The SST has four bulkheads to separate the flooded mid-body from free flooding compartments and support internal cargo tanks and buoyancy tubes. There are two watertight bulkheads at the forward and aft vessel and two non-watertight bulkheads, which are placed at the flooded mid-body. All bulkheads are also checked against nominal diving, test diving, and collapse pressures. The vessel is divided by two watertight bulkheads into three sections. The general arrangement is presented in Fig. 3.4.

- Free flooding aft compartment: it includes the moisture-sensitive parts such as the motor, gearbox, rudder controls battery, aft trim tank, and aft compensation.
- Flooded mid-body: the compartment includes buoyancy tanks, cargo tanks, and piping.
- Free flooding bow: compartment contains the sensors, sonar, radio, control satiation, pumps for offloading, fwd trim tank, and fwd compensation tank.

The non-watertight bulkheads are not subjected to hydrodynamic pressure, and they are utilised to provide support to the internal cargo tanks and buoyancy tubes.

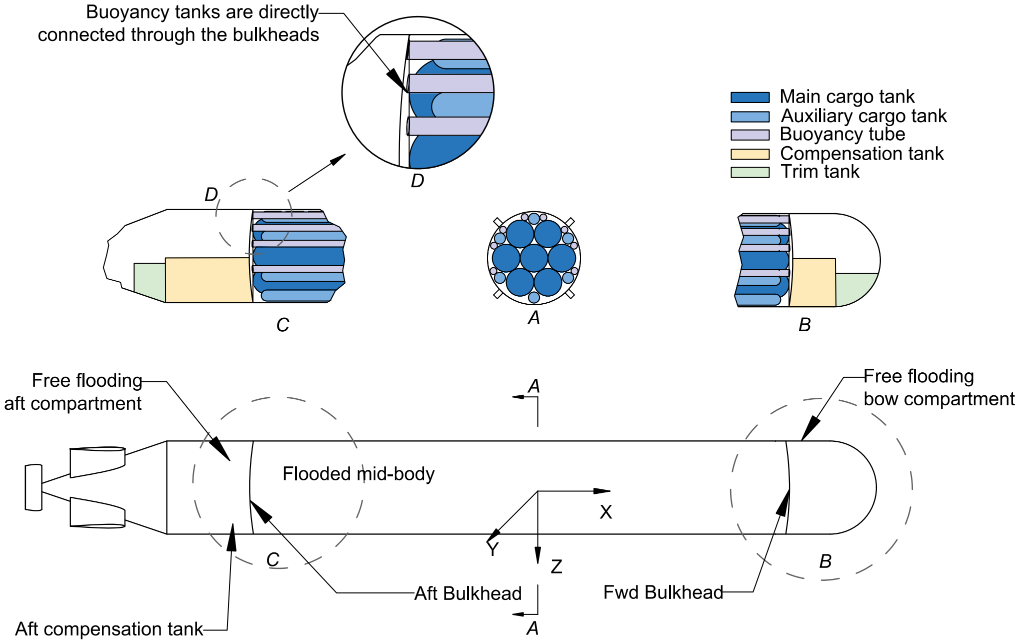

Fig. 3.4. SST general arrangement. A: Mid-vessel cross-section. B: SST fwd bulkhead. C: SST aft bulkhead. D: Buoyancy tank-bulkhead connection (Ma, Xing, Ong, et al., 2021).

3.3.2. Internal tank structures

The internal tanks comply with ASME standards BVPC Sec. VIII-2, Chapter 4.3 – Design rules for shells under internal pressure and Chapter 4.4 – Design of shells under external pressure and allowable compressive stresses (ASME, 2015). There are five kinds of internal pressure vessels: main cargo tanks, auxiliary cargo tanks, buoyancy tanks, compensation tanks, and trim tanks. It is vital to describe their main hazards during risk assessment, including fire, leakage, and explosion hazards. This is identified as the worst-case scenario that occurs during transportation of CO_2 on the sea surface when external hydrostatic pressure is 0 bar gauge, and the pressure difference is 55 bar.

A. Cargo tanks

There are 13 cylindrical cargo tanks (seven main and 6 auxiliary) placed in the flooded mid-body part of SST. These tanks have a designed burst pressure of 55 bar and are utilised for CO_2 storage.

B. Compensation tanks

Compensation tanks are placed in the free flooding compartments. They are not exposed to external pressure.

There are two 800 m^3 compensation tanks within the SST, and they communicate directly with the open sea using pumps. Compensation tanks help the SST maintain neutral buoyancy under different hydrostatic loads by providing the trimming moment and necessary weight.

C. Trim tanks

Two 200 m3 trim tanks are located in the bow hemisphere and aft cone (free flooding compartments) in the SST. Their main goal is to archive neutral trim conditions by bringing the centre of gravity (CoG) vertically beneath the centre of buoyancy (CoB). This is accomplished by pumping water between the trim tanks.

D. Buoyancy tanks

Eight buoyancy tanks measuring 1.25 m in diameter are positioned at the top of the SST to keep the vessel neutrally buoyant. These buoyancy tanks are 100 m long and directly connected to the bulkheads. Moreover, tanks are empty, i.e., free flooding so that the moisture-sensitive equipment can be arranged inside. These tanks are designed to handle 7 bar pressure corresponding to the 70 m nominal diving depth and collapse pressure of 17 bar.

3.3.3. Propulsion systems

With the SST, a propeller-driven system will be powered by electrical batteries on board, with additional machineries such as a motor, gearbox, and control unit. The SST uses a three-bladed propeller with a diameter of 7 m, a small blade area ratio of 0.3, and a slow operating rotational speed of 38 RPM, which provide it with a high quasi-propulsive coefficient (QPC) of 0.97 (Barnitsas et al., 1981; Ma, Xing, Ong, et al., 2021).

The SST battery properties are listed in Table 3. SST uses a Li-ion battery because of its high energy density, high specific energy, and steady power output over a long period of time. The SST is projected to be built within the next decade, and it is expected that technological developments within Li-ion batteries will increase its energy density significantly (Ma, Xing, Ong, et al., 2021). In the latest disclosure by Mikhaylik et al. (Mikhaylik et al., 2018), it has been predicted that the specific energy will be increased up to 500 Wh/kg compared to the current typical specific energy of 250 Wh/kg. As a result, the battery with a total capacity of 20,000 kWh is estimated to be 40 tonnes. The battery has a life of 1000 discharge cycles or about 8.3 years if two 400 km trips are performed weekly.

3.3.4. Pressure compensation system (PCS)

The pressure compensation system was integrated into the cargo and consisted of a movable piston with seals providing separation of CO_2 against seawater. The PCS is depicted in Fig. 3.5. The piston seals can be manufactured from the polyurethane-like pigs for pipelines. Further, pistons can be equipped with intelligent sensors for monitoring parameters such as tank pressure, cargo temperature, and corrosion status.

The PCS is designed to ensure that internal pressure in the cargo tanks will always be higher or equal to external pressure. It has several operation modes to ensure the safety of operations and prevent possible overload failures.

<u>A. Normal operating case</u>

Considering the normal operating case, transporting liquid CO_2 at 70 m depth is presented in Fig. 3.5. The CO_2 will be transported at 35-55 bar depending on water temperature, which varies from 0 to 20 °C. Seawater is at the other end of cargo tanks to fill up the remaining void and equalise pressure. The valve closes as the pressure reaches a defined value for a given temperature.

B. Uncontrolled descent case

As shown in Fig. 3.5 (b), in an accidental uncontrolled descent case, i.e., the SST descents to a water depth of 500 m, the external hydrostatic pressure will increase to 50 bar. At this point, a valve at one end of the cargo tank will be opened to allow seawater to flood in. The seawater will push against the piston. The internal pressure in the cargo tank will be equalised with hydrostatic pressure in the mid-body so that differential pressure will be eliminated. It can ensure the integrity of cargo tanks and avoid leakage in a nonrecoverable accident when the SST sinks.

C. Uncontrolled ascent case

Fig. 3.5 (c) presents an uncontrolled ascent case where the SST ascent to a water depth of 40 m, external hydrostatic pressure will reduce to 4 bar. The CO_2 pressure will increase from 45 bar to 50.9 bar due to increased temperature. The valve is closed, and CO_2 will push the piston against seawater. Therefore, seawater pressure will be increased and equalised. In this case, the differential burst pressure loading is 46.9 bar.

D. Seawater filled cases

As illustrated in Fig. 3.5 (d), the seawater-filled cases are situations where the cargo tanks are filled with seawater after the SST is offloaded at a subsea well. As intended, valves are closed, but if any accident occurs, which implies for SST to immerse deeper, valves will open and allow seawater to entre. As a result, the pressure difference is neglected.

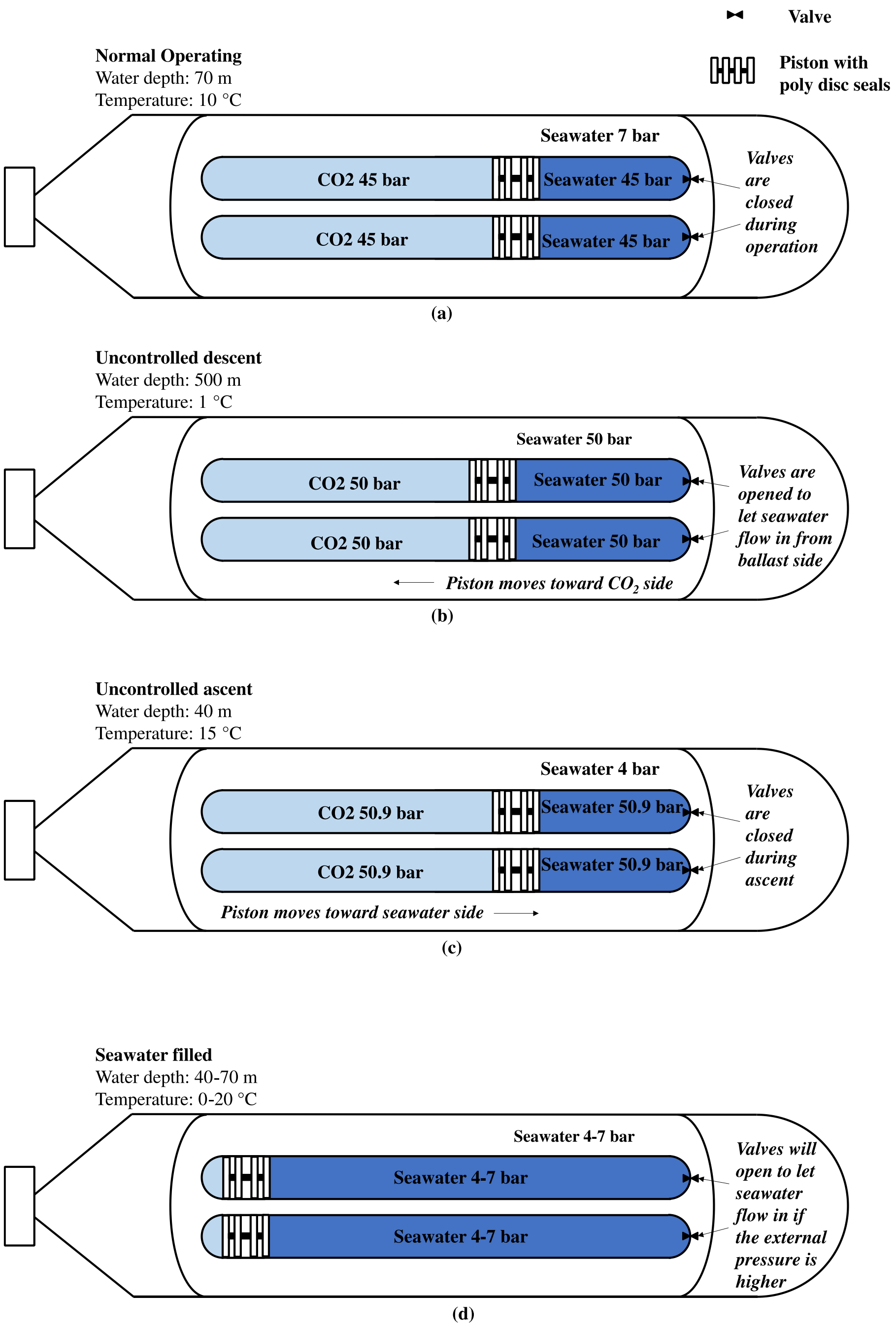

Fig. 3.5. Pressure compensation system.

3.3.5. Offloading

The SST is designed to offload CO_2 through a flexible flowline or riser connected to the subsea well while hovering. This flowline will be related to SST using an ROV or resident drone. The loading and offloading process is depicted in Fig. 3.6 and described in the following steps:

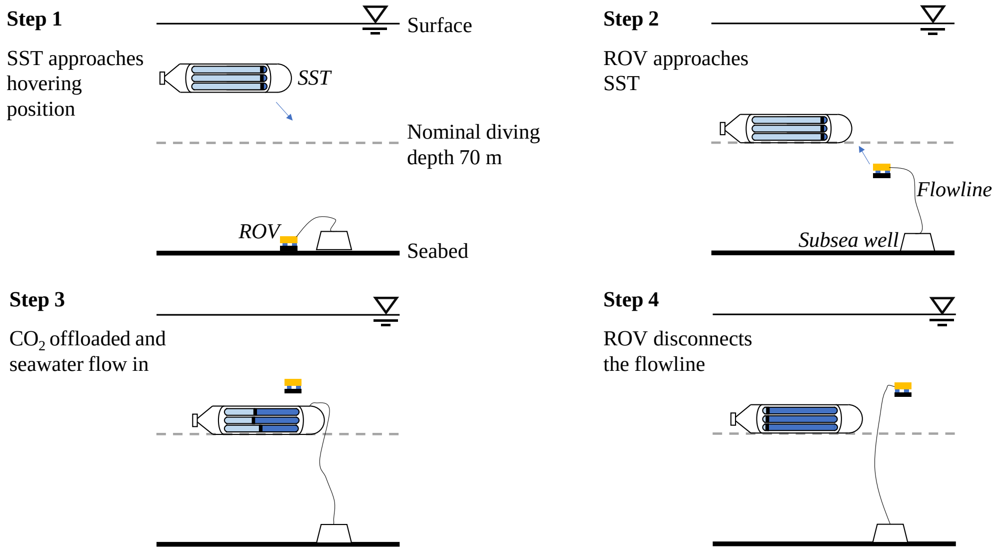

Fig. 3.6. SST loading and offloading procedure.

- Step 1. The SST navigates to the subsea well site and hovers at the operating depth.
- Step 2. An ROV or resident drone carries the flowline from the subsea well and mates it with SST.
- Step 3. Liquefied CO_2 is pumped out from each cargo tank through a mated connection and flowline to the subsea well. Meanwhile, seawater is pumped in from the other end of each cargo tank equalising the differential pressure inside and outside cargo tanks. The compensation and trim tanks are used to maintain the stability of the SST.
- Step 4. The ROV or resident drone disconnects the flowline.

4. Results

The main finding of the formal safety assessment and preliminary hazard analysis will be presented below. Additionally, an overview of AUV, tanker vessels and hoses systems hazards will be presented and discussed with threads. **Appendix A** is provided with documentation of the PHA process and hence unabridged results.

4.1. Risk factors and failure modes

Transportation of CO_2 using SST can be divided into three main stages, loading, transportation, and offloading. Fig. 4.1 depicts a functional flow diagram showing stages involved in the operation of transportation.

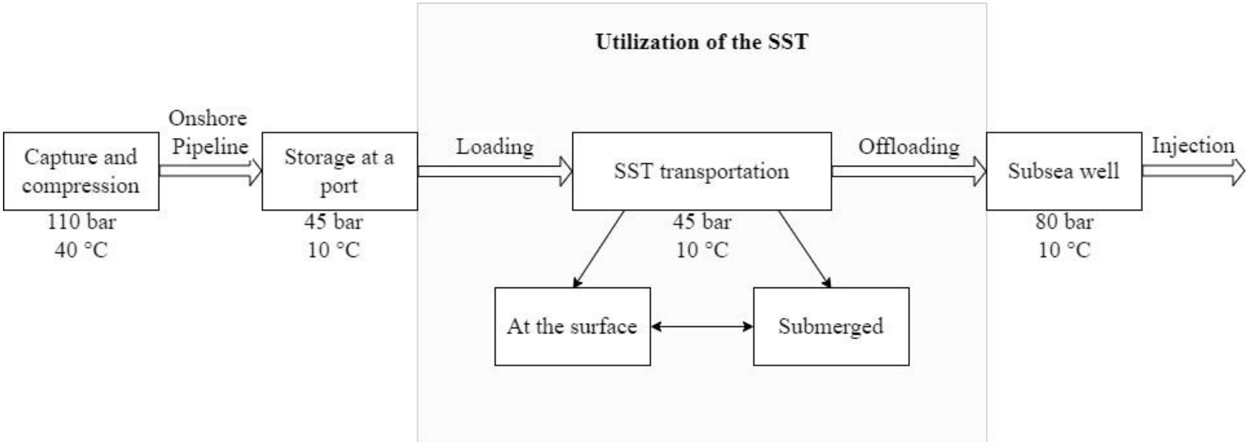

Fig. 4.1 SST functional diagram of operational phases.

Fig. 4.2 represents the list of main system components, functions, and energy sources that should be considered for PHA. The description of major SST subsystems and a list of equipment were given in **Chapter 3**.

Equipment List	Subsystems	Energy Sources
Radar and Sensors	SST Navigation	CO_2
Tanks	SST Loading/Offloading	Electricity
Pumps	SST Propulsion	Battery
Control Unit	SST Powering	
Piping	SST Environmental Detection System	
Buoyancy Tubes	SST Communication	
PCS	SST Emergency	
Motor		
Propeller		
Rudder		
Valves		

Fig. 4.2 SST system information.

Before hazard identification, the main risk factors have to be described. Real information about failure modes and accident data for SST is lacking. To give a general understanding of risk factors and main failure modes of systems with similar operational contexts will be considered. The SST combines functions of tanker vessels and autonomous underwater vehicles; furthermore at the phase of loading and offloading, hoses are used. Analysis of risk factors will be mainly based on technical factors and wouldn't go deep into human-related causes of risk.

4.1.1. AUV hazards

The SST has a similar operational principle, technical systems, and components as an AUV. An AUV consists of subsystems such as propulsion system, navigational system, communication system, power system, security detection system, sensor system, and others (Chen et al., 2021). The main AUV subsystems and corresponding risk factors are (Aslansefat et al., 2014; Bian et al., 2009a, 2009b; Fan & Ishibashi, 2015; Hegde et al., 2018; Xu et al., 2013; Yu et al., 2017):

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communication system, power system, security detection system, sensor system, and others (Chen et al., 2021). The main AUV subsystems and corresponding risk factors are (Aslansefat et al., 2014; Bian et al., 2009a, 2009b; Fan & Ishibashi, 2015; Hegde et al., 2018; Xu et al., 2013; Yu et al., 2017):

A. Propulsion system

In general, the propulsion system provides the required forces for vessel/vehicle movement. It can be based either on propeller or buoyancy-created hydrodynamic forces or combining both. Risk factors could be represented as propeller failure, buoyancy pump failure, actuator failure or a broken rudder.

B. Navigation system

The navigation system is employed to measure position, attitude, and velocity, allowing the vehicle to follow a predefined trajectory. Risk factors are characterised as failures of single components, including wrong interpretation of measured parameters.

C. Power system

The power system provides electrical energy by the batteries, either lithium-ion or alkaline. The relevant risk factors for power systems are failing to charge, overcharging, energy depletion, and failures related to voltage and current.

D. Communication system

The communication system is utilised in proposes to establish a connection between vehicles and operators. Risk factors are described as failure of acoustic transducers or sensors and loss of signal by any means.

E. Environmental detection system

The environmental detection system process data from sensors to detect the obstacles as well as prevent collision and grounding. The main components of the system are sonars and another sensor. Risk factors are a wrong interpretation of data leading to the collision and failure of sonars.

F. Emergency system

Emergency systems typically imply backup procedures in case of any significant failures.

Three studies are concluded to evaluate the characteristic of failures qualitatively. The first study analyses 205 AUV missions with 63 mission accidents (Brito et al., 2014). The second considers four-year missions' data of the Autosub3 AUV (Griffiths et al., 2003). In the third study, more than 400 missions and failures occurring during Sentry AUV operations are revied (Kaiser et al., 2018). The most significant failure modes of each study are presented in Table 4.1.

Table 4.1 Prioritised failure modes encountered during AUV operation.

	Failure mode	**Number of failures**	**Contribution factor**
1st Study			
	Leakage	15	Loss of integrity
	Failure of power system	9	Equipment failure
	Failure of the buoyancy pump	6	Equipment failure
	Collision with vessel	4	Collision/Grounding
	Sensor failure	4	Equipment failure
2nd Study			
	Incorrect predive programming	15	Software/Programming
	Electronic hardware failure	7	Equipment failure
	Acoustic sensor failure	6	Equipment failure
	Software error	5	Software/Programming
3rd Study			
	Incorrect predive programming	21	Software/Programming
	Collision with seabed	17	Collision/Grounding
	Acoustic sensor failure	15	Equipment failure
	Code problem	10	Software/Programming

4.1.2. Tanker vessels hazards

The results showed the occurrence of 212 accidents and failures. The majority of failures contributed to equipment failure, and it takes up about 42% of total cases. The following factor is software or programming problems, approximately 27%. Among all considered cases, only one single failure was related to emergency system breakdown. In most instances, equipment failure does not involve breakdowns of other subsystems and the integrity of the systems as a whole. The distribution of failures by the type of subsystems is the following: Navigation system (41%), propulsion system (29%), power system (22%), communication system (7%) and emergency system (<1%). The data is depicted in pie charts shown in Fig. 4.3.

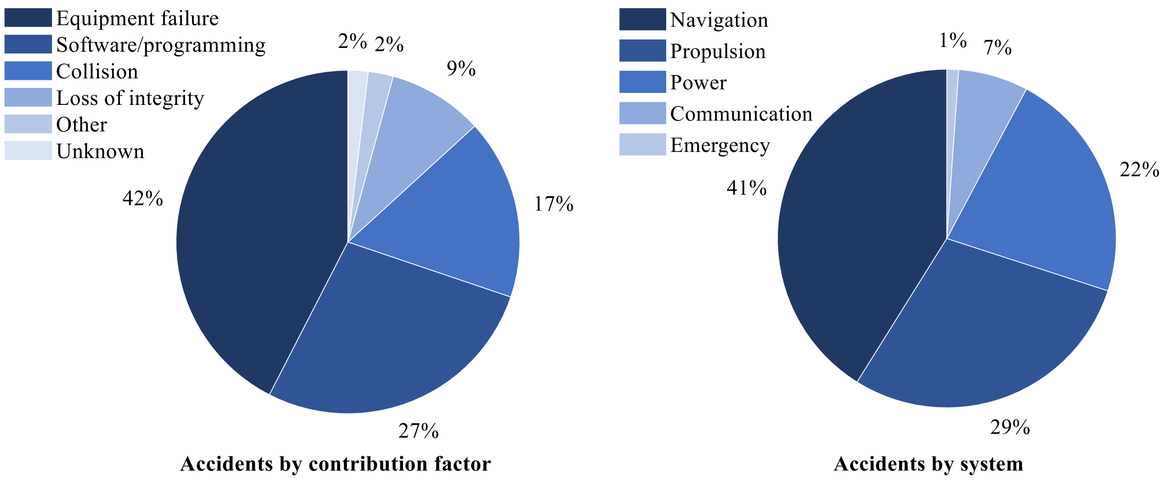

Fig. 4.3. Distribution of the accidents by their contribution factor and involved subsystems

The SST also involves operations at the sea surface, e.g., at the port, and it is relevant to compare it to traditional and chemical tankers. Information on vessels' accidents and breakdowns is broadly available, and EMSA annually presents an overview of casualties and incidents. We will use acquired data from EMSA 2021 annual report. Fig. 4.4 shows the distribution of tankers' accident types (Agency, 2021).

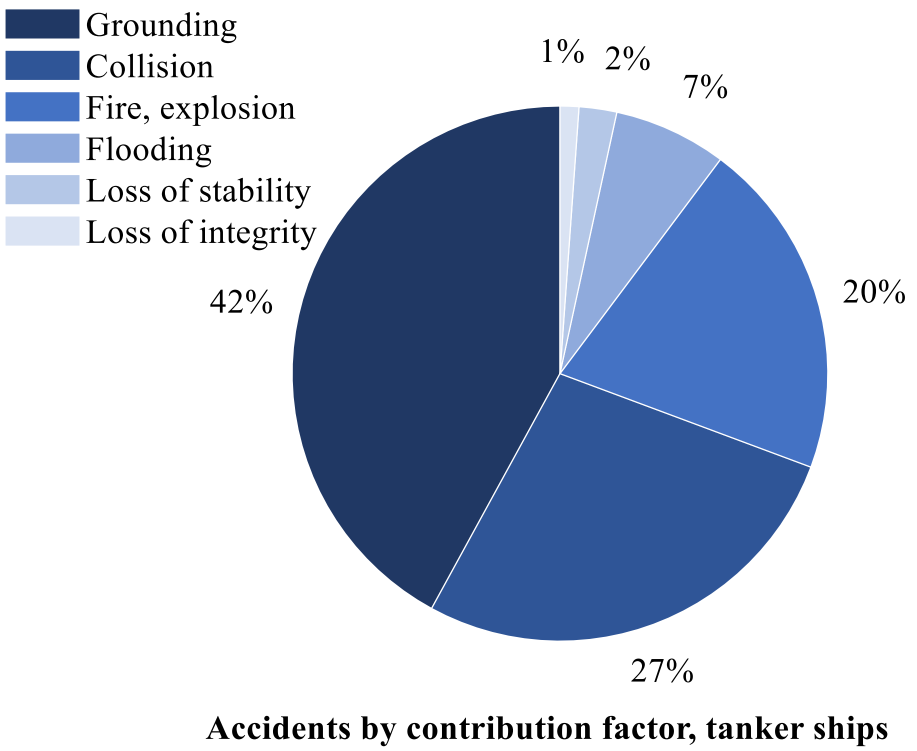

Fig. 4.4. Distribution of the accidents by contribution factor for tanker ships.

However, the information presented above considers crewed tanker vessels. Thus, Wrobel et al. (Wróbel et al., 2017) consider 100 instigation reports about accidents that happened to cargo ships. But implementing SWIFT, Wrobel compared if the vessel in question were unmanned, the probability or consequences would differ. According to the conducted WHAT-IF analysis, introducing the automation system would reduce the likelihood of 47% of the total accidents while resulting in a greater probability of 16% of the cases (Wróbel et al., 2017).

4.1.3. Hoses systems hazards

Different infrastructures such as CO_2 plants, external pumps, and boreholes are involved in the loading and offloading of the SST. However, the authors limit the scope only to the vessel itself in this work. Therefore, only the hose system is considered in this section when identifying the hazards during the loading and offloading process.

The general list of hose system equipment is:

- Hoses
- Hose winches
- Flanges
- Quick coupling systems

- Rapid cut-off valves
- Deploying and retracting devices
- Pumps

Sun et al. (Sun et al., 2016) conducted a failure mode and effects analysis (FMEA) on an FPSO offloading system. The general failure modes and failure effects are:

<u>A. Failure modes</u>

- Hose accidental release
- Integrity loss
- Hose wear
- Pump's malfunction

<u>B. Failure effects</u>

- Leakages and spills
- Hull damage
- Fire
- Explosion

4.1.4 Threats

There are also potential antagonistic threats towards the platform and operation. Typically, these threats can either have a criminal, terrorist or military purpose with the aim to interrupt or take control over the system. The tight coupling between the threat's intent, chosen risk controls, and the operators' preparedness needs to be considered when conducting a risk assessment on antagonistic threats (Liwång et al., 2015). Security threats need to be analysed concerning each specific threat's intent, capability and likelihood of exploiting the system's vulnerability (Liwång, 2017).

Compared to traditional maritime tanker solutions, the cargo contains a lower monetary value and lower potential for severe consequences for the SST. This leads to the possible modus operandi for using an SST, and creating severe consequences is limited compared to threats towards LNG carriers (Bubbico et al., 2009). However, the SST is an infrastructure that needs to be protected according to relevant standards, especially against cyber security threats.

4.2. Preliminary Hazard Analysis

The PHA and hazard identification results have been archived during a number of workshops and brainstorming sessions and presented in tables. Based on risk factors and failure modes, PHA tables have been formed.

Scenarios have been considered for five operational phases depicted in Fig. 4.1. Moreover, the preparation phase has also been analysed. During preliminary hazard analysis, 90 scenarios and their hazards were identified. The distribution of scenarios by their operational phase has the following outlook: 30 cases can be attributed to the underwater navigation phase, 10 cases are attributed to underwater-water transition, 14 cases are related to surface navigation, 13 cases are related to the loading phase, 14 cases are related to offloading phase, and 9 scenarios refer to the preparation phase.

After PHA tables were formed, risks were assessed and represented in the form of a risk matrix. The obtained risk matrix is depicted in Fig. 4.5. Each point on the chart shows risk ratings with the corresponding number of cases. Risk assessment has a qualitative character and represents a general understanding of presented hazards.

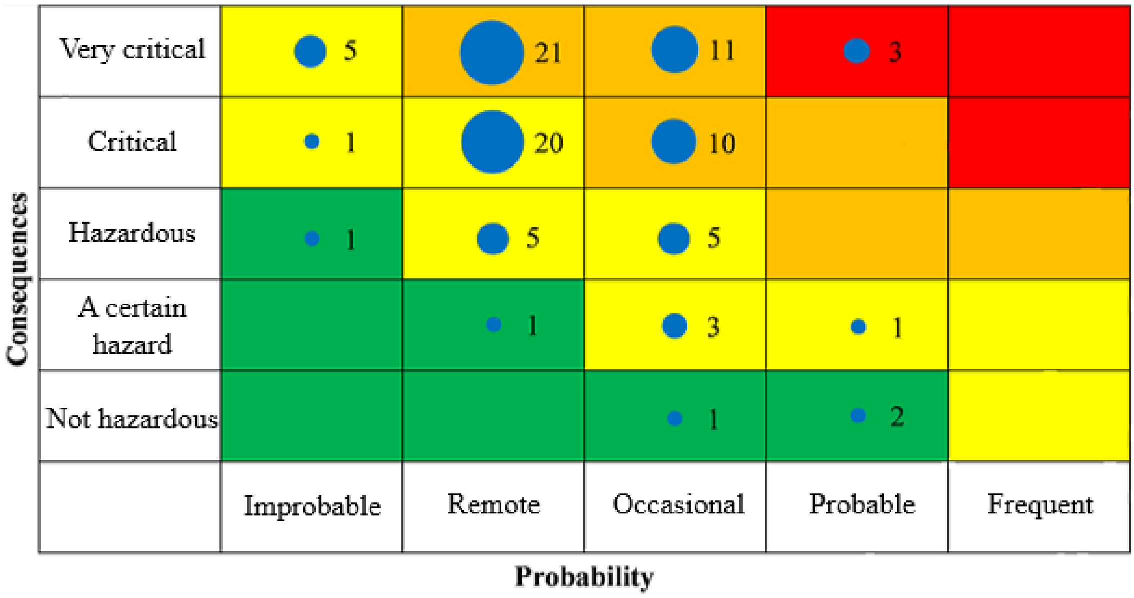

Fig. 4.5. Risk matrix of identified scenarios and hazards, including the number of cases.

As a result, the most prioritised risks belong to the adjacent region of high and medium-high rating risks. Those risks and respective scenarios from PHA are presented in Table 4.2.

Table 4.2. Prioritised hazard scenarios by risk rating

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
UNP-13	Software failure	Unexpected behaviour during a mission	Software failure during product development	Misson is aborted, loss of the SST	4	5	20	Programming testing, software testing
UNP-12	Human error	Unexpected behaviour during a mission	Wrong pre-drive programming	Misson is aborted, loss of the SST	4	5	20	Programming testing, software testing
UNP-6	Human error	Not correctly eliminated faults during the preparation of mission, leading to systems fault during maintenance	Unclear fault, complex interaction, few experience of technical personnel	Misson is aborted, unplanned behaviour, and even total loss of the vessel	4	5	20	Test runs, elimination of faults, maintenance

When the unacceptable limit of ALARP is set at the high-risk ratings, the majority of scenarios in the distribution of risk ratings presented in Fig. 4.5 are located within acceptable region limits. Only three of identified cases belong to the unacceptable region, those cases were denoted as prioritized. In the future, detailed limits evaluation for the ALARP region should be performed during the cost-benefit assessment.

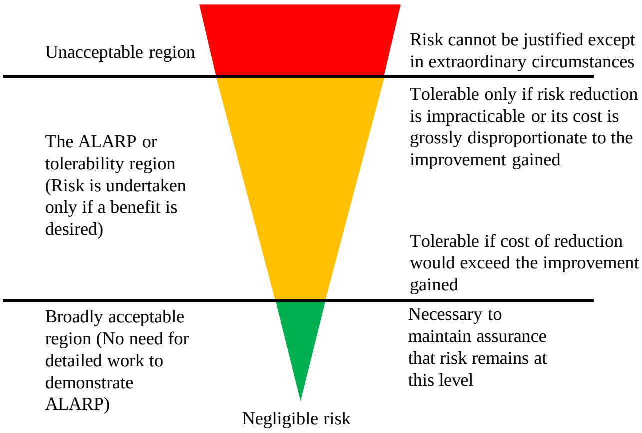

Fig. 4.6. ALARP principle (Rausand, 2020).

During PHA execution, risk control methods were proposed in addition to hazard identification and risk assessment. From Table 4.2, it can be noticed that the most prioritised hazards with the highest corresponding risk rating. Two of them are related to human involvement, and the other one is related to the software Human related hazards should be managed with properly designed procedural safeguards before starting SST operations. It can be archived by validating and testing/checking programming and mission parameters.

As the utilization of the SST mainly relies on autonomous operations, software hazards must be addressed with the most importance.

In the second place, with a risk rating of 15, ten cases have been identified, the majority of them related to the navigational system. Considering failures related to the navigation system or any other systems with active equipment principle of safe fail guards should be considered. The safe fail principle is closely related to reliability, redundancy segregation, and diversity. Here reliability is the primary core, and subsequently, redundancy segregation and diversity are used to archive it.

General recommendations for ensuring safety for SST utilisation will be given in **Chapter 6** Discussion. The full list of results of PHA is presented in **Appendix A-F**.

5. Cost-benefit assessment

The cost-benefit assessment for the SST has not been done yet. The main reason for that as the SST at the conceptual design, it is difficult to prepare a cost-benefit assessment at this stage.

We expect that risk control options identified during preliminary hazard analysis will be included in the SST system. Part of those control options relies on operation in accordance with standards IMO, DNV, etc. Operation following standards is not only necessary but an effective mitigation option. Accordance with standards helps to design the system with an initial level of safety, as it includes all principles for safety engineering (Moller & Hansson, 2008).

For the risks which are not directly regulated in any of the applied standards, a cost-benefit assessment will be carried out to choose adequate risk control options in future works.

Despite that we cannot perform a cost-benefit assessment at the present stage of design, the following statements have to be considered in future dedicated studies and assessments.

- Hazards with corresponding high-rated risks must be considered, first of all with excessive details.
- The safety of the system and environment must be prioritised against any economic aspects.

6. Discussion/Recommendations

Following the DNVGL-CG-0264 (DNV, 2018a), autonomous vessels must have a level of safety equivalent to or better, compared to conventional vessels, regarding safeguarding life, property and environment. From the performed work and analysis, we can infer that possible catastrophic scenarios to the SST do not necessarily lead to more severe consequences than human-crewed ships. However, it is essential to ensure that hazards do not escalate to situations that dangerous for manned platforms and the environment.

In this chapter, based on the conducted FSA and PHA, the main recommendation for the design perspective of the SST and for autonomous freight vessels are presented.

A. Equipment

The analysis showed that scenarios involving mechanical failure of equipment are the most severe ones. Active components such as navigation, propulsion and electrical power systems have to be designed with the safe failure principle of safety engineering. It can be archived with redundant design or alternating options to remain the system operational. Failure of active components should not affect other systems. In addition, systems or components designed with the redundancy principle should be mutually independent. Passive components such as pipes and valves could be exempted from the redundant requirement as they have lower failure probabilities.

In general, failures may affect the capabilities of the SST system but should not prevent the safe operation of the vessel. Self-diagnostic functions should be implemented to prevent failures and provide communication links with the onshore centre in abnormal situations. Data transferring could be archived by acoustic and satellite communication when the vessel is underwater and on the surface, respectively.

At the fully autonomous phase, the system has to be able to restore an essential vessel function without any assistance. Otherwise, the system has to switch to safe mode for further retrieving.

B. Software

The implemented hazard analysis on AUV safety identified software failures among common and prioritised risks. The SST also implies primarily autonomous operation; thus, software failures should be carefully considered. Related recommendations are the following.

Software must be controlled during the development and configuration in the first place. Furthermore, before each mission, software testing must be carried out. The main software errors such as coding errors, atrocious logic, data mismatch and communication errors should be considered.

C. Cyber security

From a security perspective, the SST is a cyber-physical system, which means the physical and digital components of the system are interrelated (Caprolu et al., 2020). For operational safety, cyber security should be considered.

Cyber security must be addressed during the design phase. Detailed cyber security analysis should be implemented on the communication system, including vessel systems, datalinks and shore centres. All parts of cyber systems should be regulated by an up-to-date cyber security policy, procedures and technical requirements defined by cyber security frameworks. Examples of widely used regulatory standards and practices concerning cyber security which could be considered in the design of the SST are (Al-Dhahri et al., 2017; Barrett, 2018; Organization, 2017).

In case of a cyber-attack or any other abnormal situation, the SST system has to be able to restore its function.

D. Human involvement

Despite that, the SST does not imply crew presence at any part of the operational phase. Human involvement still plays a big part in SST operations, and major involvement takes part in the preparation phase and mission configuration. The implemented analysis shows that the wrong mission configuration is a severe risk factor related to human involvement. Mission parameters and system configuration should be adequately checked and tested before each operation. The people involved must have sufficient qualifications and experience working with autonomous vessels.

E. Risk control options

Risk control options must be implemented to eliminate, prevent, and reduce the occurrence of identified hazards for the SST and manage their consequences in case of occurrence. According to the engineering safety principles proposed by Möller and Hansson (N. Möller & S. O. Hansson, 2008). The SST must be based on four principles of risk control options.

- Inherently safe design
- Safety reserves
- Safe fail
- Procedural safeguards

Focusing on these principles allows one to analyse the safety of the system from different perspectives on safe design.

From the baseline design of the SST (Ma, Xing, Ong, et al., 2021), inherently safe design and safety reserves principles have been considered. Furthermore, some safe fail control options have been discussed and included in the design. One of them is pressure compensation systems, as discussed in **Chapter 3.3.4**.

The authors will evaluate risk control options proposed during preliminary hazards analysis during cost-benefit assessment in future works.

F. CO2 quality

CO_2 impurities increase the risk for corrosion and hydrate formation. The most undesired impurity is free water. In contact with CO_2, free water dissolves and forms highly corrosive carbonic acid. As a result, acid can lead to severe corrosion issues in cargo tanks and piping of the SST. By ensuring that water's concertation is always lower than its solubility, free water formation is avoided in the SST.

On the other hand, in case of violation of thermobaric conditions, hydrates may form, causing blockage and/or sealing issues. This issue is particularly relevant for the seals in the pistons of the pressure compensation system. Besides, chemical injection with MEG must be foreseen in case of hydrate formation.

7. Conclusion

Risk assessment based on IMO formal safety assessment is developed to support research studies into autonomous underwater freight vehicles. This work aimed to close the gap between operative context and design characteristics. Outcomes of previous studies on marine transportation and traffic risks and risk-related studies of autonomous and unmanned vessels have been used to develop frameworks for the risk assessment of the SST. A risk assessment was performed based on analysed studies and processed historical data. IMO formal safety assessment utilisation helped build an effective structure and present a consistent basis for autonomous transportation safety evaluation.

The approach in this work utilised PHA as hazard identification and risk evaluation. During PHA, five operational phases of the SST utilisation, 90 hazards and related scenarios were identified. For each of the scenarios, risks have been evaluated and ranked. Moreover, initial risk control options have been proposed for each scenario. PHA helped define and assess the main challenges emerging for autonomous transportation. Moreover, it pointed out where design and development efforts need to be focused. Although in work, the SST was considered at an early stage of design, identified hazards and relevant scenarios will help to mitigate them in the future. Moreover, the presented assessments may be useful for future unmanned and autonomous marine transportation studies.

Based on performed work, generic recommendations for the main design aspects of the SST were provided. Recommendations on equipment, software, cyber security, human involvement, risk control options and CO_2 quality should be served as a framework for cost-benefit assessment and further design stages development of the SST.

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Appendix A – Preliminary Hazard Analysis – Underwater Navigation

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk Prob.	Risk Con.	Risk	Risk reduction methods
UNP-1	Excessive external pressure	Failure of the ballast water system	The SST dives below 500 meters depth	Collapse of SST structures	2	5	10	Pressure compensation system
UNP-2	Structural failure	Failure of the Pressure Compensation System	One or several cargo tanks doesn't fully filled with CO2	Collapse of SST structures	2	5	10	Evaluate the need to monitor amount of CO_2 in each storage tank
UNP-3	Stability	Loss of stability/trim	Uneven storage of fluid within cargo tanks	Mission is aborted, loss of position	2	3	6	Adjust ballast in compensation tanks, tank filling monitoring, install mitigation system.
UNP-4	Structural failure	Draught after following uncontrolled incident	Unexpected failure of ballast water system equipment	Grounding, loss of the SST	2	5	10	Regular inspections

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
UNP-5	Structural failure	CO2 emission due to the drowning	Unexpected failure of ballast water system equipment	CO_2 emission into the water, loss of the SST	2	5	10	Pressure compensation system, bulkheads
UNP-6	Human error	Not correctly eliminated faults during the preparation of mission, leading to systems fault during maintainance	Unclear fault, complex interaction, few experience of technical personnel	Misson is aborted, unplanned behaviour, and even total loss of vessel	4	5	20	Test runs, elimination of faults, maintenance
UNP-7	Thermic Hazard	Battery pack ignites during operations	Short circuit, water in water-free section with batteries/wiring, wrong charging	Loss of the SST, external and internal damage, mission is aborted	2	5	10	Charge and discharge on recommendations, regular inspections, emergency power source
UNP-8	Thermic Hazard	Fire, blowout	Fire occurred as a result of cargo self-heating	Loss of the SST	1	5	5	Operations have to be performed within a designed temperature, self-monitoring

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
UNP-9	High voltage	Battery pack galvanise corrosion	Large DC currents resulting ignition	Loss of the SST, external and internal damage, mission is aborted	2	5	10	Monitoring of battery state, self-check, emergency power source
UNP-10	Short circuit	Short circuit during the mission	Water in water-free section with batteries/wiring, bad connections internally	Mission is aborted, partial power loss	3	4	12	Monitoring of battery state, self-check, emergency power source
UNP-11	Kinetic Energy	Collision with other vessels	Vessel not aware about the SST, near-surface mission	Misson is aborted, damage to SST, loss of SST	2	5	10	Other vessels have to be aware of the SST presence, the SST operation in exclusion of safety zone
UNP-12	Human error	Unexpected behaviour during a mission	Wrong pre-drive programming	Misson is aborted, loss of the SST	4	5	20	Programming testing, software testing

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
UNP-13	Software failure	Unexpected behaviour during a mission	Software failure during product development	Misson is aborted, loss of the SST	4	5	20	Programming testing, software testing
UNP-14	System failure	Failure of the system	Failure of Inertial Navigation System	Mission is aborted, loss of the SST, external damage	3	5	15	Programming testing, software testing
UNP-15	System failure	Seabed Collision	Failure of the Navigation system	Misson is aborted, loss of the SST	3	5	15	Alternating navigation equipment/sensors
UNP-16	System failure	Seabed Collision	Complete failure of SST sensors, loss of positioning	Misson is aborted, loss of the SST	3	5	15	Alternating navigation equipment/sensors

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
UNP-13	Software failure	Unexpected behaviour during a mission	Software failure during product development	Misson is aborted, loss of the SST	4	5	20	Programming testing, software testing
UNP-14	System failure	Failure of the system	Failure of Inertial Navigation System	Mission is aborted, loss of the SST, external damage	3	5	15	Programming testing, software testing
UNP-15	System failure	Seabed Collision	Failure of the Navigation system	Misson is aborted, loss of the SST	3	5	15	Alternating navigation equipment/sensors
UNP-16	System failure	Seabed Collision	Complete failure of SST sensors, loss of positioning	Misson is aborted, loss of the SST	3	5	15	Alternating navigation equipment/sensors

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
UNP-21	System failure	System failure (propulsion)	Fault of control system	Mission is aborted, retrival	3	4	12	Testing before mission, maintenance and inspection, emergency system
UNP-22	Structural failure	System failure (propulsion)	Fault of Propeller	Mission is aborted, retrival	3	4	12	Testing before mission, maintenance and inspection, emergency system
UNP-23	Structural failure	System failure (propulsion)	Fault of gear box	Mission is aborted, retrival	3	4	12	Testing before mission, maintenance and inspection, emergency system
UNP-24	Structural failure	System failure (propulsion)	Fault of single rudder	Mission is aborted, retrival	3	2	6	Testing before mission, maintenance and inspection, emergency system

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
UNP-25	Human error	Misson is planned without considering the capabilities of the SST	Bad knowledge, few experience on a decision maker level	Unplanned behaviour, the SST grounding, loss of the SST	3	5	15	Testing before mission, maintenance and inspection, emergency system
UNP-26	Chemical interaction	Internal degradation of cargo tanks	Local corrosion/ wall thinning within cargo tanks	Damage/destruction of internal equipment,	2	4	8	Regular maintenance and inspection, pressure compensation system, corrosion-resistant alloys
UNP-27	Chemical interaction	Loss of integrity within cargo tanks	Through wall corrosion	Damage/destruction of internal equipment, loss of the SST, emission of CO2	1	4	4	Regular maintenance and inspection, pressure compensation system, corrosion-resistant alloys
UNP-28	Criminal activity	the SST loss control	IT hacking	Loss of the SST, damage to 3rd parties	1	5	5	Safety philosophy to be described

No.	Hazard/Threat	Hazardous event	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
		(What, where, when)			Prob.	Con.	Risk	
UNP-29	Structural failure	Cargo tanks leakage	Thermal/Vibration fatigue cracking	Damage to equipment, leakage, emission	2	4	8	Operations have to be performed within designed parameters, inspection maintenance
UNP-30	Environmental interaction	Loss of position due to hydrodynamic loads from currents	Strong currents way above designed current speed	Lost of position	1	3	3	Alternating navigation equipment/sensors

Appendix B – Preliminary Hazard Analysis – Underwater-Water Transition

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk Prob.	Risk Con.	Risk	Risk reduction methods
UWP-1	Environmental interaction	Loss of stability, overturn	Rough weather, waves, currents, swell, wind above designed values	Mission is aborted, damage to equipment	3	4	12	Operations have to be performed within the weather window
UWP-2	Environmental interaction	Collision with a tug boat, ascent	Rough weather, waves, currents, swell, wind above designed values	Loss of tug boat, damage to SST	2	5	10	Operations have to be performed within the weather window
UWP-3	Kinetic energy	Collision with a tug boat	Failure of communication and sensors between tug boat and SST.	Loss of tug boat, damage to SST	2	5	10	Communication between a tug boat and the SST must be archived, sensors, sonars
UWP-4	Human error	Collision with a tug boat	Collision happened due to poor training, human factor, poor tow planning	Loss of tug boat, damage to SST	3	5	15	Training, operating with compliance to standards

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
UWP-5	Human error	Girting of a tug boat	Loss of stability, poor tug handling, procedure	Loss of tug boat, damage to SST	3	5	15	Training, operating with compliance to standards, tug's emergency quick release system
UWP-6	Environmental interaction	Collision with a tug boat, descent	Rough weather, waves, currents, swell, wind above designed values	Loss of tug boat, damage to SST	2	5	10	Operations have to be performed within the weather window
UWP-7	Criminal activity	The SST loss control	IT hacking	Loss of the SST, damage to 3rd parties	2	5	10	Safety philosophy to be described
UWP-8	Thermic Hazard	Fire, blowout	Fire occurred as a result of cargo self-heating	Loss of the SST	1	5	5	Operations have to be performed within a designed temperature, self-monitoring

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
UWP-9	Thermic Hazard	The battery pack ignites during operations	Short circuit, water in water-free section with batteries/wiring, wrong charging	Loss of the SST, external and internal damage, mission is aborted	2	5	10	Charge and discharge on recommendations, regular inspections, emergency power source
UWP-10	Structural failure	Cargo tanks leakage	Thermal/Vibration fatigue cracking	Damage to equipment, leakage, emission, blowout	2	4	8	Operations have to be performed within designed parameters, inspection maintenance

Appendix C – Preliminary Hazard Analysis – Surface Navigation

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk Prob.	Risk Con.	Risk	Risk reduction methods
SNP-1	Environmental interaction	Loss of stability, overturn	Rough weather, waves, currents, swell, wind above designed values	Mission is aborted, damage to equipment	3	4	12	Operations have to be performed within the weather window
SNP-2	Environmental interaction	Collision with a tug boat, ascent	Rough weather, waves, currents, swell, wind above designed values	Loss of tug boat, damage to SST	2	5	10	Operations have to be performed within the weather window
SNP-3	Human error	Collision with a tug boat	Collision happened due to poor training, human factor, poor tow planning	Loss of tug boat, damage to SST	3	5	15	Training, operating with compliance to standards
SNP-4	Human error	Girting of a tug boat	Loss of stability, poor tug handling, procedure	Loss of tug boat, damage to SST	3	2	6	Training, operating with compliance to standards, tug's emergency quick

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
SNP-5	Structural failure	Damage to external equipment of the SST	Tow wire breakdown	Damage to external equipment	2	3	6	Training, operating with compliance to standards, ensuring wire position
SNP-6	Human error	Collision with obstacles, terrain	Poor tow planning before operation	Damage to SST structure	3	4	12	Training, operating with compliance to standards
SNP-7	Human error	Collision with obstacles, terrain	Incorrect tug approach and manoeuvring, human error during operation	Mission is aborted, damage to equipment, tug	3	4	12	Training, operating with compliance to standards
SNP-8	Criminal activity	The SST loss control	IT hacking	Loss of the SST, damage to 3rd parties	2	5	10	Safety philosophy to be described

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
SNP-9	High pressure	Leakage	Degradated overpressure protection	Damage to cargo tanks, emission	2	4	8	Inspection and maintenance, two layers of safety barriers - primary and secondary
SNP-10	High pressure	Fracture/Rupture of cargo tanks	Operation at temperatures over design limits	Damage to cargo tanks, emission	2	4	8	Operation with designed parameters
SNP-11	Chemical interaction	Internal degradation of cargo tanks	Local corrosion/ wall thinning within cargo tanks	Damage/destruction of internal equipment,	2	4	8	Inspection and maintenance, two layers of safety barriers - primary and secondary
SNP-12	Thermic Hazard	Fire, blowout	Fire occurred as a result of cargo self-heating	Loss of the SST	2	5	10	Operations have to be performed within a designed temperature, self-monitoring

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
SNP-13	Thermic Hazard	The battery pack ignites during operations	Short circuit, water in water-free section with batteries/wiring, wrong charging	Loss of the SST, external and internal damage, the mission is aborted	2	5	10	Charge and discharge on recommendations, regular inspections, emergency power source
SNP-14	Structural failure	Cargo tanks leakage	Thermal/Vibration fatigue cracking	Damage to equipment, leakage, emission, blowout	2	4	8	Operations have to be performed within designed parameters, inspection maintenance

Appendix D – Preliminary Hazard Analysis – Loading

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk Prob.	Risk Con.	Risk	Risk reduction methods
LHP-1	High pressure	Leakage cargo tank	Degradated overpressure protection	Damage to equipment, emission	2	4	8	Inspection and maintenance, two layers of safety barriers - primary and secondary, operation within
LHP-2	High pressure	Water hammer effect	Rapid opening or closure of valves	Potential damage to the structures but unlikely to happen	4	1	4	Inspection and maintenance, two layers of safety barriers - primary and secondary, operation within designed pressure values
LHP-3	High pressure	Leakage with the loading hose	Leakage happened due to the wear of hose, high pressure	Emission of CO_2	2	3	6	Inspection and maintenance, two layers of safety barriers - primary and secondary
LHP-4	High pressure	Fracture/Rupture of cargo tanks	Operation at temperatures/pressure over design limits	Damage to cargo tanks	2	4	8	Operation with designed parameters

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk Prob.	Risk Con.	Risk	Risk reduction methods
LHP-5	Chemical interaction	Internal degradation of cargo tanks	Local corrosion/ wall thinning within cargo tanks	Damage/destruction of internal equipment,	2	4	8	Inspection and maintenance, two layers of safety barriers - primary and secondary
LHP-6	System failure	PCS piston stucked	unplanned situation, failure	Damage to cargo tanks	2	4	8	Training,operating with compliance to standarts
LHP-7	System failure	Valve failure	Wear, degradation, fatigue	Damage to pipings	2	4	8	Training, operating with compliance to standards
LHP-8	Criminal activity	The SST loss control	IT hacking	Loss of the SST, damage to 3rd parties	2	5	10	Safety philosophy to be described

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
LHP-9	Structural failure	Cargo tanks leakage	Thermal/Vibration fatigue cracking	Damage to equipment, leakage, emission, blowout	2	4	8	Safety philosophy to be described
LHP-10	Thermic Hazard	The battery pack ignites during operations	Short circuit, water in water-free section with batteries/wiring, wrong charging	Loss of the SST, external and internal damage, the mission is aborted	2	5	10	Charge and discharge on recommendations, regular inspections, emergency power source
LHP-11	Thermic Hazard	Fire, blowout	Fire occurred as a result of cargo self-heating	Loss of the SST	2	5	10	Operations have to be performed within a designed temperature, self-monitoring
LHP-12	System failure	Loading cannot be completed	Pump failure	Misson is aborted	3	3	9	Inspection and maintenance

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
LHP-13	Chemical interaction	Water contamination	Discharge of processed seawater	Pollutuion contamintion	2	2	4	Discharge into tanks, to be studied

Appendix E – Preliminary Hazard Analysis – Offloading

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk Prob.	Risk Con.	Risk	Risk reduction methods
OFP-1	High pressure	Water hammer effect	Rapid opening or closure of valves	Potential damage to the structures but unlikely to happen	4	1	4	Inspection and maintenance, two layers of safety barriers - primary and secondary, operation within
OFP-2	High pressure	Leakage with the offloading hose	Leakage happened due to the wear of hose, high pressure	Emission of CO_2	2	3	6	Inspection and maintenance, two layers of safety barriers - primary and secondary
OFP-3	High pressure	Fracture/Rupture of cargo tanks	Operation at temperatures/pressure over design limits	Damage to cargo tanks	2	4	8	Operation with designed parameters
OFP-4	System failure	PCS piston stucked	unplanned situation, failure	Damage to cargo tanks	2	4	8	Training,operating with compliance to standarts

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
OFP-5	System failure	Valve failure	Wear, degradation, fatigue	Damage to pipings	2	4	8	Training, operating with compliance to standards
OFP-6	Interaction	The SST loss control	IT hacking	Loss of the SST, damage to 3rd parties	1	5	5	Safety philosophy to be described
OFP-7	Structural failure	Cargo tanks leakage	Thermal/Vibration fatigue cracking	Damage to equipment, leakage, emission, blowout	2	4	8	Safety philosophy to be described
OFP-8	Thermic Hazard	The battery pack ignites during operations	Short circuit, water in water-free section with batteries/wiring, wrong charging	Loss of the SST, external and internal damage, the mission is aborted	2	5	10	Charge and discharge on recommendations, regular inspections, emergency power source

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk Prob.	Risk Con.	Risk Risk	Risk reduction methods
OFP-9	System failure	Loading cannot be completed	Pump failure	Misson is aborted	3	3	9	Inspection and maintenance
OFP-10	Stability	Loss of stability	Failure to maintain hydrostatic stability during offloading	Disconnect with subsea well	3	3	9	Emergency shut down
OFP-11	Environmental interaction	Unable to hook up with well	Problems with positioning due to high current	Mission on halt	3	3	9	Positioning facing current
OFP-12	Environmental interaction	Collision with a well	Strong hydrodynamic forces created by current	Loss of SST or well	3	5	15	Safety zone to be defined

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
OFP-13	Environmental interaction	Damage and total ructure of flowline	Strong hydrodynamic forces created by current	Flowline damage and SST structural damage	3	4	12	Positioning facing current
OFP-14	Chemical interaction	Hydrate formation	Hydrates formed during offloading as impure CO2 loaded on SST	Occlusion of cargo tanks or piping	2	4	8	Proper treat of CO2, potential MEG injection

Appendix F – Preliminary Hazard Analysis – Preparation

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk Prob.	Risk Con.	Risk	Risk reduction methods
PPH-1	Thermic Hazard	The battery pack ignites during operations	Short circuit, water in water-free section with batteries/wiring, wrong charging	Loss of the SST, external and internal damage, the mission is aborted	2	5	10	Charge and discharge on recommendations, regular inspections, emergency
PPH-2	Less then adequate maintenance	The SST is in bad condition/ damaged when need	Inadequate maintanace/ damaged when needed	External and internal damage	2	4	8	Verify maintenance plan and schedule, follow instructions
PPH-3	Kinetic energy	The SST is subjected to external imapct at the dock (natural/3rd parties)	External impact	Damage to equipment	2	4	8	To be studied, safety zone
PPH-4	Human error	Wrong mission parameters are implemented during preparation	Wrong programming, misunderstanding, unclear procedures	Loss of the SST, the mission is aborted	3	5	15	Validate programming and mission parameters, the SST monitoring

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
					Prob.	Con.	Risk	
PPH-5	Software failure	Software containing errors is implemented	Software faults	Fix the faults after pre-text before operation	3	2	6	Can be found during pre-test
PPH-6	Environmental interaction	Deployment is not possible	Restricted weather conditions	Reschedule the operation	2	3	6	
PPH-7	Software failure	A pre-test is passed with an undetected fault	Undetectable software faults	Delayed deployment	3	3	9	Inspection and maintenance, the SST monitoring during operation
PPH-8	Human error	Hardware and software faults are not eliminated during preparation	Unclear fault description, few experience	Fix the faults after pre-text before operation	4	2	8	Inspection and maintenance, the SST monitoring during operation

No.	Hazard/Threat	Hazardous event	Cause (Triggering event)	Potential consequences	Risk			Risk reduction methods
		(What, where, when)			Prob.	Con.	Risk	
PPH-9	Human error	The mission is planned without considering the capabilities of the SST	Bad knowledge, few experience	No impact on primary functions	3	1	3	Operation within design parameters, re-evaluate mission

Appendix C – Paper Draft

Risk assessment of utilising an extra-large autonomous underwater vehicle for liquid CO_2 transportation

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Abstract

The development of autonomous maritime systems has been proliferating in recent years. One of these systems is a subsea shuttle tanker (SST) concept proposed as a potential alternative to pipelines and tanker ships for liquid CO_2 transportation. The SST is an extra-large merchant autonomous underwater vehicle. It travels from onshore facilities, where CO_2 is captured and transiently stored, to subsea wells for permanent storage and enhanced oil recovery projects. It is believed that introducing such extra-large AUVs can reduce the occurrence frequency of human-induced accidents. However, the potential accidents related to these vessels are still not detailed identified. Therefore, this paper presents the full risk assessment of the SST for liquid CO_2 transportation. This work aims to close the gap within the operative context and design characteristics of such autonomous underwater freight vehicles. To do so, a formal safety assessment is performed in accordance with International Maritime Organization standards. First, the most critical information about the SST regarding the risk assessment process is highlighted. Then, the preliminary hazard analysis is implemented to identify hazards and evaluate relevant risks based on the presented baseline SST. Subsequently, systematic hazard identification is used to find critical safety and security risks. Further, corresponding control safety options are addressed for risk mitigation. Finally, generic recommendations for the main design aspects of the SST are provided based on the work results.

Keywords: Subsea technology, autonomous underwater vehicles, preliminary risk analysis, risk assessment, International Maritime Organization

1. Introduction and Background

The most convenient way of transportation offshore oil and gas is via pipeline transportation from floating production units (FPUs) to onshore facilities [1]. However, there are limitations to this mode of transportation due to technical and economic restrictions. One essential constraint is the deployment cost, which increases with pipeline length and water depths. Besides significant capital expenditures (CAPEX) considerations, deep-water installations require constant inspections and surveillance, which may be challenging and expensive. Furthermore, pipeline maintenance and repair operations imply a whole line or partial shutdown, which can be economically undesirable. Thus, utilisation of offshore pipelines is desirable for large and high marginal fields located not far from the shoreline [2]. If a single field is remotely located, it is simpler to employ a shuttle tanker [3]. However, tankers are exposed to dynamic load effects from wind and waves. Further, tanker operations are vulnerable to weather and cannot be carried out in severe sea states. Subsea Shuttle Tanker (SST) (illustrated in Fig. 1) proposed by Xing et al. [4] can serve as a potential alternative to conventional tankers and subsea pipelines. Placing transportation underwater will allow overcoming weather-related limitations described above [5-7].

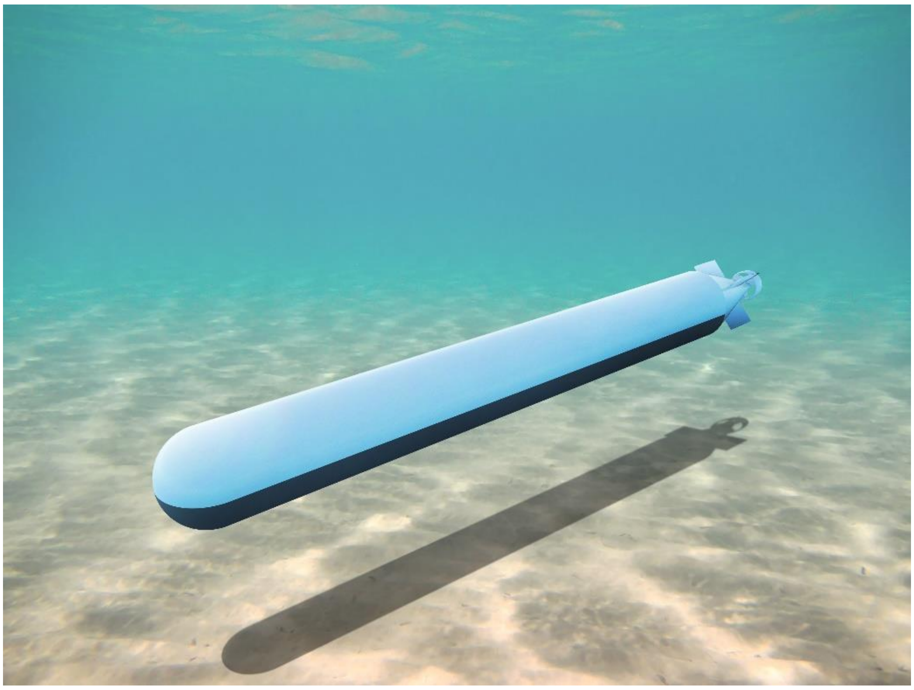

Fig. 1. Illustration of the subsea shuttle tanker [7].

1.1. Previous Research in Underwater Cargo Vessels

The idea of utilising underwater vehicles as means of transportation is not new and was proposed first in the 1970s by Jacobsen [8] and Taylor et al. [9], who presented the use of nuclear-powered submarines in a variety of sizes, 20,000 to 420,000 dead (DWT), to transport crude oil in the arctic region. Further, in the 1980s, Jacobsen et al. [10, 11] proposed two new submarines with higher capacities for LNG transportation: the first one is a 660,000 DWT nuclear-powered vehicle, and the second one is a 727,400 DWT conventionally powered submarine. More recently, Ellingsen et al. [5] published several underwater freight vehicles in a disclosure. One of these vehicles is an innovative vehicle, a ‘cargo train’ made up of interconnected subsea tanks with independent propulsion units located either at the bow or aft of the vessel. Another proposed vehicle is an ultra-efficient large glider vehicle. Based on that, Xing [12] came up with a 785 DWT subsea cargo glider that has a calculated power consumption below 10 kW. Furthermore, Ma et al. [7] closed this knowledge gap by defining a baseline SST design and presenting the most critical design aspects, including weight distribution, structural capacities, cargo properties, and offloading methods. Defined baselined design can be used as the fundament for safety and risk assessment, which will allow to identify potential improvements and system safety in general.

1.2. Risk Assessment Towards Autonomous Maritime Industry

Due to recent technological advancement and experience gained in operations of unmanned systems, such as autonomous underwater vehicles and unmanned surface vessels, the interest in the projects as SST showed to be relevant [1, 7, 13-15]. It is believed that the first unmanned sub-sea vessels will become available within the next 5-10 years [16]. Nevertheless, insurance companies are still sceptical about the concept of autonomous cargo vessels and unmanned vessels in general. This is because of the lack of legal framework for autonomous marine systems to operate in international waters. Existing regulations and conventions will need to be updated to account for their existence [17]. So, it is vital to ensure that the utilisation of autonomous vessels would increase maritime safety or at least will maintain it at the same level as crewed vessels.

The present studies have been elaborated to establish the initial safety and risk management challenges that autonomous vessels will face. Wrobel et al. [13, 18] analysed safety risks for the concept of an autonomous vessel, identifying the main challenges for the execution operations and prevention of accidents. Other studies have been aimed to assess the human role involved in the management of safety and during operations of autonomous vessels [19-21]. Further, more studies focusing on the analysis, reviewing a semi-defined operative context and a determined escalation process for various degrees of autonomy [15, 22, 23].

The previous studies have shown the need to consider the safety management of autonomous vessels from all possible perspectives for future successful operations. However, most of the presented studies were based on data lacking specific details about actual design characteristics, its operative context, and relative statistics used [14].

This work is aimed to close the gap within the operative context and design characteristics by implementing the full risk assessment for a novel SST vessel. The risk assessment would start by identifying operational scenarios and hazards in the different phases of operational activities. After, risk analysis will be implemented for each scenario based on evaluated probabilities and consequences. Furthermore, risk control options, cost-benefit assessment and general safety recommendations will be given following the overall structure of the IMO Formal Safety Assessment (FSA) [24].

Risk assessment provides a structured basis for offshore operators to identify hazards and to ensure risks have been cost-effectively reduced to appropriate levels. It aims to identify risk at acceptable levels, point out potential improvements in an existing design, or choose between alternative design options [25].

A significant number of studies have been elaborated regarding risk analysis of operational modes within marine traffic, including collision [26-30], grounding [31-34] and fire-related risks [35-37]. Furthermore, studies in the domain of autonomous underwater vehicle safety have been elaborated recently [38-40]. Despite the fact that the SST does not belong to the conventional class of tanker or AUV, these studies provide the basis to develop frameworks for the risk analysis of SST. These frameworks are considered for transferring the main components of safety assessment and hazard identification with the domain of underwater freight vessels. Further extensive description of tools and techniques applied during the evaluation will be specified in the upcoming section of methods.

2. SST baseline design / system

This section is intended to briefly summarise the design considerations for the Subsea Shuttle Tanker and the systems involved during offloading and loading. The presented design will be based on the work presented by Ma et al. [7]. The systems introduced here serve as a basis for the risk assessment in the following sections.

2.1. Overview

The main objective of the SST is to transport CO_2 in a liquid state autonomously underwater from land or offshore facilities to subsea wells for direct injection. The baseline SST is designed to be deployed in the Norwegian sector's carbon capture and storage (CCS) programmes. There are currently three ongoing projects: Sleipner, Utgard, and Snøhvit [41]. Furthermore, the Northern Lights project is set to start operation in 2024, where CO_2 generated from non-petroleum industrial activities will be transported and injected into the Troll field [42]. The position of SST in the CCS supply chain is depicted in Fig. 2. Accordingly to the baseline SST [7], the SST's cargo capacity is 15,000 tonnes to match the maximum annual carbon storage capacity of the CCS projects, i.e., 1.5 million tonnes annually. The locations of the above-mentioned projects are shown in Fig. 3.

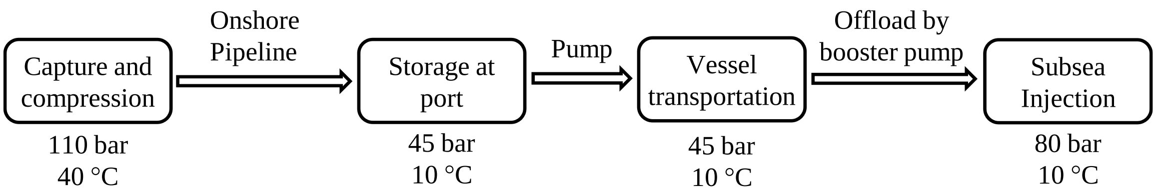

Fig. 2. CCS offshore storage process with SST transportation [43].

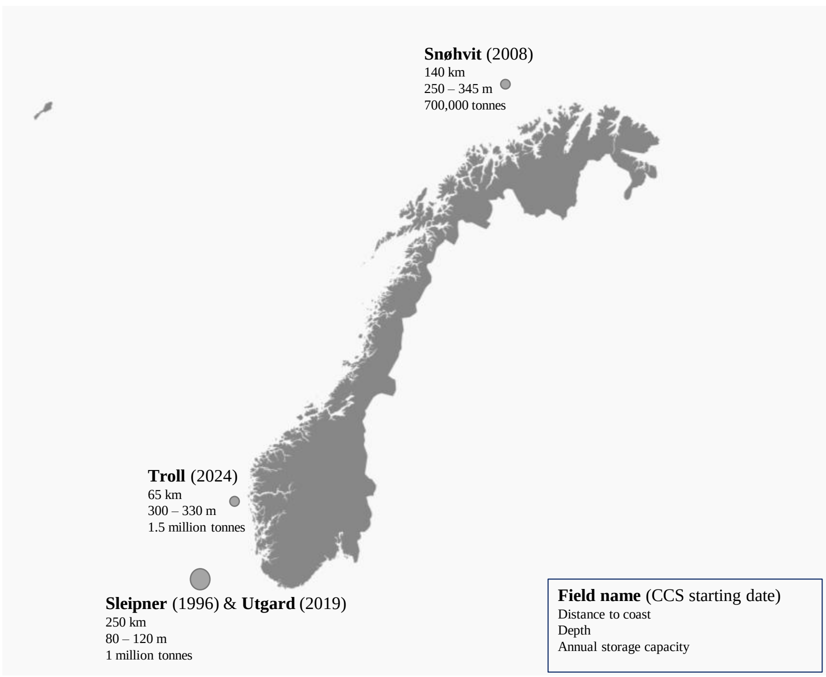

Fig. 3. Carbon storage sites in the Norwegian sector, current and planned [7].

The SST can be designed to be utilised for the transportation of other types of cargo such as hydrocarbons, electrical power (through batteries), and subsea tools. Also, SST can contribute to the mitigation of global warming in a different manner. It is fully electrically powered and emission-free, which contributes to the sustainability of shipping. Approximately 3.3% of fossil-fuel-related CO_2 emissions currently contribute from shipping [44]. On the other side, SST enables the flexibility to utilise marginal subsea fields as CO_2 storage sites without considering flow insurance problems relevant to pipeline transportation.

2.2. Mission requirements

The SST system by classification belongs to a cargo type of vessel. From the study proposed by Ma et al. [7], SST is a submarine with 164 meters in length and 17 meters in beam, and calculated displacement constitutes 33,619 tonnes. The presented design is capable of carrying up to 16,362 m^3 of CO_2 for a range up to 400 km at a speed of 6 knots. The main design parameters are presented in Table 1.

A. Operating depth range

- The safety depth is set to be 40 meters. This is needed to avoid collision with surface ships or floating installations.
- The nominal diving depth is 70 meters. The SST is designed for operation at a constant 70 m depth. This depth is defined based on minimum recoverable depth from lost-control situations [7].
- The test diving depth is 105 meters, and the collapse depth is 190 m. Those depths were established following DNVGL-RU-NAVAL-Pt4Ch1 [45]. The test diving depth is 1.5 times of nominal diving depth. Considering the collapse depth, the SST is designed not to collapse at a maximum 190 meters depth which is defended to be 2.7 times of nominal diving depth.

B. Range

The SST is designed to have a range of 400 km, which is sufficient to make a return trip to Snøhvit and Troll or a one-way trip to Sleipner and Utgard. Furthermore, the SST can be recharged using the existing offshore facilities in the latter case.

C. Environmental data

The SST will operate in the Norwegian Sea. In this region, the seawater temperature range is 2 °C –12 °C [46]. The temperature in seawater usually does not go below 0 °C, and for the summer months, 20 °C is the maximum temperature that can be reached.

The observed seasonal average current speed in the Norwegian Sea is 0.2 m/s, and the highest seasonal speed of the North Atlantic Current and Norwegian coastal current is 1 m/s [47, 48]. The latter is used as the SST designed current speed.

Table 1. Subsea shuttle tank main design parameters.

Parameter	Value	Unit
Length	164	[m]
Beam	17	[m]
Displacement	34,000	[tonnes]

Operating depth	70	[m]
Collapse depth	190	[m]
Operating speed	6	[knots]
Maximum range	400	[km]
Cargo volume	16,000	[m^3]
Cargo pressure	35-55	[bar]
Cargo temperature	0-20	[°C]
Design current speed	1	[m/s]

D. Carbon dioxide properties

Two methods are commonly utilised for the transportation of CO_2. First, CO_2 could be transported through the pipelines in the supercritical state and by using ships in the saturated liquid state. The utilisation of SST implies transportation in the saturated liquid state, in which the temperature and pressure are passively regulated by the environment, i.e., maintaining them at the defined setpoints requires no external energy. During transportation with SST, the pressure of liquid CO_2 will vary along the boiling line in the phase diagram as presented in Fig. 4. Furthermore, the liquid CO_2 at 45 bar can be directly pumped into the reservoir using a single-stage booster pump, as opposed to gas carriers, where there are multiple booster pumps and interheaters required.

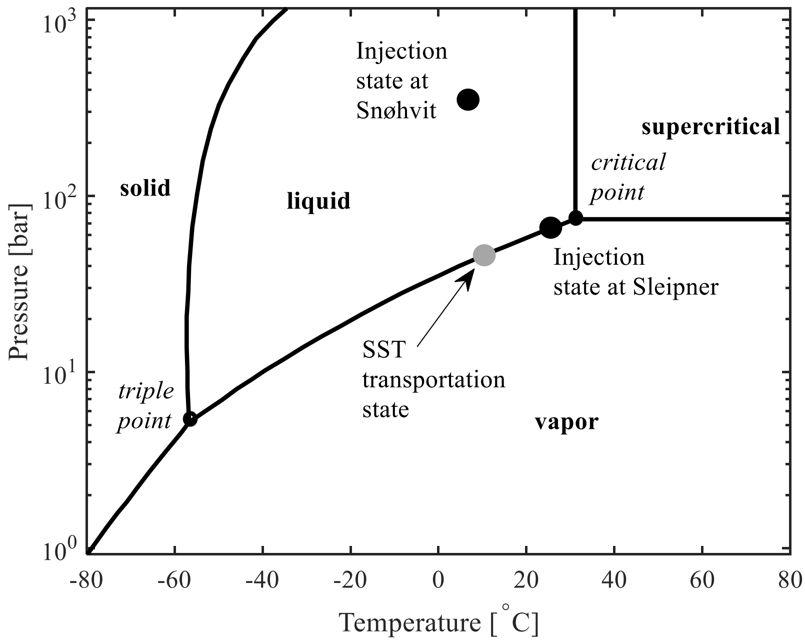

Fig. 4. CO_2 phase diagram with corresponding CO_2 states of transportation methods (data from [7, 43]).

2.3. Systems and components

2.3.1. General arrangement

The SST is constructed with a torpedo-shaped hull that has a hemispherical bow, a 130.5 m long cylindrical mid-body section and a 25 m long conical aft, the diameter is 17 m. To simplify geometry and reduce drag resistance the torpedo shape had been chosen. However, it is particularly challenging to design large submarines to resist collapse in deep waters. For the large diameter thin-walled structures, it is extremely costly to increase the collapse capacity [4].

A double hull design is utilised at the cylindrical mid-body to avoid the need for collapse pressure design. That means water can enter the internal space of the mid-body, as result internal and external pressures on the external hull cancel each other. In turn, cargo tanks and buoyancy tubes are designed to handle burst and collapse loads. The hemispherical bowl and conical aft are free flooding compartments, however, they a relatively smaller in size allowing them to efficiently withstand pressure loads. All compartments are checked for the collapse diving depth (19 bar). The steel VL D47 is chosen to be the material for all three compartments, the detailed characteristic of the material is presented in Table 2.

Table 2 SST external hull properties.

Parameter	Free flooding compartments	Flooded mid-body	Unit
Length	23.75	100.0	m
Thickness	0.041	0.025	m
Frame spacing	1.0	1.5	m
Steel weight	521	1374	tonnes
Material type	VL D47	VL D47	
Yield strength	460	460	MPa
Design pressure	20	7	Bar

The SST has four bulkheads to separate the flooded mid-body from free flooding compartments and support internal cargo tanks and buoyancy tubes. There are two watertight bulkheads at the forward and aft vessel and two non-watertight bulkheads, which are placed at the flooded mid-body. All bulkheads are also checked against nominal diving, test diving, and collapse pressures. The vessel is divided by two watertight bulkheads into three sections. The general arrangement is presented in Fig. 5.

- Free flooding aft compartment: it includes the moisture-sensitive parts such as the motor, gearbox, rudder controls battery, aft trim tank, and aft compensation.
- Flooded mid-body: the compartment includes buoyancy tanks, cargo tanks, and piping.
- Free flooding bow: compartment contains the sensors, sonar, radio, control satiation, pumps for offloading, fwd trim tank, and fwd compensation tank.

The non-watertight bulkheads are not subjected to hydrodynamic pressure, and they are utilised to provide support to the internal cargo tanks and buoyancy tubes.

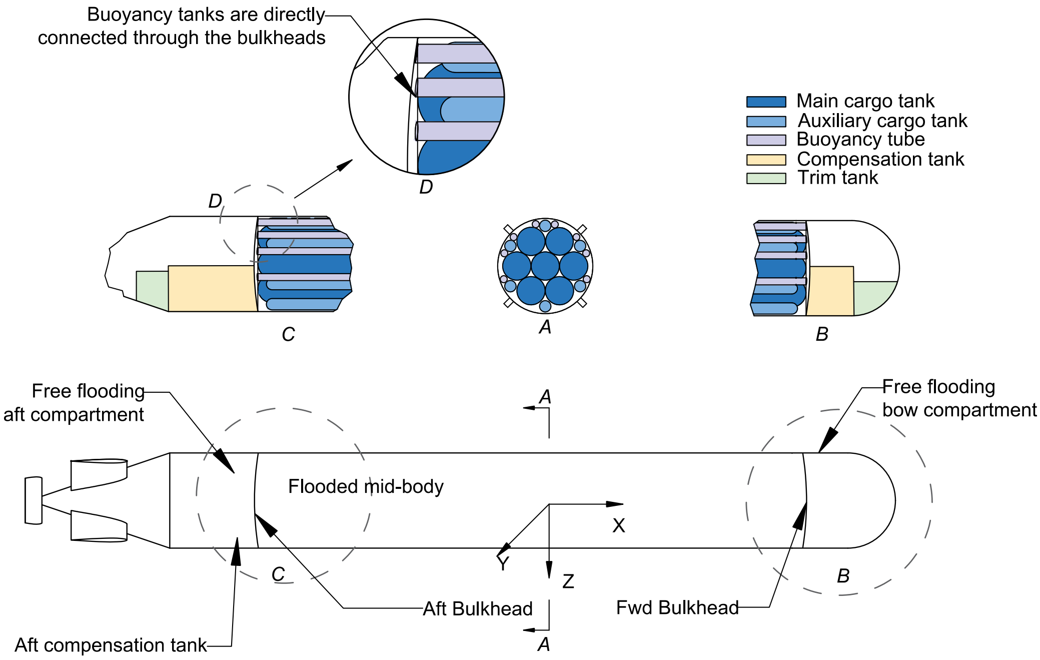

Fig. 5. SST general arrangement. A: Mid-vessel cross-section. B: SST fwd bulkhead. C: SST aft bulkhead. D: Buoyancy tank-bulkhead connection [7].

2.3.2. Internal tank structures

The internal tanks comply with ASME standards BVPC Sec. VIII-2, Chapter 4.3 – Design rules for shells under internal pressure and Chapter 4.4 – Design of shells under external pressure and allowable compressive stresses [49]. There are five kinds of internal pressure vessels: main cargo tanks, auxiliary cargo tanks, buoyancy tanks, compensation tanks, and trim tanks. It is vital to describe their main hazards during risk assessment, including fire, leakage, and explosion hazards. This is identified as the worst-case scenario that occurs during transportation of CO_2 on the sea surface when external hydrostatic pressure is 0 bar gauge, and the pressure difference is 55 bar.

<u>A. Cargo tanks</u>

There are 13 cylindrical cargo tanks (seven main and 6 auxiliary) placed in the flooded mid-body part of SST. These tanks have a designed burst pressure of 55 bar and are utilised for CO_2 storage.

<u>B. Compensation tanks</u>

Compensation tanks are placed in the free flooding compartments. They are not exposed to external pressure.

There are two 800 m^3 compensation tanks within the SST, and they communicate directly with the open sea using pumps. Compensation tanks help the SST maintain neutral buoyancy under different hydrostatic loads by providing the trimming moment and necessary weight.

C. Trim tanks

Two 200 m3 trim tanks are located in the bow hemisphere and aft cone (free flooding compartments) in the SST. Their main goal is to archive neutral trim conditions by bringing the centre of gravity (CoG) vertically beneath the centre of buoyancy (CoB). This is accomplished by pumping water between the trim tanks.

D. Buoyancy tanks

Eight buoyancy tanks measuring 1.25 m in diameter are positioned at the top of the SST to keep the vessel neutrally buoyant. These buoyancy tanks are 100 m long and directly connected to the bulkheads. Moreover, tanks are empty, i.e., free flooding so that the moisture-sensitive equipment can be arranged inside. These tanks are designed to handle 7 bar pressure corresponding to the 70 m nominal diving depth and collapse pressure of 17 bar.

2.3.3. Propulsion systems

With the SST, a propeller-driven system will be powered by electrical batteries on board, with additional machineries such as a motor, gearbox, and control unit. The SST uses a three-bladed propeller with a diameter of 7 m, a small blade area ratio of 0.3, and a slow operating rotational speed of 38 RPM, which provide it with a high quasi-propulsive coefficient (QPC) of 0.97 [7, 50].

The SST battery properties are listed in Table 3. SST uses a Li-ion battery because of its high energy density, high specific energy, and steady power output over a long period of time. The SST is projected to be built within the next decade, and it is expected that technological developments within Li-ion batteries will increase its energy density significantly [7]. In the latest disclosure by Mikhaylik et al. [51], it has been predicted that the specific energy will be increased up to 500 Wh/kg compared to the current typical specific energy of 250 Wh/kg. As a result, the battery with a total capacity of 20,000 kWh is estimated to be 40 tonnes. The battery has a life of 1000 discharge cycles or about 8.3 years if two 400 km trips are performed weekly.

2.3.4. Pressure compensation system (PCS)

The pressure compensation system was integrated into the cargo and consisted of a movable piston with seals providing separation of CO_2 against seawater. The PCS is depicted in Fig. 6. The piston seals can be manufactured from the polyurethane-like pigs for pipelines. Further, pistons can be equipped with intelligent sensors for monitoring parameters such as tank pressure, cargo temperature, and corrosion status.

The PCS is designed to ensure that internal pressure in the cargo tanks will always be higher or equal to external pressure. It has several operation modes to ensure the safety of operations and prevent possible overload failures.

A. Normal operating case

Considering the normal operating case, transporting liquid CO_2 at 70 m depth is presented in Fig. 6. The CO_2 will be transported at 35-55 bar depending on water temperature, which varies from 0 to 20 °C. Seawater is at the other end of cargo tanks to fill up the remaining void and equalise pressure. The valve closes as the pressure reaches a defined value for a given temperature.

B. Uncontrolled descent case

As shown in Fig. 6 (b), in an accidental uncontrolled descent case, i.e., the SST descents to a water depth of 500 m, the external hydrostatic pressure will increase to 50 bar. At this point, a valve at one end of the cargo tank will be opened to allow seawater to flood in. The seawater will push against the piston. The internal pressure in the cargo tank will be equalised with hydrostatic pressure in the mid-body so that differential pressure will be eliminated. It can ensure the integrity of cargo tanks and avoid leakage in a nonrecoverable accident when the SST sinks.

C. Uncontrolled ascent case

Fig. 6 (c) presents an uncontrolled ascent case where the SST ascent to a water depth of 40 m, external hydrostatic pressure will reduce to 4 bar. The CO_2 pressure will increase from 45 bar to 50.9 bar due to increased temperature. The valve is closed, and CO_2 will push the piston against seawater. Therefore, seawater pressure will be increased and equalised. In this case, the differential burst pressure loading is 46.9 bar.

D. Seawater filled cases

As illustrated in Fig. 6 (d), the seawater-filled cases are situations where the cargo tanks are filled with seawater after the SST is offloaded at a subsea well. As intended, valves are closed, but if any accident occurs, which implies for SST to immerse deeper, valves will open and allow seawater to entre. As a result, the pressure difference is neglected.

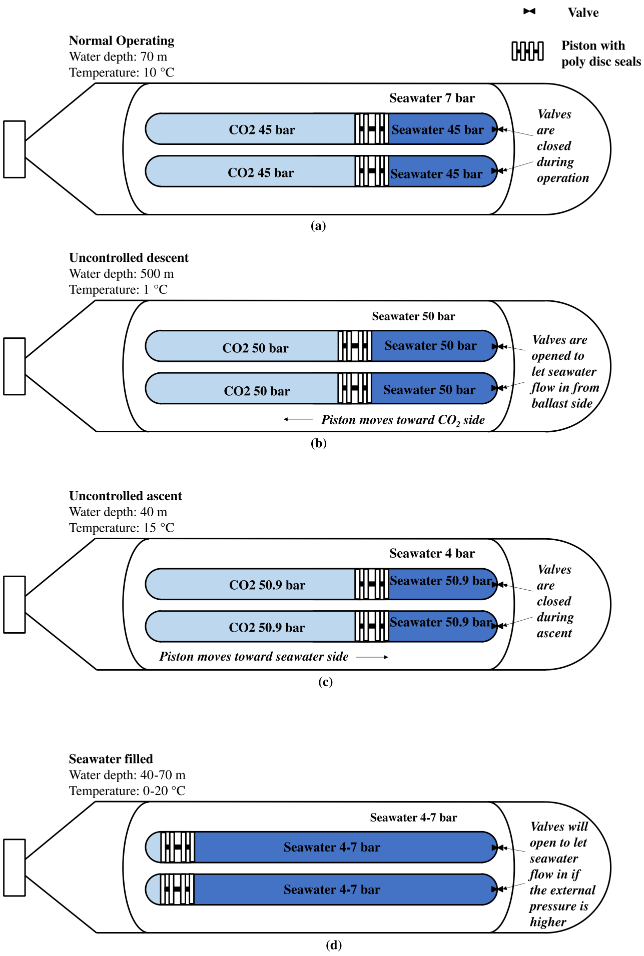

Fig. 6. Pressure compensation system.

2.3.5. Offloading

The SST is designed to offload CO_2 through a flexible flowline or riser connected to the subsea well while hovering. This flowline will be related to SST using an ROV or resident drone. The loading and offloading process is depicted in Fig. 7 and described in the following steps:

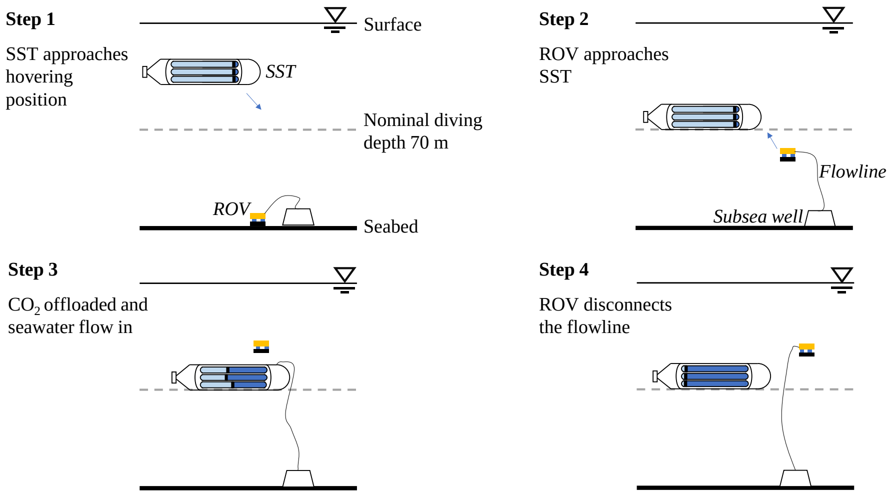

Fig. 7. SST loading and offloading procedure.

- Step 1. The SST navigates to the subsea well site and hovers at the operating depth.
- Step 2. An ROV or resident drone carries the flowline from the subsea well and mates it with SST.
- Step 3. Liquefied CO_2 is pumped out from each cargo tank through a mated connection and flowline to the subsea well. Meanwhile, seawater is pumped in from the other end of each cargo tank equalising the differential pressure inside and outside cargo tanks. The compensation and trim tanks are used to maintain the stability of the SST.
- Step 4. The ROV or resident drone disconnects the flowline.

3. Methodology

In this study, a risk assessment, including hazard identification for Subsea Shuttle Tanker during transportation of CO_2 in the Norwegian sector, is presented. The assessment aims to ensure acceptable safety and security levels for the SST and other vessels and the shipping community in general. Furthermore, the assessment points out potential improvements in an existing design or chooses between alternative design methods.

The application considers the outcomes of previous studies on maritime transportation and traffic risk, including those executed for the analysis of autonomous and unmanned vessels. The primary type of accidents and hazards in the operational context will be identified based on this information.

The risk assessment used for the SST system is based on the Formal Safety Assessment (FSA) method from IMO guidelines [24]. Formal Safety Assessment (FSA) is a structured and systematic methodology that enhances maritime safety, including the protection of life, health, the marine environment, and property, by using risk analysis and cost-benefit assessment [24]. This is an internationally accepted method for risk-based analysis. Thus, it is a reasonable baseline for a novel vessel such as SST. FSA includes a 5-step process, including hazard identification, risk assessment, development of risk control options, cost-benefit assessment, and making recommendations for decision making. The FSA process is depicted in Fig. 8.

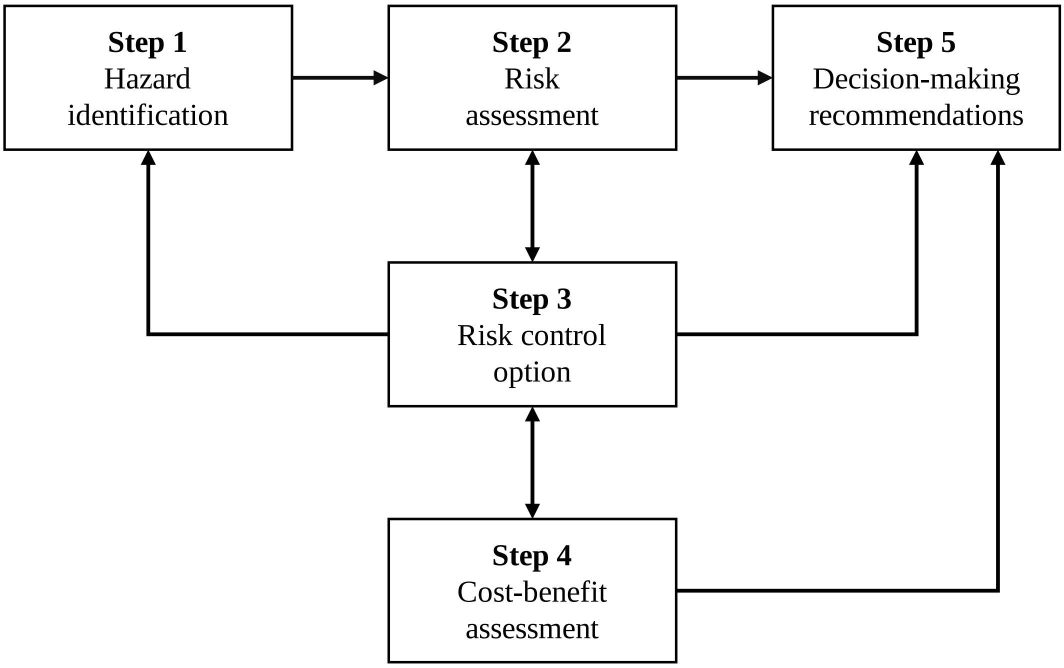

Fig. 8. FSA methodology [24].

DNVGL-CG-0264 guideline [52] provides a framework for technical guidance for the safety assessment of autonomous and remotely operated vessels concepts and technologies. Presented guidelines cover safety considerations for the entire spectrum of functions intended for the autonomous system: Vessel engineering, Navigation, Remote control, and communication. Furthermore, for autonomous type, enhanced assessment must be implemented for controlling vessel functions. This focus includes the safety-state, failure mode, and fault robustness of the functions and systems. The definition of hazard is any actual or potential condition that can cause injury, illness, or death to personnel; damage to or loss of a system, equipment, or property; or damage to the environment. The purpose of managing risk control options and safety measures will be discussed in relation to principles for safety engineering proposed by Möller and Hansson [53]. Those principles have four major categories: inherently safe design, safety reserves, safe fail and procedural safeguards.

FSA provides a framework and suggestions for assessment but doesn't regulate tools and methods for hazard identification. Previous publications regarding autonomous and unmanned shipping utilised the following methods: HAZID [15], BBN [18, 54], What If [15], and STPA [55]. However, according to DNVGL-CG-0264, a preliminary hazard analysis (PHA) method is suggested as preferred for the technology qualification process at the design stage.

The approach in this paper will utilise PHA as the hazard identification method. PHA aims to identify and analyse the hazards and ways or methods to control them in the stage of system development. In addition, PHA determines safety-critical functions and top-level mishaps to keep safety in focus during the design process. Furthermore, PHA allows for evaluating relative risks by giving general characteristics of probability and consequences together with Initial Mishap Risk Index (IMRI) or Risk Priority Number (RPN).

The process of PHA consists of the following steps, those steps described below and represented in Fig. 9:

A. Plan and prepare

The main aim is to assemble all known information, define time constraints and establish the list of participants to carry out the assessment.

Discuss main objectives and limitations; define the mission, mission phases, and operational context; acquire design, operational, and process data. Provide background data such as hazard checklist, failures and accidents, lessons learned and safety criteria.

B. Identify hazards and scenarios (hazardous events)

This step aims to establish a list of hazardous events. The identification of hazards occurs during the expert group's meetings based on a generic checklist of hazards. In addition, participants contribute their knowledge and expertise, as well as experience from the study object (or a similar system). The primary sources for judgment are reports from previous accidents and incidents, accident statistics, expert judgments, operational data, and checklists.

The outcome of this step is a list of hazards, causes, accident scenarios, and consequences. After that, a final list of hazardous events is established after structuring and filtering. It aims to filter out overlapping hazardous events and events with negligible probabilities and consequences.

C. Determine the frequency of hazardous events

In this step, the team discusses causes and evaluates the frequency of each event that was identified during step 2.

The frequency evaluation may be based on historical data, expert judgments, previous studies, and assumptions. The historical data usually comprise accident reports and statistics from similar accidents.

D. Determine the consequences of hazardous events

In this step, the potential consequences following each of the hazardous events in step 2 are identified and assessed. The scope covers consequences for different assets, such as people, equipment, and reputation. During estimations of consequences, assets are divided by their type, and estimation is performed for each. Afterwards, consequences are ranked by their severity and assigned with a corresponding value starting with 1 for least critical consequences and increasing as the severity escalates.

E. Assess the risk

Here, the risk is described as a list of all potential scenarios and their associated probabilities (frequencies) and consequences. Afterwards, to illustrate the risk, all hazardous events are inserted into the risk matrix to demonstrate the risk.

F. Identify relevant risk reduction measures

After the risk has been identified, the team will provide new reduction measures wherever possible to maintain the risk as low as reasonably practicable (ALARP). After new/updated reduction measures have been represented, the risk is assessed again to demonstrate its reduction.

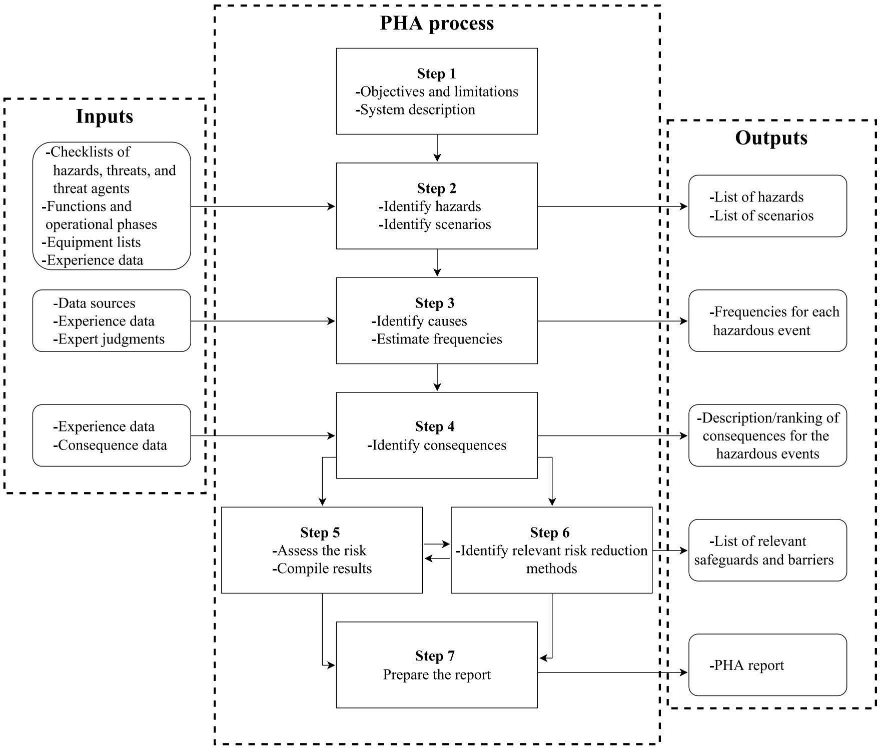

Fig. 9. PHA process.

After completing all steps, results will be presented in the form of a table PHA tables.

4. Results

4.1. Risk factors and failure modes

Transportation of CO_2 using SST can be divided into three main stages: loading, transportation, and offloading. Fig. 10 depicts a functional flow diagram showing stages involved in transportation operation.

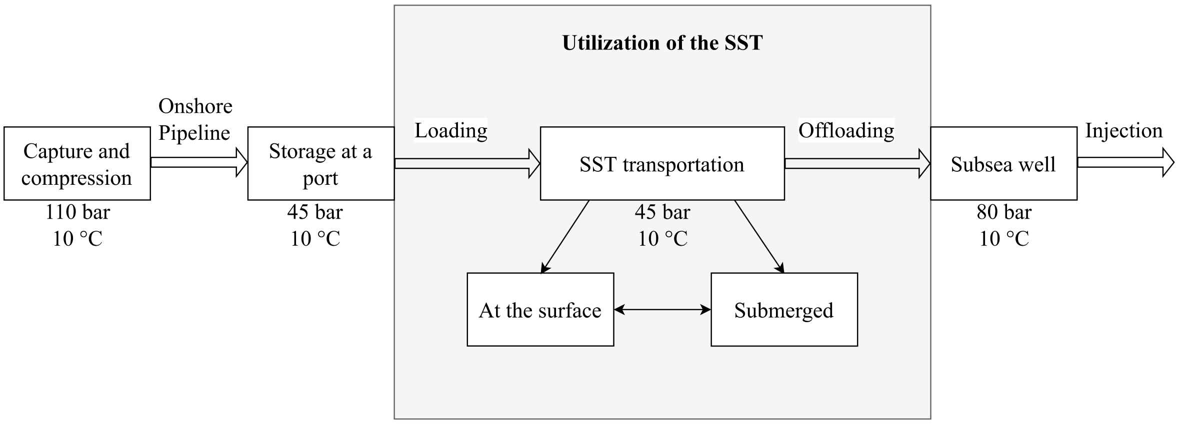

Fig. 10. SST functional diagram of operational phases.

Fig. 11 represents the list of main system components, functions, and energy sources that should be considered for PHA. The description of major SST subsystems and a list of equipment were given in Section 2.

Equipment List	**Subsystems**	**Energy Sources**
Radar and Sensors	SST Navigation	CO_2
Tanks	SST Loading/Offloading	Electricity
Pumps	SST Propulsion	Battery
Control Unit	SST Powering	
Piping	SST Environmental Detection System	
Buoyancy Tubes	SST Communication	
PCS	SST Emergency	
Motor		
Propeller		
Rudder		

Valves		

Fig. 11. SST system information.

Before hazard identification, the main risk factors have to be described. Real information about failure modes and accident data for SST is lacking. To give a general understanding of risk factors and main failure modes of systems with similar operational contexts will be considered. The SST combines the functions of tanker vessels and autonomous underwater vehicles. Furthermore, at the phase of loading and offloading, hoses are used. Analysis of risk factors will be mainly based on technical factors and wouldn't go deep into human-related causes of risk.

4.1.1. AUV hazards

The SST has a similar operational principle, technical systems, and components as an AUV. An AUV consists of subsystems such as propulsion system, navigational system, communication system, power system, security detection system, sensor system, and others [56]. The main AUV subsystems and corresponding risk factors are [57-63]:

A. Propulsion system

In general, the propulsion system provides the required forces for vessel/vehicle movement. It can be based on propeller or buoyancy created hydrodynamic forces or combined. Risk factors could be propeller failure, buoyancy pump failure, actuator failure, or a broken rudder.

B. Navigation system

The navigation system is employed to measure position, attitude, and velocity, allowing the vehicle to follow a predefined trajectory. Risk factors are characterised as failures of single components, including wrong interpretation of measured parameters.

C. Power system

The power system provides electrical energy by the batteries, either lithium-ion or alkaline. The relevant risk factors for power systems are failure to charge, overcharging, energy depletion, and failures related to voltage and current.

D. Communication system

The communication system is utilised in proposes to establish a connection between vehicles and operators. Risk factors are described as failure of acoustic transducers or sensors and loss of signal by any means.

E. Environmental detection system

The environmental detection system process data from sensors to detect the obstacles as well as prevent collision and grounding. The main components of the system are sonars and another sensor. Risk factors are a wrong interpretation of data leading to the collision and failure of sonars.

F. Emergency system

Emergency systems typically imply backup procedures in case of any significant failures.

Three studies are concluded to evaluate the characteristic of failures qualitatively. The first study analyses 205 AUV missions with 63 mission accidents [64]. The second considers four-year missions' data of the Autosub3 AUV [65]. In the third study, more than 400 missions and failures occurring during Sentry AUV operations are revied [66]. The most significant failure modes of each study are presented in Table 3.

Table 3 Prioritised failure modes encountered during AUV operation.

Failure mode	Number of failures	Contribution factor
1st Study		
Leakage	15	Loss of integrity
Failure of power system	9	Equipment failure
Failure of the buoyancy pump	6	Equipment failure
Collision with vessel	4	Collision/Grounding
Sensor failure	4	Equipment failure
2nd Study		
Incorrect predive programming	15	Software/Programming
Electronic hardware failure	7	Equipment failure
Acoustic sensor failure	6	Equipment failure
Software error	5	Software/Programming
3rd Study		
Incorrect predive programming	21	Software/Programming
Collision with seabed	17	Collision/Grounding
Acoustic sensor failure	15	Equipment failure
Code problem	10	Software/Programming

The results showed the occurrence of 212 accidents and failures. The majority of failures contributed to equipment failure, and it takes up about 42% of total cases. The following factor is software or programming problems, approximately 27%. Among all considered cases, only one single failure was related to emergency system breakdown. In most instances, equipment failure does not involve breakdowns of other subsystems and the integrity of the systems as a whole. The distribution of failures by the type of subsystems is the following: Navigation system (41%), propulsion system (29%), power system (22%), communication system (7%) and emergency system (<1%). The data is depicted in pie charts shown in Fig. 12.

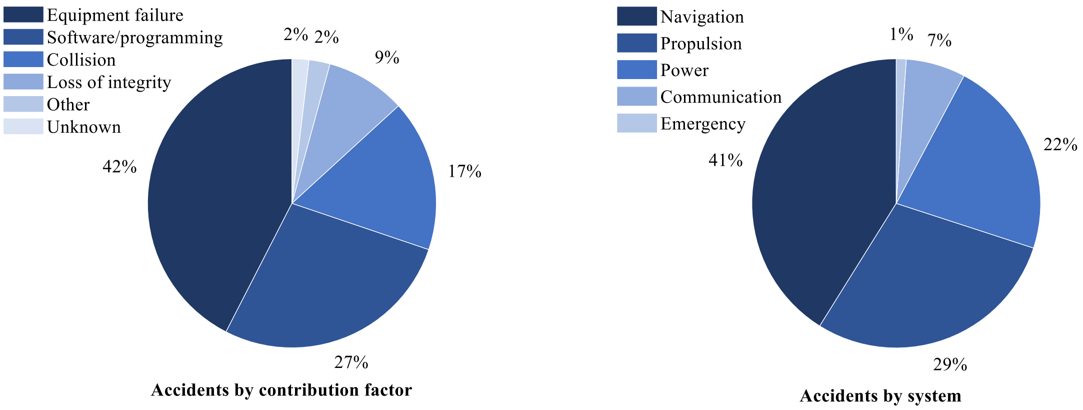

Fig. 12. Distribution of the accidents by their contribution factor and involved subsystems.

4.1.2. Tanker vessels hazards

The SST also involves operations at the sea surface, e.g., at the port, and it is relevant to compare it to traditional and chemical tankers. Information on vessels' accidents and breakdowns are broadly available, and EMSA annually presents an overview of casualties and incidents. We will use acquired data from EMSA 2021 annual report. Fig. 13 shows the distribution of tankers' accident types [67].

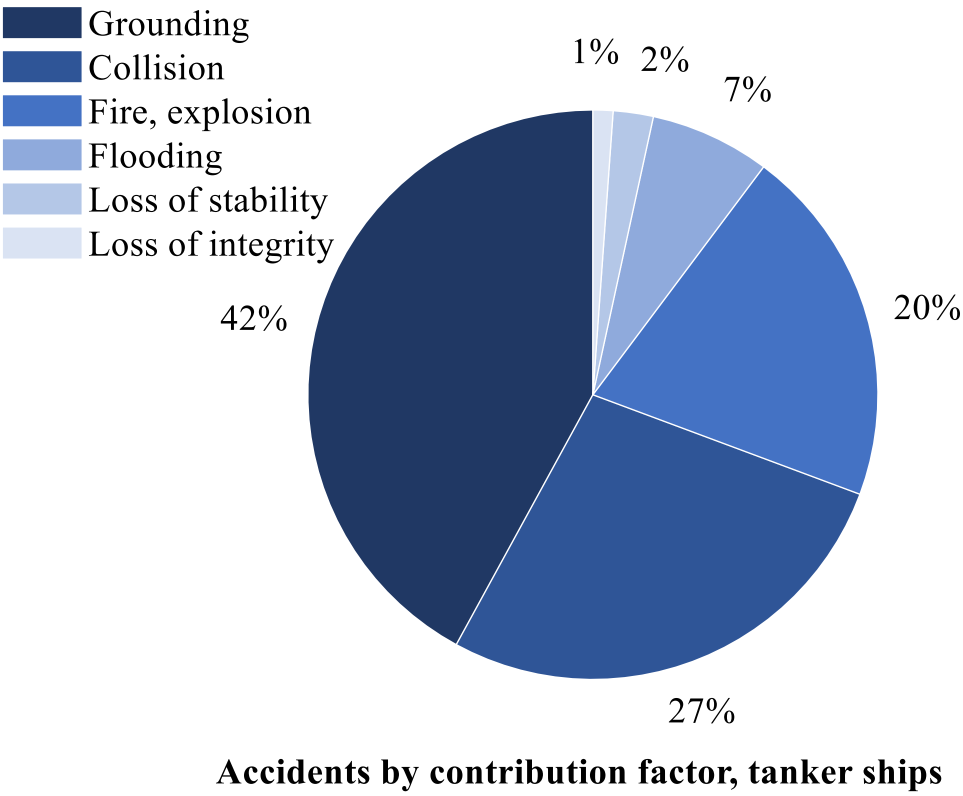

Fig. 13. Distribution of the accidents by contribution factor for tanker ships.

However, the information presented above considers crewed tanker vessels. Thus, Wrobel et al. [13] considers 100 instigation reports about accidents that happened to cargo ships. But implementing SWIFT, Wrobel compared if the vessel in question were unmanned, the probability or consequences would differ. According to the conducted WHAT-IF analysis, introducing the automation system would reduce the likelihood of 47% of the total accidents while resulting in a greater probability of 16% of the cases [13].

4.1.3. Hoses systems hazards

Different infrastructures such as CO_2 plants, external pumps, and boreholes are involved in the loading and offloading of the SST. However, the authors limit the scope only to the vessel itself in this work. Therefore, only the hose system is considered in this section when identifying the hazards during the loading and offloading process.

The general list of hose system equipment is:

- Hoses
- Hose winches
- Flanges
- Quick coupling systems
- Rapid cut-off valves
- Deploying and retracting devices
- Pumps

Sun et al. [68] conducted a failure mode and effects analysis (FMEA) on an FPSO offloading system. The general failure modes and failure effects are:

<u>A. Failure modes</u>

- Hose accidental release
- Integrity loss
- Hose wear
- Pump's malfunction

<u>B. Failure effects</u>

- Leakages and spills
- Hull damage
- Fire
- Explosion

4.1.4 Threats

There are also potential antagonistic threats towards the platform and operation. Typically, these threats can either have a criminal, terrorist or military purpose with the aim to interrupt or take control over the system. The tight coupling between the threat's intent, chosen risk controls, and the operators' preparedness needs to be considered when conducting a risk assessment on antagonistic threats [69]. Security threats need to be analysed concerning each specific threat's intent, capability and likelihood of exploiting the system's vulnerability [70].

Compared to traditional maritime tanker solutions, the cargo contains a lower monetary value and lower potential for severe consequences for the SST. This leads to the possible modus operandi for using a SST and creating severe consequences is limited compared to threats towards LNG carriers [71]. However, the SST is an infrastructure that needs to be protected according to relevant standards, especially against cyber security threats.

4.2. Preliminary Hazard Analysis

The PHA and hazard identification results have been archived during a number of workshops and brainstorming sessions and presented in tables. Based on risk factors and failure modes, PHA tables have been formed.

Scenarios have been considered for five operational phases depicted in Fig. 10. Moreover, the preparation phase has also been analysed. During preliminary hazard analysis, 91 scenarios and their hazards were identified. The distribution of scenarios by their operational phase has the following outlook: 32 cases can be attributed to the underwater navigation phase, 10 cases are attributed to underwater-water transition, 14 cases are related to surface navigation, 13 cases are related to the loading phase, 14 cases are related to offloading phase, and 9 scenarios refer to the preparation phase.

After PHA tables were formed, risks were assessed and represented in the form of a risk matrix. The obtained risk matrix is depicted in Fig. 14. Each point on the chart shows risk ratings with the corresponding number of cases. Risk assessment has a qualitative character and represents a general understanding of presented hazards.

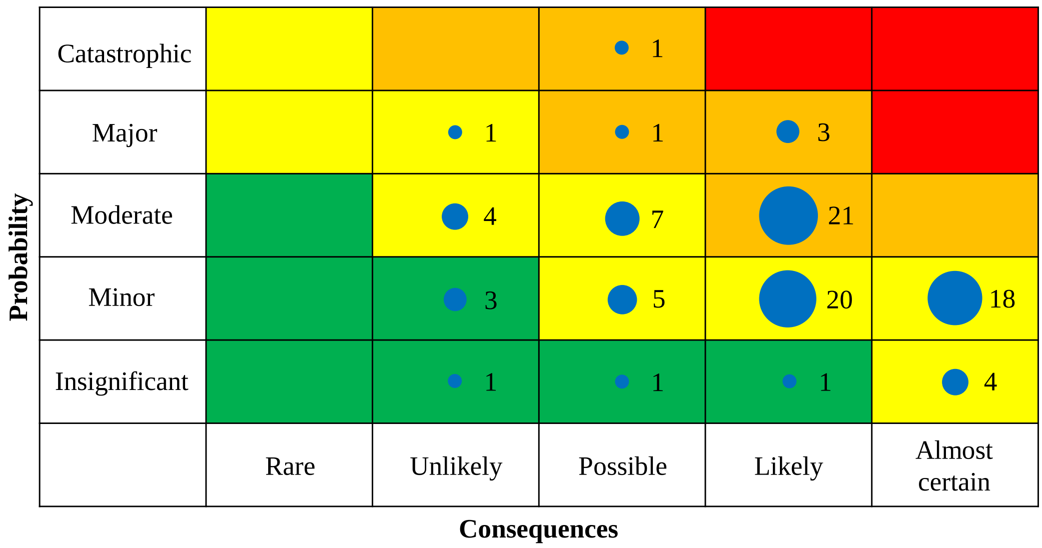

Fig. 14. Risk matrix of identified scenarios and hazards, including the number of cases.

As a result, the most prioritised risks belong to the adjacent region of high and medium-high rating risks. Those risks and respective scenarios from PHA are presented in Table 4.

Table 4. Prioritised hazard scenarios by risk rating.

No.	Hazard/Threat	Hazardous event (What, where, when)	Cause (triggering event)	Consequences	Risk Prob.	Cons.	Risk	Risk reduction methods
UNP-6	Human error	Not correctly eliminated faults during the preparation of mission, leading to systems fault during maintenance	Unclear fault, complex interaction, few experience of technical personnel	Mission is aborted, unplanned behaviour, and even total loss of vessel	4	5	20	Test runs, elimination of faults, maintenance
UNP-12	Human error	Unexpected behaviour during a mission	Wrong pre-drive programming	Mission is aborted, loss of the SST	4	5	20	Programming testing, software testing
UNP-13	Software failure	Unexpected behaviour during a mission	Software failure during product development	Mission is aborted, loss of the SST	4	5	20	Programming testing, software testing
UNP-14	System failure	Failure of the system	Failure of Inertial Navigation System	Mission is aborted, loss of the SST, external damage	3	5	15	Programming testing, software testing
UNP-15	System failure	Seabed Collision	Failure of the Navigation system	Mission is aborted, loss of the SST	3	5	15	Alternating navigation equipment/sensors
UNP-16	System failure	Seabed Collision	Complete failure of SST sensors, loss of positioning	Mission is aborted, loss of the SST	3	5	15	Alternating navigation equipment/sensors
UNP-17	Interaction	Collision with fishnets	External impact from fishing vessel	Loss of fishing vessel and vessel crew	3	5	15	Other vessels have to be aware of the SST presence, the SST operation in exclusion of safety zone
UNP-18	System failure	the SST doesn't follow the designed path	Wrongly programmed, failure of the navigation system	Damage to the SST, mission is aborted	3	5	15	Internal control algorithms, alternating navigation equipment/sensors

UNP-27	Human error	Mission is planned without considering the capabilities of the SST	Bad knowledge, few experience on a decision maker level	Unplanned behaviour, the SST grounding, loss of the SST	3	5	15	Testing before mission, maintenance and inspection, emergency system
UWP-4	Human error	Collision with a tugboat	Collision happened due to poor training, human factor, poor tow planning	Loss of tugboat, damage to SST	3	5	15	Training, operating with compliance to standards
UWP-5	Human error	Girting of a tugboat	Loss of stability, poor tug handling, procedure	Loss of tugboat, damage to SST	3	5	15	Training, operating with compliance to standards, tug's emergency quick release system
SNP-3	Human error	Collision with a tugboat	Collision happened due to poor training, human factor, poor tow planning	Loss of tugboat, damage to SST	3	5	15	Training, operating with compliance to standards
OFP-12	Environmental interaction	Collision with a well	Strong hydrodynamic forces created by current	Loss of SST or well	3	5	15	Safety zone to be defined
PPH-4	Human error	Wrong mission parameters are implemented during preparation	Wrong programming, misunderstanding, unclear procedures	Loss of the SST, the mission is aborted	3	5	15	Validate programming and mission parameters, the SST monitoring during operation

When the unacceptable limit of ALARP is set at the high-risk ratings, all scenarios in the distribution of risk ratings presented in Fig. 14 are located within acceptable region limits. In the future, detailed limits evaluation for the ALARP region should be performed during the cost-benefit assessment.

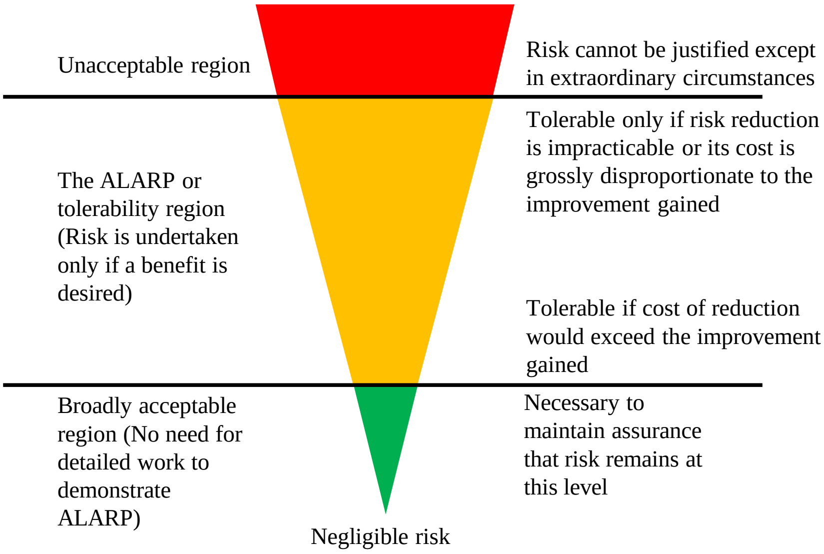

Fig. 15. ALARP principle [25].

During PHA execution, risk control methods were proposed in addition to hazard identification and risk assessment. From Table 4, it can be noticed that the most prioritised hazards with the highest corresponding risk rating. Two of them are related to human involvement, and the other two are related to the navigation system. Human related hazards should be managed with properly designed procedural safeguards before starting SST operations. It can be archived by validating and testing/checking programming and mission parameters.

Considering failures related to the navigation system or any other systems with active equipment principle of safe fail guards should be considered. The safe fail principle is closely related to reliability, redundancy segregation, and diversity. Here reliability is the primary core, and subsequently, redundancy segregation and diversity are used to archive it.

General recommendations for ensuring safety for SST utilisation will be given in Section 6.

5. Cost-benefit assessment

A cost-benefit analysis can entail the evaluation of the limit for the ALARP region. This cost-benefit analysis will be conducted in the following stage after more details of the SST are determined. Therefore only preliminary discussions are provided in this section.

The authors expect risk control options identified during PHA will be included in the SST system. Part of those control options relies on operation in accordance with standards proposed by IMO, DNV, etc. Operation following standards is not only necessary but an effective mitigation option. Accordance with standards helps design the system with an initial level of safety, as it includes all principles for safety engineering [53].

For the risks that are not directly regulated in any applied standards, cost-benefit assessment will be carried out to choose adequate risk control options in future works.

Although we cannot perform a cost-benefit assessment at the present design stage, the following statements must be considered in future dedicated studies and assessments.

- Hazards with corresponding high rated risks must be considered - first of all, with excessive details.
- The safety of the system and environment must be prioritised against any economic aspects.

6. Discussion/Recommendations

Following the DNVGL-CG-0264 [52], autonomous vessels must have a level of safety equivalent to or better, compared to conventional vessels, regarding safeguarding life, property and environment. From the performed work and analysis, we can infer that possible catastrophic scenarios to the SST do not necessarily lead to more severe consequences than human-crewed ships. However, it is essential to ensure that hazards do not escalate to situations that danger manned platforms and the environment.

Central aspects of the design of the SST are described below.

A. Equipment

The analysis showed that scenarios involving mechanical failure of equipment are the most severe ones. Active components such as navigation, propulsion and electrical power systems have to be designed with the safe failure principle of safety engineering. It can be archived with redundant design or alternating options to remain the system operational. Failure of active components should not affect other systems. In addition, systems or components designed with the redundancy principle should be mutually independent. Passive components such as pipes and valves could be exempted from the redundant requirement as they have lower failure probabilities.

In general, failures may affect the capabilities of the SST system but should not prevent the safe operation of the vessel. Self-diagnostic functions should be implemented to prevent failures and provide communication links with the onshore centre in abnormal situations. Data transferring could be archived by acoustic and satellite communication when the vessel is underwater and on the surface, respectively.

At the fully autonomous phase, the system has to be able to restore an essential vessel function without any assistance. Otherwise, the system has to switch to safe mode for further retrieving.

B. Software

The implemented hazard analysis on AUV safety identified software failures among common and prioritised risks. The SST also implies primarily autonomous operation; thus, software failures should be carefully considered. Related recommendations are the following.

Software must be controlled during the development and configuration in the first place. Furthermore, before each mission, software testing must be carried out. The main software errors such as coding errors, atrocious logic, data mismatch and communication errors should be considered.

C. Cyber security

From a security perspective, the SST is a cyber-physical system, which means the physical and digital components of the system are interrelated [72]. For operational safety, cyber security should be considered.

Cyber security must be addressed during the design phase. Detailed cyber security analysis should be implemented on the communication system, including vessel-systems, datalinks and shore centres. All parts of cyber systems should be regulated by an up-to-date cyber security policy, procedures and technical requirements defined by cyber security frameworks. Examples of widely used regulatory standards and practices concerning cyber security which could be considered in the design of the SST are [73-75].

In case of a cyber-attack or any other abnormal situation, the SST system has to be able to restore its function.

D. Human involvement

Despite that, the SST does not imply crew presence at any part of the operational phase. Human involvement still plays a big part in SST operations, and major involvement takes part in the preparation phase and mission configuration. The implemented analysis shows that the wrong mission configuration is a severe risk factor related to human involvement. Mission parameters and system configuration should be adequately checked and tested before each operation. The people involved must have sufficient qualifications and experience working with autonomous vessels.

E. Risk control options

Risk control options must be implemented to eliminate, prevent, and reduce the occurrence of identified hazards for the SST and manage their consequences in case of occurrence. According to the engineering safety principles proposed by Möller and Hansson [53]. The SST must be based on four principles of risk control options.

- Inherently safe design
- Safety reserves
- Safe fail
- Procedural safeguards

Focusing on these principles allows one to analyse the safety of the system from different perspectives on safe design.

From the baseline design of the SST [7], inherently safe design and safety reserves principles have been considered. Furthermore, some safe fail control options have been discussed and included in the design. One of them is pressure compensation systems, as discussed in Section 2.3.4.

The authors will evaluate risk control options proposed during preliminary hazards analysis during cost benefit assessment in future works.

F. CO2 quality

CO_2 impurities increase the risk for corrosion and hydrate formation. The most undesired impurity is free water. In contact with CO_2, free water dissolves and forms highly corrosive carbonic acid. As a result, acid can lead to severe corrosion issues in cargo tanks and piping of the SST. By ensuring that water's concertation is always lower than its solubility, free water formation is avoided in the SST.

On the other hand, in case of violation of thermobaric conditions, hydrates may form, causing blockage and/or sealing issues. This issue is particularly relevant for the seals in the pistons of the pressure compensation system. Besides, chemical injection with MEG must be foreseen in case of hydrate formation.

7. Conclusion

Risk assessment based on IMO formal safety assessment is developed to support research studies into autonomous underwater freight vehicles. This work aimed to close the gap between operative context and design characteristics. Outcomes of previous studies on marine transportation and traffic risks and risk-related studies of autonomous and unmanned vessels have been used to develop frameworks for the risk assessment of the SST. A risk assessment was performed based on analysed studies and processed historical data. IMO formal safety assessment utilisation helped build an effective structure and present a consistent basis for autonomous transportation safety evaluation.

The approach in this paper utilised PHA as hazard identification and risk evaluation. During PHA, 5 operational phases of the SST utilisation, 91 hazards and related scenarios were identified. For each of the scenarios, risks have been evaluated and ranked. Moreover, initial risk control options have been proposed for each scenario. PHA helped define and assess the main challenges emerging for autonomous transportation. Moreover, it pointed out where design and development efforts need to be focused.

Based on performed work, generic recommendations for the main design aspects of the SST were provided. Recommendations on equipment, software, cyber security, human involvement, risk control options and CO_2 quality should be served as a framework for cost-benefit assessment and further design stages development of the SST.

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