Zero waste Heat vessel towards relevant Energy savings also thanks to IT technologies

D 5.1 | ZHENIT Solutions regulatory inventory

WP5 – Technologies evaluation and impact assessment towards replication

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Clean and competitive solutions for all transport modes - Innovative on-board energy saving solutions

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List of Organizations

Participant Name		Short Name	Country	Logo
1	RINA Consulting Spa	RINA-C	Italy	
1.1	RINA Services Spa	RINA-S	Italy	
2	Ethnicon metsovion polytechnion	NTUA	Greece	
3	Kyma as	KYMA	Norway	
4	Fundacion tecnalia research & innovation	TECNALIA	Spain	
4.1	Universidad del pais vasco/ euskal herriko unibertsitatea	UPV/EHU	Spain	
5	Anonimi naftiliaki eteria kritis (anek) s.a.	ANEK	Greece	
6	Consiglio nazionale delle ricerche	CNR	Italy	
6.1	Consorzio di ricerca per l'innovazione tecnologica, sicilia trasporti navali, commerciali e da diporto scarl	NAVTEC	Italy	
7	Sorption technologies gmbh	SORTECH	Germany	
7.1	Sorption technologies srl	SORTIT	Italy	
8	Bound 4 blue sl	B4B	Spain	
9	Encontech bv	ECT	Netherlands	
10	Gruppo sigla srl	SIGLA	Italy	
11	The university of Birmingham	UoB	United kingdom	

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Abbreviation and Acronyms

Acronym	Description
ABS	American Bureau of Shipping
AC	Alternating Current
ALARP	As Low As Reasonably Practicable
DC	Direct Current
DNV	Det Norske Veritas
FMEA	Failure Mode and Effect Analysis
GHG	Greenhouse Gases
HSE	Health, Safety and Environment
IACS	International Association of Classification Societies
IGC	International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF	International Code of Safety for Ship Using Gases or Other Low flashpoint Fuels
IMO	International Maritime Organization
LR	Lloyd’s Register
MED	Marine Equipment Directive
MR	Mutual Recognition
ORC	Organic Rankine Cycles
PCM	Phase Change Material
PDA	Prototype Design Assessment
RCO	Risk Control Options
RO	Recognised Organisation
SOLAS	IMO International Convention for the Safety of Life at Sea
TA	Type Approval
TQP	Technology Qualification Process
TR	Technical Requirement
WAPS	Wind Assisted Propulsion System
IEE	Isobaric Expansion Engine

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Executive summary

The ZHENIT Project aims to promote Waste Heat Recovery (WHR) as key and "ready-to-implement" solutions to achieve 2030 International Maritime Organisation and European Union targets for shipping sector decarbonization. ZHENIT goal is to fully untap "on-board WH potential" developing and validating WHR solutions at different temperature levels for different on-board services (cooling, power, desalination), thus promoting heat in different vessel processes.

The present document constitutes the Deliverable D5.1 "ZHENIT Solutions regulatory inventory", developed within Work Package (WP) 5, which aims at identifying Rules and Regulations applicable to novel technologies investigated within the ZHENIT project as well as providing preliminary insight into the certifications possibly required for their approval by Class Societies. All novel technologies are to be approved according to existing Rules and Regulations before considering their installation onboard vessels, thus a detailed analysis of applicable regulatory framework and certification schemes available from Class Societies is of paramount importance to ensure a broad impact of the project.

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1 Introduction

This deliverable was prepared in the framework of Work Package 5 and it is released at M12.

The main objective of D5.1 is to provide a detailed inventory of Rules and Regulations applicable to novel technolgoies investigated in the ZHENIT project as well as to give an overview of the certifications required for approval by Class Societies.

The following chapters are included in this document:

- Chapter 1: Introduction;
- Chapter 2: Ship classification and mutual recognition;
- Chapter 3: Systems for essential/non-essential services;
- Chapter 4: Rules for testing and certification of marine materials and equipment;
- Chapter 5: Marinization;
- Chapter 6: Integration onboard;
- Chapter 7: ZHENIT technologies;
- Chapter 8: Concluding remarks and future perspectives on ZHENIT technologies.

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2 Ship classification and mutual recognition

When safety and reliability of materials, equipment and components present on board a vessel play a relevant role, classification is involved. Depending on how critical the system is to safety, classification is involved differently, as shown by the safety hierarchy shown in Figure 2.1.

Figure 2.1: Safety hierarchy usually considered for equipment classification purposes

Specifically, six different levels of safety relevance are identified:

- Level 1: no Class involvement and certification are required. This level applies to non-safety critical systems as well as to equipment out of safety critical systems. Examples of equipment belonging to Level 1 are furniture and entertainment systems.

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- Level 2: quality certificate from the Manufacturer is sufficient. This level applies to equipment dealing with weak safety relevance, hence certification is not mandatory, despite certain individual Class Societies may have requirements on it. Examples of equipment belonging to Level 2 are converters, condensers, sounding rods,…
- Level 3: Type Approval certification is required and Class involvement is necessary. This level applies to equipment dealing with low grade of safety criticality, hence Type Approval is sufficient to guarantee that the design and manufacturing processes comply with specifications and standards. Examples of equipment belonging to Level 3 are electrical heating cables and sensors.
- Level 4: each manufactured unit requires certification. This level applies to equipment which is safety critical, hence each unit shall be approved and its manufacturing process and/or testing is to be witnessed. Examples of equipment belonging to Level 4 are large electrical machines, pumps, propeller shafts and sub-components of main and auxiliary prime movers installed onboard.
- Level 5: both main unit and its components require certification. This level applies to complex equipment (i.e., system) specifically designed and manufactured for a particular vessel, whose sub-assemblies may be relevant for the ship safety. In this case, both the system and the components require certification. Examples of equipment belonging to level 5 are main engines, thrusters and podded thrusters.
- Level 6: certification requires deep knowledge of the complete system. This level applies to complete systems which are highly relevant for safety purposes. In this case deep knowledge concerning both construction and operation of the ship is required, together with specifications related to many other onboard systems. Examples of equipment belonging to Level 6 are main propulsion systems and dynamic positioning systems.

When the certification process of onboard systems (e.g., Approval in Principle of new technologies) and the classification of the vessel are performed by two distinct Class Societies, relationships and procedures are regulated by the "Mutual Agreement on the implementation of Mutual Recognition Provisions of Art 10 of Regulation (EC) No 391/2009 of the European Parliament and of the Council of 23 April 2009 on Common Rules and Standards for Ship Inspection and Survey Organizations", which entered into force on 7 October 2010.

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Mutual Recognition (MR) typically works for equipment classified in Level 3 (Type Approval required) or, eventually, in Level 4 (certification of each single unit required). Indeed, equipment belonging to Level 3 are characterized by low safety criticality and are typically manufactured in series in standardized form, hence technology providers have a strong interest in reducing multiple certifications. Furthermore, no specific Class requirements exist for the manufacturing and testing processes of equipment belonging to Level 3, since Type Approval is issued according to standards and specifications agreed with the technology provider. Thus, MR can be useful for establishing a common and widely recognized procedure.

However, almost all components may generate serious safety risk under particular operating conditions. E.g., failure of a pressure or temperature sensor installed into a boiler may have strong effect on its safe operation. For this reason, a common and widely recognized framework for Type Approval issuance is necessary to minimize risks. Towards this end, mutual recognition has been introduced. Nevertheless, within the MR framework, further testing aimed at demonstrating safety compliance may be possibly requested by Class Society for equipment which previously obtained Type Approval.

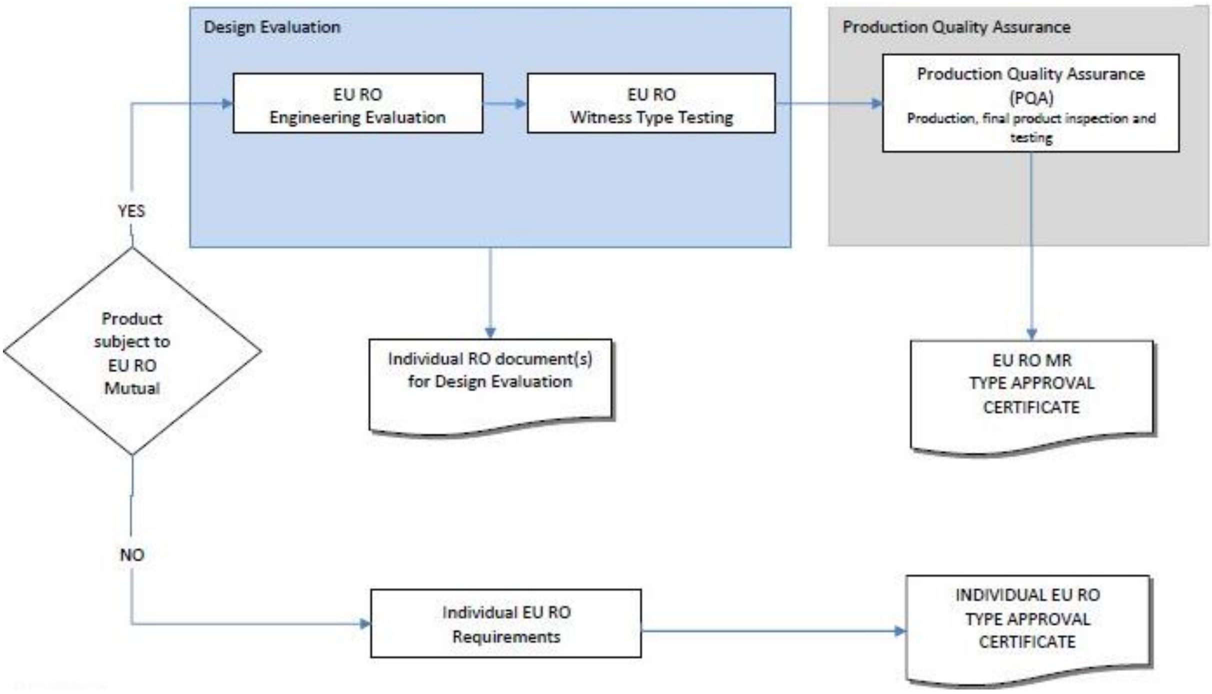

Figure 2.2: Flow chart technical and procedural conditions for EU RO Mutual Recognition of Type Approval Certificates for equipment and components based on equivalent standards [1].

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Overall, technical requirements for mutual recognition as well as for relevant certificates are agreed among EU Recognized Organizations (RO) and are included in Tiers.

Figure 2.2 shows the flow chart underlying the mutual recognition of Type Approval Certificates by the EU RO entities. Overall, the following rules are valuable for the EU RO MR Type Approval Certification process:

- EU RO MR Type Approval Certification may be requested on a voluntary basis
- EU RO MR Type Approval Certification can be requested by Manufacturers independently from their company location
- the Manufacturer is free to choose the organization issuing the EU RO MR Type Approval of its product and no need to repeat the same procedure with other RO is present. Updated list of the EU Recognized Organizations is reported below:
    - American Bureau of Shipping (ABS) - *www.eagle.org*
    - Bureau Veritas - *www.veristar.com*
    - China Classification Society - *www.ccs.org.cn/ccswzen/*
    - Croatian Register of Shipping – *www.crs.hr*
    - DNV – *www.dnv.com*
    - Indian Register of Shipping – *www.irclass.org*
    - Korean Register - *www.krs.co.kr*
    - Lloyd's Register Group Ltd. (LR) - *www.lr.org*
    - Nippon Kaiji Kyokai General Incorporated Foundation - *www.classnk.or.jp*
    - Polish Register of Shipping - *www.prs.pl*
    - RINA Services S.p.A. - www.rina.org/en
- in case a product is not already covered by the existing Technical Requirements (TRs), the Manufacturer can ask the EU RO MR Group to consider the development of suitable MR TR for such a product. As an examples, product belonging to the Tier 9 release (2022) are:
    - Cable glands
    - Corrosion-resistant paints

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- Electric space heating equipment
- Electric motor starters other than soft starters
- Inverters
- Resilient mountings of machinery
- Strainers
- Vertical surface reference system for DP system
- Wind velocity and direction gauge for DP system
- Power supply units (<5 kVA)
- In case change requests for the Technical Requirements arise with respect to procedural updates, test requirement updates, rule changes or industry feedback, the procedure reported in Figure 2.3 is followed.

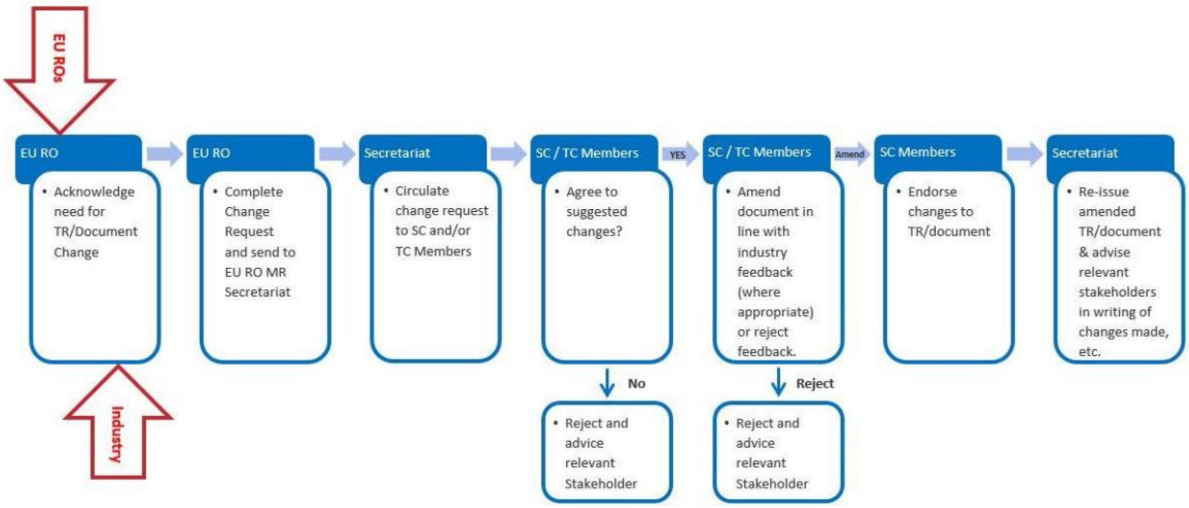

Figure 2.3: Flow chart underlying the procedure underlying possible change requests of Technical Requirements [2].

Further details concerning the procedural requirements as well as terms and conditions of EU RO MR Type Approval Certification are available in the EU RO Framework Document. Instead, Technical Requirements for products being eligible for EU RO MR Type Approval Certification are included into the TR table embedded in the Regulation (EC) No 391/2009 on Common Rules and Standards for Ship Inspection and Survey Organizations.

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3 Systems for essential/non-essential services

In this section, distinction between essential and non-essential services is outlined, according to the IACS Unified Interpretation (UI) SC134.

Essential services serve for ship propulsion, steering, safety and minimum comfortable conditions of habitability. They are classified into two groups, depending on their nature:

- Primary essential services: they serve to continuously guarantee propulsion and steering. Typical primary essential services are listed in the following:
  - Steering gears
  - Pumps enabling the actuation of controllable pitch propellers
  - Scavenging air blowers, fuel oil supply pumps, lubricating oil pumps and cooling water pumps for prime movers supplying propulsion power
  - Forced draught fans, feed water pumps, water circulating pumps, vacuum pumps and condensate pumps for vessels equipped with steam power plants as well as with auxiliary boilers generating steam which is necessary for equipment supplying primary essential services
  - Oil burning installations for steam power plants installed onboard ships and for auxiliary boilers generating steam which is necessary for equipment supplying primary essential services
  - Azimuth thrusters being the only means for propulsion and/or steering with lubricating oil pumps, cooling water pumps
  - Electrical equipment for electric propulsion plants with lubricating oil pumps and cooling water pumps
  - Electric generators and associated power sources supplying the above equipment
  - Hydraulic pumps supplying the above equipment
  - Viscosity control equipment for heavy fuel oil
  - Control, monitoring and safety devices/systems for equipment to primary essential services

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- Secondary essential services: they serve to guarantee safety of the ship and minimum comfort onboard, without any continuous operation requested to maintain propulsion and steering. Typical secondary essential services are listed in the following:
    - Windlass
    - Fuel oil transfer pumps and fuel oil treatment equipment
    - Lubrication oil transfer pumps and lubrication oil treatment equipment
    - Pre-heaters for heavy fuel oil
    - Starting air and control air compressors
    - Bilge, ballast and heeling pumps
    - Fire pumps and other fire extinguishing medium pumps
    - Ventilating fans for engine and boiler rooms
    - Services considered necessary to maintain dangerous spaces in a safe condition
    - Navigation lights, aids and signals
    - Internal safety communication equipment
    - Fire detection and alarm system
    - Lighting system
    - Electrical Equipment for watertight closing appliances
    - Electric generators and associated power sources supplying the above equipment
    - Hydraulic pumps supplying the above equipment
    - Control, monitoring and safety systems for cargo containment systems
    - Control, monitoring and safety devices/systems for equipment to secondary essential services

Since essential services need to continuously guarantee propulsion and steering (primary services) as well as safety (secondary services), their reliability, availability and maintainability properties gain importance. For the sake of clarity, the definitions of these properties are reported below:

- Reliability: it measures the ability of a system to function correctly, i.e. to provide correct outputs following allowed inputs. The average time between two successive failures is

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commonly adopted to quantify reliability. Reliability can be effectively enhanced by means of installing control systems able to reduce the probability of faults, ensure prompt detection of them and guarantee fast and easy repair of damaged elements.

- Availability: it measures how often the system is available for use, independently from the correctness of outputs it provides. To quantify availability, the ratio (also in percentage form) between the amount of time the system is actually operating and that it is expected to operate is commonly adopted. Highly available systems continue to work when faults possibly occur, since the out-of-order portion of the system is confined and separated from the remaining parts.
- Maintainability: it measures the easiness and rapidity required for maintaining and, in case fault occurred, repairing the system.

Specifically, where essential services are concerned, IGF Code, Part A, Paragraph 2.2.40 introduces the concept of "unacceptable loss of power", which means that "it is not possible to sustain or restore normal operation of the propulsion machinery in the event of one of the essential auxiliaries becoming inoperative, in accordance with SOLAS regulation II-1/26.3".

Therefore, equipment providing essential services is required to have backup (i.e. redundant systems providing the same service) or to be quickly restored in correct operation. This implies that proper arrangement is to be adopted for the installation of systems providing essential services.

Furthermore, essential services also serve to guarantee minimum comfortable conditions of habitability for the crew and passengers. Specifically, the normal operating and habitable conditions onboard vessels are defined by SOLAS definitions relating to parts C (machinery installations), D (electrical installations) and E (additional requirements for periodically unattended machinery spaces) as: "condition under which the ship as a whole, the machinery, services, means and aids ensuring propulsion, ability to steer, safe navigation, fire and flooding safety, internal and external communications and signals, means of escape, and emergency boat winches, as well as the designed comfortable conditions of habitability are in working order and functioning normally".

Examples of equipment usually necessary for maintaining minimum comfortable conditions of habitability onboard are:

- Cooking
- Heating

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- Domestic refrigeration
- Mechanical ventilation
- Sanitary and fresh water
- Electric generators and other power sources (e.g., auxiliary engines) providing services reported above

On the other hand, non-essential services play no role for safety nor are required for continuous operation due to ship propulsion, steering or minimum comfortable conditions onboard. Thus, they do not face specific constraints on reliability, maintainability and availability.

It must be underlined here that power sources supplying non-essential services may help to restore essential services under specific circumstances, such as those related to black-out or dead ship conditions. In this case, each power flow delivered by equipment supplying non-essential services and aimed at restoring propulsion, steering or safety conditions onboard is to be identified, documented and approved with respect to applicable rules and regulations.

Furthermore, automatic load shedding of services is regulated by guidelines included within the IACS UI SC134 "Essential Services and Arrangements of Sources of Power, Supply, Control and Monitoring to the different Categories of Essential Services (SOLAS Regulations II-1/40 & 41)". In detail, attention is focused on two main points:

- disconnections shall not cause immediate disruption of systems required for safety
- services required for safety are to be immediately available when the power is supplied to restore normal operating conditions

Therefore, performances of equipment supplying power to non-essential services must not compromise the safety of the ship, hence they can be switched off or disconnected without negative effects on essential services. Consequently, the Class Society needs to verify compliance with these two requirements present in IACS UI, by assessing system configuration and performing functionality tests.

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4 Rules for testing and certification of marine materials and equipment

The relevant provisions are fully covered by the RINA (NCC23)" Rules for Testing and Certification of Marine Materials and Equipment" and the following sections of this deliverable summarize their application for testing and certification of the ZHENIT technologies.

The materials and equipment to be assessed by Class are defined in the RINA Rules for the Classification of Ships, Part A, Chapter 2, Section 1, [2.1.3] and [2.1.5].

As a general rule, it is stated in Part A, Chapter 2, Sec 1, [2.1.6] that "all materials, machinery, boilers, auxiliary installations, equipment, items, etc. (generally referred to as "products"), which are covered by the Class and used or fitted on board ships surveyed by the Society during construction, are to be new and, where intended for essential services (ref. previous sections of this deliverable) as defined in Ch 1, Sec 1, [1.2.1], tested by the Society".

Products which are required by IMO Regulations to be type approved by an Administration are also subject to Class assessment, whenever and to the extent that the Class Society is recognized by or is acting on behalf of the ship flag Administration.

In general, the testing operations and inspections shall be carried out in the facility of the Manufacturer. Additionally, testing operations and acceptance tests to be carried out onboard during and/or after installation shall be also considered for products which are assembled onboard or connected to other plants originally present on the vessel.

Products already tested by other recognized organizations may be accepted on a case-by-case basis, using the relevant certificates and/or testing reports, provided that no further tests are required according to the Rules and that the products refer to the relevant certificates.

For product certification, the acceptability criteria of testing laboratories other than those of Class Society and relative testing reports are generally indicated in the Class Rules (e.g., RINA Rules for Testing and Certification of Marine Materials and Equipment, NC/C.23, Ch 5).

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4.1 Certification schemes

Where certification of a generic product is concerned, Chapter 2 of the RINA Rules for Testing and Certification of Marine Materials and Equipment, NC/C.23 specifies the procedures to be applied in each possible phase (e.g., document reviews, inspections, onboard tests, etc.), even though a specific product may not deal with all the phases reported in general. Specifications for reviews and inspections include the following aspects:

- Approval of technical documentation: the Manufacturer needs to prepare the technical documentation according to applicable Class Rules and to submit it to RINA. Understanding of design, manufacturing and operation processes is required to be guaranteed by the submitted documentation, in order to assess compliance with Rules and applicable standards. Among all the technical documents possibly required, the most common consist of:
    - general description of the product
    - the conceptual design, the component schemes, the manufacturing drawings as well as standards
    - explanatory notes and descriptions referring to the drawings, schemes and operation of the product
    - computations and assumptions underlying the design procedure
    - manuals addressing installation, usage and maintenance
    - control and test procedures applied to the product

  Eventually, attestations and certificates related to components and manufacturing/inspecting/monitoring methods shall be included into the design documentation.
- Type tests: they consist of more extensive tests compared with standard production tests and aim at validating prototype design. They can be applied to purpose-built prototype or product randomly sampled within the production line. Tests can be carried out at either the Manufacturer’s facility, RINA laboratory or independent laboratory. In case tests are performed at independent laboratory, witness from a RINA Surveyor is required, unless stated otherwise, with complete reporting to be submitted to RINA for approval or information.

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- Design approval: the Manufacturer shall prepare technical documentation in accordance with applicable Rules and Standards. Generally, the design documentation is to include:
  - general description of the product
  - conceptual design, schemes of components as well as sub-assemblies and the Standards adopted for manufacturing. Additional descriptions and explanations of drawings and schemes may be required to improve understanding.
  - description of the operation and limitations of the product
  - analyses, computations and examinations related to the design process
  - control and test procedures
  - manuals addressing installation, use and maintenance
- Manufacturer and manufacturing process approval: details on the requirements related to the approval of Manufacturers and manufacturing processes are available in the RINA "Rules for the approval of Manufacturers of materials".
- Material testing: material testing shall be carried out according to applicable Rules and Standards. Surveyors need to attend material testing if required by the Rules, and shall be allowed to access certificate of material testing. The raw material supplier must provide the chemical composition of the materials and the corresponding analyses shall be carried out in adequately equipped laboratories by qualified personnel. All the testing and measuring equipment shall be kept in good conditions as well as properly calibrated.
- Attendance and final inspection and testing at workshop: free access of Surveyors to all the production phases, collection of test samples and internal control shall be guaranteed. Final inspection of products encompasses document review, visual examination, dimensional check, non-destructive examination, as far as applicable. Instead, equipment and materials to be installed onboard are to be tested through a procedure similar to tests at workshops, integrated together with all the products or materials they are part of. In particular, testing may include, depending on the complexity of the product as well as on application standards:
  - final tests of completed product (e.g., hydrostatic tests for pressure vessels)
  - performance tests (e.g., running tests for reduction gears)

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- collection of data (e.g., performance data for energy systems)

Three main certification schemes are identified by the Rules:

- individual or traditional inspection scheme: it is applicable if inspection and testing are carried out as prescribed in the Rules and are witnessed by a RINA Surveyor.
- alternative inspection scheme: it involves a properly qualified Manufacturer in the inspection, testing and certification processes. The type of product, its mass production and the quality control plans of the Manufacturer are considered in setting up the alternative inspection scheme. Qualification of Manufacturers must be periodically checked.
- type approval scheme: it is applicable either when product certification is required by the Rules and in case no specific requirements exist, i.e. certification is requested by the Manufacturer on a voluntary basis. In the latter case, particular standards and/or specifications agreed with the Manufacturer are adopted by the Class Society for product approval. Type Approval certificate can be optionally combined with Production Control Certificate, which in turn is divided into two schemes:
  - Product verification
  - Production quality assurance, for Manufacturers having a certified Quality Assurance System

  Generally, the type approval certificate remains valid for five years, despite variations can arise depending on specific requirements of the reference Standards the certification is based on.
- MED Type Approval scheme: it concerns products listed in the implementing Regulation of the European Directive 2014/90/EU and, simultaneously, intended to be installed on vessels flying European Community flags. These products need to be certified in accordance with the requirements of the RINA "Rules for the certification of marine equipment in accordance with European Directive 2014/90/EU and subsequent amendments". Alternatively, they can be certified using equivalent Rules developed by other Class Societies.

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In the following, deep insight into the two main certificates possibly issued by RINA for either equipment and software products is provided, focusing on the steps and requirements the certification process relies on:. Thus, attention is paid to:

- Type Approval Certificate (TA)
- Prototype Design Assessment Certificate (PDA)

Both the certification schemes can be applied either when product certification is required by the Class Rules and in case no specific requirements exist, i.e. certification is requested by the Manufacturer on a voluntary basis. In the latter case, industrial standards and/or particular specifications agreed with the Manufacturer are adopted for approval.

4.2 Type Approval certification

Type Approval certificate is compulsory for products covering essential services to be fitted on board ships and consists in the approval of the product design, including drawing appraisal, and prototype test performance. Nevertheless, Type Approval can also be requested on a voluntary basis by the Manufacturer. The Type Approval for a specific product is assessed once, since the certificate successively remains valid for all the subsequent products dealing with identical design and manufacturing process. For this reason, Type Approval is a commercially valuable option for Manufacturers who intend to broaden their selling activities. In detail, since it gives evidence of compliance with performance as well as safety requirements, Type Approval can be useful to facilitate product acceptance by potential buyers.

The type approval certification procedure consists of the following operational steps:

- the Manufacturer forwards an application to RINA for requesting Type Approval
- technical documentation requested by applicable Rules is thoroughly examined
- technical drawings are preliminarily approved, if required by the Rules
- test campaign for prototypes or sample products is defined according to the Rules or industrial standards
- the laboratory where to conduct tests is identified (Manufacturer’s facility, RINA laboratory or independent laboratory). In particular, initial audit and evaluation of the Manufacturer's production facility is first carried out as starting point

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- the type tests are conducted in laboratory and reports containing the required information are generated
- the technical reports related to the testing activity are reviewed in detail
- the Type Approval certificate is issued, in case results obtained from the tests met industrial standards/specifications as well as rules

Successively, the Production Quality Assurance Certificate is issued. It remains valid for 5 years, subject to the positive outcome of periodical audits according to the following surveillance cycles:

- An intermediate audit at the Manufacturer's facility is required in case of products for which testing shall be carried out by the Surveyor for each unit or batch
- At least an annual audit to the Manufacturer's production site is required in case of products for which testing of each unit or batch is not required to be attended by the Surveyor (e.g., sensors).

In case of certification of software, the TA certificate is issued upon satisfactory outcome of design approval and prototype tests only. The initial audit to the software house and the issuance of a Production Quality Assurance Certificate is not required.

4.3 Prototype Design Assessment Certification

This certification is applicable to products for which there are no specific requirements in the Class Rules. For this reason, Prototype Design Assessment Certification cannot be applied to products which are required to be Type Approved and can be requested on voluntary basis by Manufacturers.

The approval process is established against standards/specifications agreed with the Manufacturer and shipowner installing prototypes onboard, according to a case-by-case approach.

The Prototype Design Assessment Certification consists of the two following steps:

- Design approval and prototype tests, intended to verify compliance of the product with the Manufacturer's specification and/or the applicable standards
- Issuance of the Prototype Design Assessment Certificate.

The procedure aims at verifying that performance of the product guarantees the service for which the shipowner intends to install and operate it onboard (fit for service). Furthermore, it must be ensured

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that the installation of the product on board does not have negative consequences due to the marine environment rather than land based (marinization).

In general, the validity of Prototype Design Assessment Certificates lasts for 5 years, subject to possible changes in the reference Standards in terms of product requirements/specifications.

4.3.1 Technical documentation review and inspection procedures

The Manufacturer needs to forward an application to the Classification Society and submit technical documentation for approval. Specifically, the technical documentation should allow a clear as well as precise understanding of the design, manufacturing, installation and operation of the product. Furthermore, compliance of the technical documentation with the Rules and the applicable Standards should be easily investigated.

In general, all information relevant to verify compliance with Rules and Standards is to be included into documentation and encompasses, as far as applicable:

- general description of the product
- description of both location and layout of the product onboard
- the conceptual design, the building standard, the manufacturing and construction drawings as well as the schemes of components, sub-assemblies, etc.
- all the specifications, descriptions and explanations necessary for the understanding of drawings, schemes and operation of the product
- the results obtained by computations and examinations carried out during the design process
- preliminary test reports, if present
- manuals for product installation, usage and maintenance
- control and test procedures

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No	Document
1	Technical specification of the system, including technical data as power output parameters including min./max. design voltage and current, information about min./max. temperature/pressure/rate of process air/cooling water/ventilation, etc.
2	List of mechanical and electrical components which are part of the system with specification of the pumps, compressors and fans.
3	P&I diagrams of systems conveying fluids, exhaust air/gas, cooling media, process air, technical water, ventilation and of other systems
4	Description of thermal insulation (if any), electrical heat tracing
5	System module / casing construction details with max. design pressure
6	Construction drawings of all components of the equipment considered as pressure vessel e.g., heat exchangers
7	Functional description of the system including at least its design, safety principles, auxiliary systems arrangement (e.g. cooling medium, process air, ventilation, venting, process water, as applicable)
8	Block diagram of the safety, alarm, control and monitoring system
9	Wiring diagrams of power supply and automation system
10	List of controlled and monitored parameters and cause and effect matrix with normal/emergency shutdown functions.
11	Electrical protection and hazardous zones categorization study with calculation according to IEC 60079-10 (using CFD simulations or empirical formula) and list of EX equipment with relevant EX certificates, as applicable.
12	Functional profile description of the system, highlighting if the power generation is used for essential or non-essential ship services according to IACS Unified Interpretation (UI) SC134
13	A FMEA according to the RINA (GUI23) "*Guide for Failure mode and Effect Analysis*" or other equivalent methods for the system installations
14	Type test reports including information about overview, adopted standards, test laboratory, test rig description, witnessing persons and final results.
15	Lifecycle operational, maintenance and inspection manual of the system

Figure 4.1: Technical documents to be generally submitted during a Prototype Design Assessment Certification procedure.

Table shown in Figure 4.1 reports in detail the technical documents which are generally required during a Prototype Design Assessment Certification procedure.

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Additional documents to be possibly submitted are:

- certificates related to components
- certificates related to the product manufacturing/inspection/monitoring methods
- any other document possibly required by the Classification Society with the aim of facilitating the assessment of compliance with Rules and Standards

4.3.2 Type tests

Type tests aim at validating the design of the prototype. Generally, they are more extensive than tests required during normal production processes and may include destructive testing.

Type tests can be performed at either the Manufacturer's facility, independent laboratory or Class Society laboratory (if available). In case tests are performed at independent laboratory, they need approval from Class Society and witness from a Surveyor is required, unless stated otherwise in the applicable Rules. Tests are to be witnessed by a Class Society Surveyor also when the campaign is carried out in the Manufacturer's facility, unless otherwise stated.

- Test reporting must contain the following basic information:
- description and identification of the product
- identification of the testing specifications
- description of testing setup and measuring instruments (where the instruments are concerned, the identification number and the last calibration date shall be reported)
- environmental conditions being present during the test campaign
- test results, including any negative results.

4.3.3 Issuance of certificate

Once the technical documentation has been approved and the prototype has been validated by type tests, the Class Society can issue a Prototype Design Assessment Certificate. It must be reminded here that certificate can be issued when compliance with reference specification and/or Standards previously accepted by the Manufacturer, Class Society and shipowner is clearly proved.

However, further supplementary verifications can be required, if appropriate, within a twofold aim:

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- ensuring that the product performances guarantee its fit for service onboard
- verifying that negative consequences on performances are avoided when the product is installed onboard (marinization and integration), hence complying with RINA rules.

1	2	3	4	5	6	7	8	9	10	11	12
No.	PRODUCT	ORIGIN OF THE REQUIREMENT	TYPE OF CERTIFICATE	DRAWING OR DESIGN APPROVAL	MANUFACTURER AND/OR MANUFACTURING PROCESS APPROVAL	MATERIAL TESTING	NDT	SHOP ATTENDANCE DURING FABRICATION	FINAL INSPECTION AND/OR CONFORMITY VERIFICATION	FINAL TESTS	FUNCTIONING TESTS
1	Air, water and oil coolers	FOR PRESSURE PARTS SEE TABLE J									
2	Clutches	SEE TABLE H									
3	Control, monitoring and alarm systems	SEE TABLE Q									
4	Cooling water, lubricating oil, fuel oil injection and fuel oil transfer pumps	C	CT or CA							X (1)	X
5	Ejectors for bilge in machinery spaces	C	CT or CA							X (1)	
6	ITEM DELETED										
7	Electric panels and apparatus	SEE TABLE N									
8	Fuel oil and lubricating oil non-structural tanks	C	CT or CA			XM			X	X (1)	
9	Fuel oil and lubricating oil purifiers	C	CT or CA						X	X (1)	X
10	Injectors, buster pumps and injection pipes	C	CT o CA			XM			X	X (1)	
10A	Oil mist detector	C	TA						X		X
11	Piping systems	SEE TABLE K									
12	Pressure filters	FOR PRESSURE PARTS SEE TABLE J									
13	ITEM DELETED										
14	ITEM DELETED										
15	Crankcase explosion relief valves for diesel engines (4)	C	TA								
16	Scavenge air main	FOR PRESSURE PARTS SEE TABLE J									
17	Scavenging pumps	C	CT or CA						X	X (1)	X
18	Starting air compressors	C	CT or CA						X	X (1)	X

(1) Hydrostatic test
(2) For Category B the manufacturer is to adhere to a quality system designed to ensure that the designer's specifications are met, and that manufacturing is in accordance with the approved drawings.
(3) Overspeed and balancing tests on completed rotor
(4) When required by the Rules

Figure 4.2: sample of requirements related to inspection at workshop of auxiliary components and accessories for engines [3]

Detailed information on the requirements for inspection and testing of products at the workshop before their delivery to the shipyard is contained in the RINA Rules for Testing and Certification of Marine Materials and Equipment, NC/C.23, Ch. 6. As example, Table E concerning the inspection at workshop of auxiliary components and accessories for engines is reported in Figure 4.2.

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4.4 Approval in Principle

In this section Approval in Principle (AIP) of novel technologies is presented in detail.

Novel technology coincides with technology that is not proven, i.e. documented track record for its defined application does not exist. According to this definition, the concept of novel technology encompasses the application of both proven technology in a new environment and unproven technology in a known environment.

The AIP procedure is applicable to components, equipment and systems, which can be defined as novel technology. Since novel technologies are generally not adequately covered by established codes and procedures, a twofold verification is requested:

- the concept underlying novel technology needs to be feasible and realistic
- the intent of the applicable rules and regulations is to be met

Since AIP is a systematic process of verification that includes examination of the design procedure and engineering analyses, it depends on the engineering phase of the novel technology, potentially ranging from conceptual design to complete design. Complete design possibly includes tests on prototypes whereas detailed testing programs on full scale products are typically not encompassed in an AIP procedure, hence they are carried out in successive engineering phases.

The AIP verification program needs to be focused on novel elements or novel applications of known elements, hence identifying where the novelty is located constitutes the preliminary step of AIP.

The systematic application of the AIP procedure traditionally consists of the following steps:

- Description of the technology to be qualified
- Detailed assessment of the operational conditions and corresponding constraints related to the novel technology
- Definition of the functional requirements the novel technology deals with
- Risk and safety assessment aimed at identifying, ranking and controlling hazards or failures which affect the novel technology
- Engineering analyses and, possibly, tests on prototypes as supporting evidence to demonstrate that the design of the novel technology fulfils the requirements for its intended service. In details, the novel technology must be shown fit-for-service, i.e. it fulfils

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functionality, safety, reliability, availability and maintainability requirements which were defined in the qualification process.

Official statement of fitness-for-service can be obtained by Technology Qualification Process (TQP), in the form of certificate, class notation or other equivalent documents (see section below for more details on TQP). In the event engineering analyses and prototype tests are not available, the feasibility of novel technology may be demonstrated by means of alternative methods, providing proper justifications.

The typical documentation to be produced during an AIP process consists of, as far as applicable:

- Design criteria of the novel technology
- Applicable rules and regulatory framework
- Detail drawings and schemes
- Technical specifications ensuring fitness-for-service
- Engineering analyses performed during design procedure
- Reports on risk and safety assessment

Finally, following the evaluation of all the documents reported above, the AIP certificate can be issued, thus confirming that the novel technology meets the general requirements for its intended service.

Details on the systematic approach underlying the Approval in Principle of new technologies which are not adequately covered by established codes and procedures can be found in the RINA Guidelines GUI19 "Guide for Approval in Principle of Novel Technologies" or equivalent. On the other hand, risk assessment involved in the AIP procedure is to be conducted according to the methods described in the RINA GUI015 "Guide for Risk Analysis" and GUI23 "Guide for Failure Mode and Effect Analysis (FMEA)" or equivalent.

Systems to be installed on board for demonstration purposes (e.g., demo prototypes) require at least an Approval in Principle. Therefore, the required documents outlined above need to be submitted for consideration and approval to a Class Society, which in turn may witness compliance with the applicable rules and regulations as well as applicable Standards.

Successively to the AIP procedure, the assessment of the integration of the novel technology onboard ship takes place.

As said above, novel technologies are not adequately covered by established codes and procedures. Therefore, they need to be qualified through a specific procedure called Technology Qualification

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Process (TQP), in order to prove that novel technologies meet all the requirements for their intended use (fitness-for-service concept).

It must be reminded here that novel technology has no documented track record for a defined application. Thus, both new technologies applied in known environment and known technologies applied in new environment are included within the novel technology concept.

Novel technologies are considered fit for service when supporting evidence demonstrates that they fulfil all the requirements of functionality, safety, reliability, availability and maintainability defined in the Technology Qualification (TQ) basis, i.e. specified criteria, boundary conditions and interface requirements.

The systematic and documented process of qualification encompasses examination of the design, engineering analyses and testing programs.

Preliminary steps for the evaluation of the novel technology are reported below:

- the novel technology is subdivided into subsystems and components by means of system schematics and P&ID. Particularly, attention is focused on manufacturing, installation, operation processes concerning subsystems and components.
- the possible novelty of each subsystem and component is investigated
- the main challenges and uncertainties faced by the novel technology are identified

The main steps the TQP is based on are listed in the following:

- risk and safety assessment aimed at identifying, ranking and controlling failure modes which possibly compromise the fitness for service of the novel technology
- engineering analyses are carried out to demonstrate that all specific requirements for intended service are met by the design of the novel technology
- measurements and tests are needed to support evidence that the novel technology fulfils the specified requirements for its intended service
- functionality assessment aimed at ensuring that the functional requirements as well as the safety, reliability, availability and maintainability criteria are fulfilled

Where the first step is concerned, risk and safety aspects of the novel technology are to be assessed applying well established techniques to investigate compliance with regulations. Attention is here

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focused on the events possibly affecting the fitness for service of the novel technology as well as its interfaces with ship systems based on already proven technologies.

The risk assessment is typically carried out as follows:

- hazards are identified
- risks are assessed against the defined acceptance criteria and interfaces with other ship systems
- risk control options (RCO) are defined. In detail, strategies of prevention, mitigation or a possible combination of them are built up in case risk is to be reduced according to the ALARP principle to settle on acceptable levels
- the overall study is documented

Examples of potential hazards to be accounted for within the risk assessment are:

- extreme weather, influencing maximum ship motions, accelerations, inclinations, temperatures
- mechanical damage, possibly leading to liquid/gas release or progressive ship flooding
- fire and/or explosion
- release of flammable or toxic gases
- release of cryogenic liquids or gases
- loss of electrical power supply with negative impact on ship essential services
- failures related to single or possibly multiple systems onboard

Technical outcomes provided by the systematic application of TQP include:

- Description of the technology to be qualified together with its boundaries
- Detailed information on the operational conditions and corresponding constraints related to the novel technology
- Definition of the functional requirements the novel technology deals with
- Formulation of the safety, reliability, availability and maintainability criteria to be adopted for the novel technology

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Information reported above is successively used as input to define specifications concerning the design, manufacturing and installation of the novel technology. Analogously, the maintenance schedule is defined in a lifecycle perspective.

Official statement declaring that novel technology is fit for service on the TQ basis is finally issued as positive outcome of the TQP, in the form of a certificate, class notation or equivalent document. Appropriate documentation reported below must be included with the aim of supporting evidence of fitness-for-service concept:

- system specifications, drawings, technical reports, design calculations
- applicable rules, regulations and standards
- survey requirements for construction/installation/commissioning
- operational instructions in normal and in emergency situations
- maintenance requirements

Additionally, requirements in terms of crew training and/or personnel certification are to be possibly inserted in the TQP documentation.

Detailed insight into the application of Technology Qualification Process can be found in the RINA guidelines (GUI16) “Guide for Technology Qualification Processes” and both the IMO MSC/Circ. 1002 “Guidelines for alternative design and arrangements for fire safety” and the IMO MSC.1/Circ.1212 “Guidelines on Alternative Design and Arrangements for SOLAS Ch II-1 and III” shall be taken into account.

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5 Marinization

The purpose of marinization is to ensure that the installation of novel technology onboard does not have negative consequences on its operation and safety, due to the marine environment compared to land-based applications. Therefore, where marinization is concerned, design, installation and operation of the novel technology needs to comply with Class Rules (i.e., RINA Rules Part C Ch. 1 Sec. 1), which focus on three main aspects:

- Marine ambient conditions: marine environment is typically characterized by salt-bearing, wet and possibly very hot ambient conditions. Thus, all the machineries and systems installed onboard are required to be designed to operate properly under the ambient conditions reported in Figure 5.1. This is valid for all the machinery and systems covered by the Rules, unless otherwise specified.

AIR TEMPERATURE	
Location, arrangement	Temperature range (°C)
In enclosed spaces	between 0 and +45 **(2)**
On machinery components, boilers In spaces subject to higher or lower temperatures	According to specific local conditions
On exposed decks	between -25 and +45 **(1)**

WATER TEMPERATURE	
Coolant	Temperature (°C)
Sea water or, if applicable, sea water at charge air coolant inlet	up to +32

(1) Electronic appliances are to be designed for an air temperature up to 55°C (for electronic appliances see also Chapter 2).
(2) Different temperatures may be accepted by the Society in the case of ships intended for restricted service.

Figure 5.1: Ambient conditions to be considered during design for marinization purposes [4]

- Operation in inclined positions: the rolling and pitching motions of the vessel must not negatively influence operation and safety of all the systems installed onboard and covered by the Rules. Specifically, main and auxiliary machineries providing essential services onboard the vessel (i.e., propulsion and safety services) shall be designed to operate both when the ship is upright and when it deals with non-zero heeling angles or trim. Details on the heeling angles and trim, either positive and negative, to be considered during the design are reported in Figure 5.2.

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Installations, components	Angle of inclination (degrees) **(1)**			
	Athwartship		Fore and aft	
	static	dynamic	static	dynamic
Main and auxiliary machinery	15	22,5	5 **(4)**	7,5
Safety equipment, e.g. emergency power installations, emergency fire pumps and their devices Switch gear, electrical and electronic appliances **(3)** and remote control systems	22,5 **(2)**	22,5 **(2)**	10	10

(1) Athwartship and fore-and-aft inclinations may occur simultaneously.
(2) In ships for the carriage of liquefied gases and of chemicals the emergency power supply must also remain operable with the ship flooded to a final athwartship inclination up to a maximum of 30°.
(3) No undesired switching operations or operational changes are to occur.
(4) Where the length of the ship exceeds 100m, the fore-and-aft static angle of inclination may be taken as 500/L degrees, where L is the length of ship, in metres, as defined in Pt B, Ch 1, Sec 2, [3.1.1].

Figure 5.2: Values for heeling angles and trim to be considered during design for marinization purposes [4].

The Classification Society may allow deviations from heeling angles and trim values shown in Figure 5.2, owing to considerations on the specific type, size and service conditions of the vessel. E.g., all the machineries having horizontal rotation axis are generally required to be installed onboard by aligning their rotational axis with the ship length. In case this arrangement is not allowed by geometric or assembling constrains, the Manufacturer is to be informed (e.g., proper operating conditions of thrust bearings need to be guaranteed).

- Vibrations: motions of the ship can cause the amplification of vibrations generated by dynamical machineries at specific frequency (i.e., resonance frequencies), with detrimental effects on structural resistance. Therefore, the design, construction and installation of machineries covering propulsion or auxiliary services need to guarantee that vibrations generated during normal operating conditions do not trigger undue stresses, which may compromise structural resistance of machinery or its foundations. Restrictions on vibrational modes of electrical equipment are summarized in Figure 5.3 in terms of amplitude and accelerations, for various locations onboard (see Part C Ch. 2 Sec. 2 for more details). More stringent requirements on vibrations may be possibly inserted into contractual agreements between the shipyard and the shipowner.

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Location	Frequency range Hz	Displacement amplitude mm	Acceleration amplitude g
Machinery spaces, command and control stations, accommodation spaces, exposed decks, cargo spaces	from 2,0 to 13,2 from 13,2 to 100	1,0 -	- 0,7
On air compressors, on diesel engines and similar	from 2,0 to 25,0 from 25,0 to 100	1,6 -	- 4,0
Masts	from 2,0 to 13,2 from 13,2 to 50	3,0 -	- 2,1

Figure 5.3: Restrictions on vibrational modes of electrical equipment to be considered during design for marinization purposes [5]

- Noise: motions of the ship can cause unproper dampening of vibrations and noise, with negative influence on comfort and health. In order to reduce noise levels, structural foundations for machineries installed onboard need to be properly mounted and particular noise reducing solutions should be possibly taken into account. Specifically, the IMO resolution MSC. 337(91) establishes mandatory limits for noise levels achieved within machinery spaces, control rooms, workshops, accommodation and other spaces onboard ships whose gross tonnage exceeds 1600 t. Additional specifications for noise generated onboard are included in the RINA Rules Pt F, Ch 6, Sec 1. Nevertheless, more stringent noise requirements may be possibly inserted into contractual agreements between the shipyard and the shipowner.

All the requirements reported above assume that the novel technology is installed on commercial vessels. Instead, specific provisions for anti-shock protection of systems providing essential services (i.e., propulsion and safety services) are required for naval vessels.

Further requirements exist for pressure equipment, i.e. novel technologies working with pressure exceeding the ambient one. Specifically, their design, manufacturing and testing are subjected to various sections included within the RINA Rules Part C, depending on their pressure and temperature levels, volume and fluid.

Analogously, specific requirements aimed at ensuring expected quality of the power supply equipment are available in the RINA Rules Part C, Ch 2, Sec 2 (examples of the frequency and voltage variations allowed for electrical distribution systems are reported in Figure 5.4).

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Quantity in operation	Variations	
	Continuous	Transient
Voltage	+ 6% - 10%	± 20% (recovery time: 1,5 s)
Frequency	± 5%	± 10% (recovery time: 5 s)

Parameters	Variations
Voltage tolerance (continuous)	± 10%
Voltage cyclic variation deviation	5%
Voltage ripple (a.c. r.m.s. over steady d.c. voltage)	10%

Figure 5.4: Voltage and frequency variations for AC distribution systems (left side) and voltage fluctuations allowed for DC distribution systems (right side) [5].

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6 Integration onboard

The onboard integration aims at verifying the integrity of the systems originally present on the ship in the event of onboard installation of novel technologies. In other words, novel technologies are to be verified to not interfere negatively with the ship systems as originally designed and operated onboard, which need to continue to guarantee availability, maintainability, and reliability. Most importantly, onboard integration of the novel technologies must not negatively affect the safety of the ship.

Overall, where novel technologies providing non-essential services are concerned, the documentation to be submitted to Class Society is reported below:

- documentation demonstrating compliance of equipment and/or its components with applicable Rules and safety standards
- documentation proving that non-negative influence on ship safety is introduced by onboard integration of novel technologies

Redundancy is not relevant for novel technologies supplying non-essential services, by a certification point of view. However, the detailed certification required for equipment providing essential services may be requested on voluntary basis by Manufacturers, aiming at facilitating commercialization as well as scaling-up.

It must be reminded here that the evaluation of the integration onboard is the next step after AIP. As reported above, different classification societies can be in charge of these two processes, i.e. AIP and integration onboard. In this case, the "Mutual Agreement on the implementation of Mutual Recognition Provisions of Art 10 of Regulation (EC) No 391/2009 of the European Parliament and of the Council" regulates the behavior of both the Class Societies.

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7 ZHENIT technologies

Since novel technologies considered within the ZHENIT project are expected to provide non-essential services, they do not require Type Approval certification. Nevertheless, owing to the facilitation provided by Type Approval in commercializing novel products after the project closure, it can be requested on voluntary basis by the Manufacturers, if not already obtained. This choice is even more relevant in case shipowners' benefits possibly obtained by installing the novel technology onboard are clearly demonstrated. In the following, all the innovative technologies considered in the ZHENIT project are analysed, focusing on their main benefits and possible challenges to be faced when installing them onboard. In parallel, inventory of the rules and regulations applicable to each technology is provided to draw attention on the main constraints to be accounted for during the design process.

7.1 Thermal energy storage via phase change materials

Waste heat recovery from prime movers is currently receiving major attention to promote a more efficient energy usage onboard and reduce GHG as well as pollutant emissions generated by the waterborne transport. Since waste heat onboard ships is generally unsteady, with periodic and intermittent fluctuations, thermal energy storage (TES) is a key technology to ensure matching between demand and supply, with benefits in terms of energy efficiency.

One of the possible techniques for TES is latent heat storage through Phase Change Materials (PCMs). When adopting PCMs, thermal energy is stored or retrieved during the phase transition process of PCM, i.e. melting from solid to liquid or solidifying from liquid to solid, respectively.

Overall, compared with other TES technologies such as sensible heat storage, stored heat per unit volume of PCMs is 5-14 times higher than capacities obtained via sensible heat storage methods [21]. Additionally, PCMs can absorb/release heat at a nearly constant temperature, with beneficial effects on utility as well as thermodynamic efficiency points of view.

Over the past few decades, PCMs have been successfully applied in solar thermal utilization, industrial waste heat recovery, building energy saving, electronics cooling, etc.

In order to be practically viable, thermal energy storage via PCMs should deal with the desirable properties reported in the following [23,24]:

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Thermal properties:

- Suitable phase-transition temperature to guarantee efficient heat recovery from specific thermal sources and to maximize successive energy supply onboard
- High latent heat of transition to maximize thermal energy density per unit volume and weight
- Good heat transfer properties to reduce transients in thermal power charging/discharging

Physical properties:

- Favorable phase equilibrium, i.e. without phase instability during freezing/melting
- High thermal energy density per unit volume and weight
- Small volume change during phase transformation to allow low volume requiring storage systems
- Low vapor pressure at operating temperatures to allow less demanding containment systems

Kinetic properties:

- No supercooling effect: few degrees of supercooling may negatively affect heat extraction from the storage system, while 5–10 °C completely prevent it
- Sufficient crystallization rate

Chemical properties:

- Long-term chemical stability to limit performance reduction and safety issues due to degradation
- Compatibility with containment materials, with no reaction or decomposition possible
- No toxicity issues for safety of passengers, crew and aquatic environment
- No flammability to reduce fire and explosion risks

Economics:

- Large-scale availability
- Cost effectiveness

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7.1.1 PCM Classification

No PCM material dealing with all the required properties reported above exists. Since many types of PCMs exist, each characterized by different specificities and pros/cons, first it is necessary to introduce their classification, in order to make the discussion more complete and clearer. Typical classification of PCMs adopted in the scientific literature is reported in the following.

Organic phase change materials

- Paraffin: melting point temperature and latent heat of fusion of paraffin waxes increase with the length of the N-alkanes chains they are based on. Therefore, paraffin can serve as thermal energy storage over a large temperature range. Thermal properties of some paraffins are reported in tabular form in Figure 7.1, as example. Paraffin is chemically stable below 500 °C, deals with little volume changes during phase transition processes and ensures low vapor pressure in liquid state. Overall, paraffin consists of a reliable, cost effective and non-corrosive PCM. However, the most relevant drawbacks of paraffins are low thermal conductivity, incompatibility with the plastic materials and moderate

Paraffin[a]	Freezing point/ range (°C)	Heat of fusion (kJ/kg)	Group[b]
6106	42–44	189	I
P116[c]	45–48	210	I
5838	48–50	189	I
6035	58–60	189	I
6403	62–64	189	I
6499	66–68	189	I

[a] Manufacturer of technical Grade Paraffin's 6106, 5838, 6035, 6403 and 6499: Ter Hell Paraffin Hamburg, FRG.
[b] Group I, most promising; group II, promising; group III, less promising; — insufficient data.
[c] Manufacturer of Paraffin's P116: Sun Company, USA.

Figure 7.1: Melting point temperature and latent heat of fusion for paraffins PCMs [6].

flammability.

- Non-paraffins: they are a numerous class of PCMs, with highly variable properties (see Figure 7.2). The main non-paraffin PCMs are esters, fatty acids, alcohols and glycols [27,28]. Since they are flammable, their exposure to high temperatures, flames or oxidizing agents is to be avoided to guarantee safety onboard. Furthermore, they deal with high latent heat of fusion, nearly absent supercooling, low thermal conductivity, low flash points, variable

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level of toxicity and unstable degradation at high temperatures. Costs can achieve 2-2.5 times that of paraffin waxes and some of them can be mild corrosive (e.g., fatty acids) [6].

Material	Melting point (°C)	Latent heat (kJ/kg)	Group[a]
Formic acid	7.8	247	III
Caprilic acid	16.3	149	–
Glycerin	17.9	198.7	III
D-Lattic acid	26	184	I
Methyl palmitate	29	205	II
Camphenilone	39	205	II
Docasyl bromide	40	201	II
Caprylone	40	259	II
Phenol	41	120	III
Heptadecanone	41	201	II
1-Cyclohexylooctadecane	41	218	II
4-Heptadacanone	41	197	II
p-Joluidine	43.3	167	–
Cyanamide	44	209	II
Methyl eicosanate	45	230	II
3-Heptadecanone	48	218	II
2-Heptadecanone	48	218	II
Hydrocinnamic acid	48.0	118	–
Cetyl alcohol	49.3	141	–
α-Nepthylamine	50.0	93	–
Quinone	115	171	II
Acetanilide	118.9	222	II
Succinic anhydride	119	204	II
Benzoic acid	121.7	142.8	III
Stibene	124	167	–
Benzamide	127.2	169.4	III

[a] Group I, most promising; group II, promising; group III, Less promising; — insufficient data.

Figure 7.2: Melting point temperature and latent heat of fusion for non-paraffins PCMs [6].

Inorganic PCM:

- Salt hydrates: their phase transformations actually consist in dehydration or hydration of the salt. During the melting process the hydrate crystals breakup into anhydrous salt and water or into a lower hydrate and water. One major problem of salt hydrates arises in case the released water of crystallization does not manage to dissolve all the solid phase, hence generating incongruent melting [29,30]. In detail, incongruent melting results in supersaturated solution at the melting temperature and the solid salt settled down at the

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bottom of the container cannot be recombined with water during the reverse process of freezing. Each charge–discharge cycle reduces the reversibility of the melting-freezing process of the salt hydrate, thus degrading performances and reliability of the system when installed onboard. Furthermore, salt hydrates suffer from supercooling due to their poor nucleating properties (i.e., crystallization of the liquid begins at lower temperatures with respect to the designed one). They are compatible with plastics and deal with slight toxicity as well as corrosion. Where benefits are concerned, salt hydrates are characterized by high latent heat of fusion per unit volume, high thermal conductivity (2 times that of paraffin), little changes in volume during phase transition and low cost [31]. As possible solutions to limit incongruent melting, mechanical stirring, encapsulation of PCM and thickening agent addition have been identified.

- Metallics: they consist of metals melting at low temperature. They suffer from large weight penalties (low heat of fusion per unit of weight) but they occupy low volume (high heat of fusion per unit volume), hence their installation onboard should be carefully considered. Furthermore, metallics ensure high thermal conductivity and quite low vapor pressure.

Eutectics:

- They consist of minimum temperature melting mixtures of two or more components. Each component of the mixture melts/freezes congruently, with minimal segregation achieved during phase transition. The mixture can be based on inorganic-inorganic, organic-inorganic and organic-organic components [32].

Overall, following the properties summarised above, the RINA Rules reported below should be considered during the design of the PCM thermal energy storage:

- Piping: RINA Rules Pt C, Ch 1, Sec 10
- Heat exchangers: RINA Rules Pt C, Ch 1, Sec 3, where applicable

Additionally, the design process of PCM storage should take into account typical operation within marine environment. Particularly, vibrations levels, ambient conditions (salt-bearing, wet and possibly very hot) and inclination angles reported in RINA Rules Pt C, Ch 1, Sec 1 shall be considered.

Furthermore, the integration of PCM storage systems onboard for waste heat recovery shall not cause negative effects on other ship systems with the aim of ensuring fitness-for-service and safety. In detail, since exhaust flue gases from prime movers need to pass inside heat exchangers (in case intermediate heat transfer fluid is present) or directly through PCM storage (e.g., packed beds for both macro- and

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micro- encapsulated PCMs) [25,26], backpressure in the discharge manifold of prime movers is generated. Therefore, negative influence played by higher pressure levels in the discharge manifold on the safe operation of prime movers and related auxiliaries (e.g., cooling circuits, steam and freshwater generators, safety monitoring and control systems, etc.) shall be avoided during design, off-design and transient operating conditions as well as during emergency shut down. Furthermore, as outlined in the above paragraphs concerning PCM classification, the materials used for the latent thermal energy storage shall comply with HSE principles, i.e. they have to deal with low environmental impact as well as safety characteristics (e.g., no corrosive, no toxic, no flammable,…).

Finally, to give evidence that no negative effects are triggered by the integration onboard of thermal energy storage systems based on PCMs, the Manufacturer shall provide installation guidelines and system schematics reporting all the interfaces (structural, mechanical, thermal, etc.) of the storage with other systems present on the vessel as well as relevant connection/segregation criteria.

7.2 Isobaric expansion engines

Small- and medium-size waste heat recovery from low-temperature sources can be addressed by means of Isobaric Expansion engines, which transform heat in mechanical energy (in hydraulic or pneumatic forms) [22,34].

Differently from other heat engines, useful work is generated at high pressure, whereas the rest of the cycle takes place at the low-pressure level, hence generating particularly low thermal and mechanical losses.

Thanks to their simple kinematics and few energy conversion steps, isobaric expansion engines are attractive as vapor-driven pumps and compressors, i.e. they can be effectively used for pumping and compression services with no intermediate generation of electricity. In this case, mechanical energy can be used directly, with no further conversions. Alternatively, the energy stored in the high pressure pumped liquid can be converted to electricity using hydraulic motors. Despite theoretically high efficiencies, close to the Carnot ones, actual efficiency levels of isobaric expansion engines are low owing to the negative effect of the dead volumes.

Bush and Worthington engines are the main types of isobaric expansion engines, including many variants on the cycle configuration depending on pumping, compression or power generation purposes [22].

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Generally, Bush engines can work with heat sources ranging from 40 to 600°C, hence resulting in a waste heat recovery system dealing with flexible applications [35]. However, their two major drawbacks consist of small power generated (<30 W) and relatively low efficiencies (3–7%) [36]. Overall, power density per unit volume does not exceed 1.2 kW/L [36].

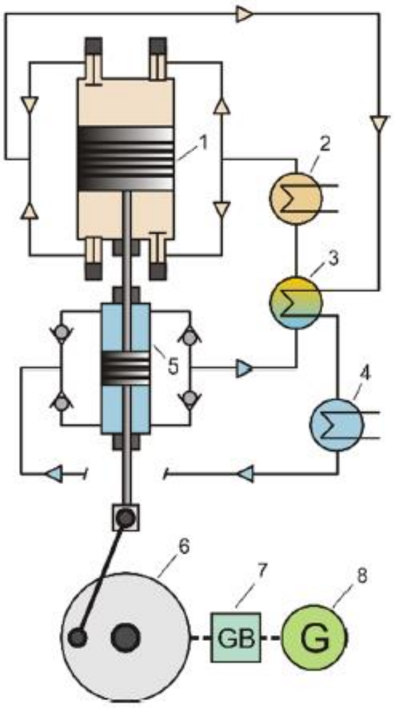

Figure 7.3: Schematic view of Worthington type isobaric expansion engine used for a driving-pump applications [7]. 1 - engine driver, 2 – heater, 3 – recuperator, 4 – cooler, 5 – feed pump, 6 – crank gear, 7 – gearbox, 8 – alternator

Relevant challenges in the design arise for large installations of Bush isobaric expansion engines, which depend on the availability of properly sized heat exchangers dealing with small internal volume (i.e., printed circuit heat exchangers) [37]. Furthermore, these heat exchangers are required to withstand pressure cycling due to charge/discharge alternating modes.

In order to improve performances with respect to the Bush-type engine for similar waste heat temperatures, the Worthington isobaric expansion engine was developed (its schematic view is reported in Figure 7.3 for a driving-pump application). No limitation on the types of heat exchanger (gasketed and brazed plate, pillow plate etc.) to be adopted is present for the Worthington engine, hence larger sizes and cost savings can be achieved in comparison to the Bush configuration.

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Furthermore, since larger internal volumes are available in the Worthington engine with respect to the Bush configuration, pressure fluctuations are dampened and, consequently, higher fatigue resistance is obtained. Analogously, large volumes allow the simultaneous usage of multiple heat sources and sinks, possibly at distinct temperatures, hence enhancing the system flexibility.

Independently from the type of isobaric expansion engine considered, various pure and mixed working fluids have been analyzed within the scientific community (see Figure 7.4).

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Fluid	Type	Toxicity	Flammability	GWP	Normal boiling point [°C]	P_{cr} [bar]	T_{cr} [°C]	BWR[a)] [%]	η[a)] [%]	P_{sat} [bar]
Propane	Alkane	A	3	20	−42.25	42.5	96.7	4.2	1.1	10.79
n-Butane		A	3	20	−1.00	38.0	152.0	1.5	2.6	2.84
n-Pentane		A	3	11	36.00	33.6	196.5	0.8	4.2	0.83
n-Hexane		NA	3	NA	69.00	30.6	234.7	92.6	0.0	0.25
n-Heptane		NA	3	NA	98.38	27.3	267.0	93.5	0.0	0.08
Isobutane		A	3	20	−12.00	36.4	134.7	2.0	2.1	4.05
Neopentane		A	3	20	10.00	32.0	160.6	0.7	3.1	2.01
isopentane		A	3	20	28.00	33.7	187.2	0.9	4.0	1.09
Isohexane		NA	3	NA	60.00	30.4	224.6	92.4	0.0	0.35
Cyclopentane	Cycloalkane	A	3	NA	49.20	45.7	238.6	0.7	4.2	0.51
Cyclohexane		A	3	NA	80.74	40.8	280.5	93.7	0.0	0.16
Propylene	Alkene	A	3	NA	−47.60	46.7	92.4	5.0	0.9	13.07
Butene		NA	3	NA	−7.00	40.1	146.1	0.1	2.2	3.44
Isobutene		A	3	20	−6.90	40.1	144.9	1.8	2.2	3.54
Benzene		NA	3	NA	80.10	48.9	288.9	93.7	0.0	0.16
Methanol	Alcohol	NA	3	NA	64.70	81.0	240.2	93.7	0.0	0.21
Ethanol		NA	3	NA	78.00	62.7	241.6	94.1	0.0	0.11
Acetone	Ketone	NA	3	NA	56.00	47.0	235.0	0.5	4.0	0.38
Dimethylether	Ether	NA	4	NA	−24.00	53.7	127.2	2.1	1.5	6.84
Diethylether		NA	4	NA	34.60	36.4	193.6	0.8	4.2	0.86
Dimethyl carbonate	Carbonate ester	NA	4	NA	90.00	49.1	284.2	93.2	0.0	0.09
Ammonia	Pnictogen hydride	B	2	1	−33.00	113.3	132.3	0.3	1.0	11.67
Water					100.00	220.6	373.9	97.6	0.0	0.04
Hexamethyldisiloxane		A	3	NA	0.00	19.4	245.5	93.3	0.0	0.08
Novec649		NA	NA	1	49.00	18.7	168.7	1.5	3.1	0.50
R32	HFC	A	2	675	−52.00	57.8	78.1	4.7	0.7	19.28
R134a	HFC	A	1	1300	−26.00	40.6	101.0	2.9	1.3	7.71
R227ea	HFC	A	1	257	−16.00	29.3	101.8	3.3	1.4	5.28
R245fa	HFC	B	1	925	15.00	36.5	154.0	1.1	2.9	1.77
R1234yf	HFO	A	2L	4	−29.00	33.8	94.7	3.7	1.3	7.84
R152a	HFC	A	2	120	−24.00	45.2	113.3	2.6	1.3	6.91
R161	HFC	A	3	12	−37.00	50.1	102.1	3.2	1.1	10.56
RC318	PFC	A	1	8700	−6.00	27.8	115.2	2.5	1.8	3.66
R218	PFC	A	1	8830	−36.70	26.4	71.9	6.7	0.9	9.96
RE245Fa2	HFC	B	1	950	15.00	34.3	171.7	1.0	3.3	1.04
RE245cb2	HFC	NA	NA	NA	5.61	28.9	133.7	1.8	2.2	2.43

a) At $T_H = 80\,°C$ and $\Delta P = 1$ bar.

Figure 7.4: Pure and mixed working fluids typically considered in IE engines together with their corresponding characteristics [8]. GWP, P_{cr}, T_{cr}, BWP, η, P_{sat} represent global warming potential, critical pressure, critical temperature, back work ratio, efficiency and saturation pressure, respectively.

For low and ultra low waste heat recovery temperatures, common refrigerants may be adopted. Generally, working fluids belonging to hydrofluorocarbons mixtures mainly suffer from flammability and explosion risks, hence adequate air ventilation systems are to be included onboard and exposure to

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flames, sparks or hot surfaces should be avoided. Despite the fluorocarbon mixtures are mild toxic, possibilities of health issues and death only exist in unusual situations (e.g., failure), hence, again, effective ventilation is necessary where heavy vapors might accumulate.

On the other hand, in case ammonia is adopted as working fluid, two are the main drawbacks to be faced by a safety point of view. First, ammonia is highly toxic to life, including humans, at very low concentrations (ammonia threshold exposure without any adverse effect on health is 25-50 ppm). Furthermore, due to its alkaline nature, ammonia is highly corrosive, with the most relevant degradation levels achieved in presence of copper, zinc, tin and moisture. For these reasons, the safe use of ammonia onboard is subjected to precise measures for accidental leakage handling and should comply with specific Rules and Regulations. Where ammonia is concerned, RINA Rules for ammonia fuelled ships Part C, Chapter 1, Section 1, [2.9.1] and Appendix 13 are available and specific requirements are introduced by the IGF Code and SOLAS, Part F – "Alternative design and arrangements".

Instead, where methanol is considered, the RINA Rules Part C, Chapter 1, Section 1, [2.9.1] and Appendix 15 shall be accounted for in addition to Chapters from SOLAS and IGF code mentioned for ammonia.

Independently from the working fluid considered, the isobaric expansion engine design should comply with the following RINA Rules:

- auxiliary machineries: RINA Rules Pt C, Ch 1
- electrical machineries: RINA Rules Pt C, Ch 2, Sec 1, 3, 12, if applicable
- piping: RINA Rules Pt C, Ch 1, Sec 10
- hydraulic systems: RINA Rules Pt C, Ch 1, Sec 10 and Pt C, Ch 1, Sec 3.
- heat exchangers; RINA Rules Pt C, Ch 1, Sec 3

Additionally, noise levels allowed onboard are reported in detail in the RINA Rules Pt F, Ch 6, Sec 1.

Where integration of isobaric expansion engines onboard is concerned, they should not negatively interfere with other ship systems. In other words, reliability, maintainability, availability and safety of each system is to be guaranteed. E.g., the safe operation of prime movers and related auxiliaries (e.g., cooling circuits, steam and freshwater generators, safety monitoring and control systems, etc.) shall not be compromised by the backpressure generated by IE engine heat exchangers which are included into the exhaust gas circuit. Similarly, in case IE engines are used to pump fuels into prime movers, proper pressure and temperature levels of the fuel shall be ensured, in order to avoid damage or unsafe operation of feeding system, prime mover combustion chamber or other related auxiliaries (e.g.,

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valves). Furthermore, safe operation shall be ensured at design, off-design and transient working conditions as well as during emergency shut down. Isobaric expansion engines should work properly in marine environment without any issue, hence they shall be designed accounting for vibrations levels, ambient conditions (salt-bearing, wet and possibly very hot) and inclination angles reported in RINA Rules Pt C, Ch 1, Sec 1. Additionally, working fluids adopted in IE engines should comply with HSE principles, i.e. they are to deal with low environmental impact and possibly null safety issues (e.g., corrosion, toxicity, flammability,…). Details on the corrosion allowance for steel and non-ferrous metallic pipes are reported in the RINA Rules Pt C, Ch 1, Sec 10 [2.2.4].

To verify that the integration of isobaric expansion engines onboard does not negatively impact other vessel systems, the Manufacturer shall provide installation guidelines and system schematics reporting all the interfaces (electrical, mechanical, hydraulic, thermal) of IE engines with the ship. Additionally, segregation strategies of isobaric expansion engines should be documented.

7.3 Organic Rankine Cycles

Organic Rankine Cycles (ORCs) constitute a promising technical solution for generating electricity onboard from waste heat sources dealing with low-medium temperature (<100 °C) and small capacity [38,39].

Optimal performance of ORC systems recovering waste heat from prime movers is significantly influenced by the working fluid, operational process parameters and plant configuration. Working fluid selection must underly on thermodynamic, environmental, health and safety aspects. Since water is a suitable working fluid for waste heat sources characterized by high and medium-temperature, ORC systems adopt organic working fluids having lower boiling point at the given pressure. Specifically, ORC cycles can employ different organic working fluids such as hydrocarbons, refrigerants, siloxanes or mixtures of them. Overall, ORC working fluids should be non-flammable, non-corrosive and non-toxic, even though compromise is always necessary since one size does not fit all. Many working fluids for ORC power plants are flammable and suffer from autoignition (e.g., at temperature exceeding 200°C for long-chain alkanes) [33]. Furthermore, also the maximum allowable concentration in confined spaces should be considered to limit explosion risks, by including adequate air ventilation systems onboard and avoiding exposure to flames, sparks or hot surfaces [40,41]. Furthermore, working fluids used in ORC systems are typically affected by detrimental effect on the environment, since they may have significant Ozone Depletion Potential (ODP) and Global Warming Potential (GWP). Physical, chemical,

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environmental and safety properties of a given working fluid can be adjusted by adopting zeotropic mixtures of different components, with beneficial effects on ORC flexible usage when heat sources and sinks exhibit significant temperature differences. However, few non-flammable and non-toxic working fluids exist, e.g. the R1233zd(E), with some issues concerning chemical stability. In case ammonia (i.e., R717 refrigerant) is used as working fluid, toxicity and corrosion properties are to be accounted for as previously explained for isobaric expansion engines running on NH_3. Overall, international safety classification of refrigerants provides accurate information on safety aspects of most relevant working fluids adopted within ORC systems.

Engine specification	High-temperature WH sources				Low-temperature WH sources		
	EG		EGR		Coolant	Lubricating Oil	CA
	Temperature (K)	Mass flow rate (kg/s)	Temperature (K)	Mass flow rate (kg/s)	Temperature (K)	Temperature (K)	Temperature (K)
4 Cylinder heavy duty diesel engine (HDDE), 243 kW (Yu et al., 2016)	479–744	0.099–0.38	555–867	0.000–0.060	347–357	NA	330–426
4 Cylinder diesel engine (DE), 57 kW (Hoang and Nguyen, 2017)	564–923	NA	NA	NA	NA	NA	NA
6 Cylinder DE, 162 kW (Geng et al., 2017)	423–703	NA	NA	NA	353–358	363–373	NA
6 Cylinder DE, 247 kW (Yang et al., 2014a)	495–647	0.11–0.34	NA	NA	353–363	NA	NA
6 Cylinder marine DE, 996 kW (Song et al., 2015)	548–573	1.98	NA	NA	333–363	NA	NA
4 Cylinder DE, 1.6 MW (Uusitalo et al., 2015)	NA	NA	NA	NA	NA	NA	373–443

Figure 7.5: Characteristics of various waste heat sources related to marine Diesel engine operation [9].

Furthermore, one of the major challenges of ORC systems is guaranteeing stable performance under dynamic operation and in presence of waste heat sources dealing with variable temperature. For example, 60%–75% of the primary energy of the fuels is not converted into electrical power in Diesel engines, thus resulting in various waste heat sources. High-temperature waste heat is available from exhaust gas and Exhaust gas Recirculation (EGR) systems, while coolant and lubricating oil circuits deal with lower temperatures (e.g., Figure 7.5 shows the temperatures and mass flow rates related to various waste heat sources in Diesel engines). Working fluids with low specific volumes require small-size heat exchangers and expanders, hence positively reducing the volumes and cost of the system. Higher cycle efficiencies can be obtained in case working fluid has the critical temperature close to the maximum temperature available from the waste heat source. On the other hand, the lowest temperature of the cycle must not exceed the freezing point of the working fluid to guarantee reliability and safe operation (see Figure 7.6).

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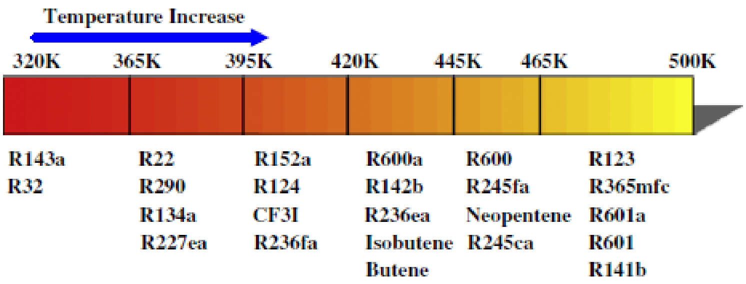

Figure 7.6: Suitability of ORC working fluids depending on the temperature [10].

The tradeoff between power output and thermal efficiency versus exhaust gas backpressure, weight, space, cost, environment, health, and safety issues should be taken into account carefully when assessing the feasibility of ORC-reciprocating engine coupling. Specifically, inclusion of waste heat recovery systems in the exhaust gas circuit of the engine increases backpressure at discharge manifolds, with consequent increase of the prime mover fuel consumption. With the aim of maximizing performances of ORC cycles, new and improved expander designs are recently under consideration, different from axial/radial flow turbines or screw/scroll/reciprocating piston/rotary vane expanders. However, when selecting expanders, temperature and pressure levels, probability of leakage, noise and safety issues should be considered other than efficiency and costs. Overall, ORC systems should be designed according to the following RINA Rules:

- auxiliary machineries: RINA Rules Pt C, Ch 1
- electrical machineries: RINA Rules Pt C, Ch 2, Sec 1, 3, 12
- piping: RINA Rules Pt C, Ch 1, Sec 10
- heat exchangers: RINA Rules Pt C, Ch 1, Sec 3
- refrigerating units: RINA Rules Pt C, Ch 1, Sec 13

Additionally, the design process should guarantee that ORC performances are not negatively affected by marine environment operation, hence vibrations levels, ambient conditions (salt-bearing, wet and possibly very hot) and inclination angles reported in RINA Rules Pt C, Ch 1, Sec 1 are to be accounted for. Noise levels allowed onboard are reported in detail in the RINA Rules Pt F, Ch 6, Sec 1.

Where integration of ORC systems onboard for waste heat recovery purposes is concerned, negative effects on the other ship systems must be avoided, such to ensure safety and fitness-for-service. In detail, pressure losses occurring in the exhaust gas system of prime movers due to waste heat recovery

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systems shall not negatively influence the safe operation of prime movers and related auxiliaries (e.g., cooling circuits, steam and freshwater generators, safety monitoring and control systems, etc.). In this case, safe operation of prime movers shall be ensured at design, off-design and transient operation as well as during emergency shut down. Furthermore, as mentioned above, HSE principles impose the working fluid to deal with low environmental impact and to ensure safety onboard (e.g., no issues of corrosion, toxicity, flammability,…). Details on the corrosion allowance for steel and non-ferrous metallic pipes are reported in the RINA Rules Pt C, Ch 1, Sec 10 [2.2.4].

Finally, to give evidence that no negative effects are triggered by the integration of ORC systems onboard, the Manufacturer shall provide installation guidelines and system schematics reporting the structural, mechanical, hydraulic, thermal and electrical interfaces of ORC with other systems present on the vessel as well as relevant connection/segregation criteria.

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Category and name	Alt. name	P_c (bar)	T_c (°C)
Hydrocarbons (HCs)			
Ethane	R-170	48.7	32
Propene	R-1270	45.3	91
Propane	R-290	41.8	96
Cyclopropane	HC-270	54.8	124
Propyne	–	56.3	129
Isobutane	R-600a	36.4	135
Isobutene	–	39.7	144
N-butane	R-600	37.9	152
Neopentane	–	31.6	160
Isopentane	R-601a	33.7	187
N-pentane	R-601	33.6	196
Isohexane	–	30.4	225
N-hexane	–	30.6	235
N-heptane	–	27.3	267
Cyclohexane	–	40.7	280
N-octane	–	25	296
N-nonane	–	22.7	321
N-decane	–	21.0	345
N-dodecane	–	17.9	382
Benzene	–	48.8	298
Toluene	–	41.3	319
p-Xylene	–	34.8	342
Ethylbenzene	–	36.1	344
N-propylbenzene	–	32	365
N-butylbenzene	–	28.9	388
Perfluorocarbons (PCFs)			
Carbon-tetrafluoride	R-14	36.8	-46
Hexafluoroethane	R-116	30.5	20
Octafluoropropane	R-218	26.8	73
Perfluoro-*N*-pentane	PF-5050	20.2	149
Decafluorobutane	R-3-1-10	23.2	113
Dodecafluoropentane	R-4-1-12	20.5	147
Chlorofluorocarbons (CFCs)			
Trichlorofluoromethane	R-11	43.7	197
Dichlorodifluoromethane	R-12	39.5	111
Trichlorotrifluoroethane	R-113	33.8	213
Dichlorotetrafluoroethane	R-114	32.4	145
Chloropentafluoroethane	R-115	30.8	79
Hydrofluorocarbons (HFCs)			
Trifluoromethane	R-23	48.3	26
Difluoromethane	R-32	57.4	78
Fluoromethane	R-41	59.0	44
Pentafluoroethane	R-125	36.3	66
1,1,1,2-Tetrafluoroethane	R-134a	40.6	101
1,1,1-Trifluoroethane	R-143a	37.6	73
1,1-Difluoroethane	R-152a	44.5	112
1,1,1,2,3,3,3-Heptafluoropropane	R-227ea	28.7	101
1,1,1,3,3,3-Hexafluoropropane	R-236fa	31.9	124
1,1,1,2,3,3-Hexafluoropropane	R-236ea	34.1	139
1,1,1,3,3-Pentafluoropropane	R-245fa	36.1	153
1,1,2,2,3-Pentafluoropropane	R-245ca	38.9	174
Octafluorocyclobutane	RC-318	27.8	114
1,1,1,2,2,3,3,4-Octafluorobutane	R-338mccq	27.2	159
1,1,1,3,3-Pentafluorobutane	R-365mfc	32.7	187
Hydrofluoroolefins (HFOs)			
2,3,3,3-Tetrafluoropropene	HFO-1234yf	33.8	94.7
Hydrochlorofluorocarbons (HCFCs)			
Dichlorofluoromethane	R-21	51.8	178
Chlorodifluoromethane	R-22	49.9	96
1,1-Dichloro-2,2,2-trifluoroethane	R-123	36.6	183
2-Chloro-1,1,1,2-tetrafluoroethane	R-124	36.2	122
1,1-Dichloro-1-fluoroethane	R-141b	42.1	204
1-Chloro-1,1-difluoroethane	R-142b	40.6	137
Siloxanes			
Hexamethyldisiloxane	MM	19.1	245
Octamethyltrisiloxane	MDM	14.4	291
Decamethyltetrasiloxane	MD2M	12.2	326
Dodecamethylpentasiloxane	MD3M	9.3	354
Octamethylcyclotetrasiloxane	D4	13.1	312
Decamethylcyclopentasiloxane	D5	11.6	346
Dodecamethylcyclohexasiloxane	D6	9.5	371
Alcohols			
Methanol	–	81.0	240

Figure 7.7: working fluids traditionally considered in the literature for ORC power plants [10]. P_c and T_c represent critical pressure and temperature, respectively.

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7.4 Adsorption cooling and desalination systems

Waste heat recovery from prime movers can be effectively used for cooling and desalination purposes onboard vessels. Differently from reverse osmosis desalination systems and compression chillers, small amount of electrical power is required in input to adsorption systems for auxiliary equipment, while useful effect is mainly carried out by thermal energy. This guarantees highly efficient energy usage onboard, since losses during thermal-to-electrical energy transformation are significantly reduced for fixed outcomes. Multiple Effect Desalination (MED) and Multi-Stage Desalination (FLASH) are the two main technologies typically adopted for water desalination purposes onboard ships.

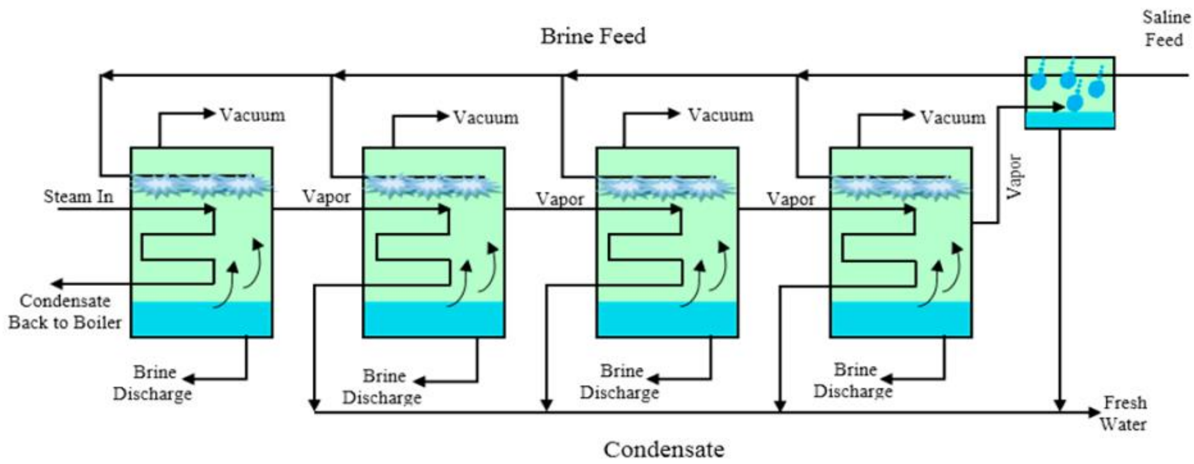

Figure 7.8: General arrangement of a MED desalination system [11].

Generally, compared with the FLASH plants, the MED systems maintain higher performances at part-loads, are weakly affected by scaling-up approach and are more cost effective (in Figure 7.8 is reported a schematic view of the MED desalination process). However, the FLASH systems require higher source temperatures (usually in steam form) with consequent corrosion problems and higher energy consumption compared to MED. Furthermore, corrosion causes a reduction in the heat transfer area, with negative effect on the reliability of the process.

On the other hand, adsorption desalination provides various benefits compared to MEF and FLASH plants for freshwater generation onboard (a schematic view of adsorption desalination systems is reported in Figure 7.9, while comparison with MED and FLASH systems is shown in Figure 7.10).

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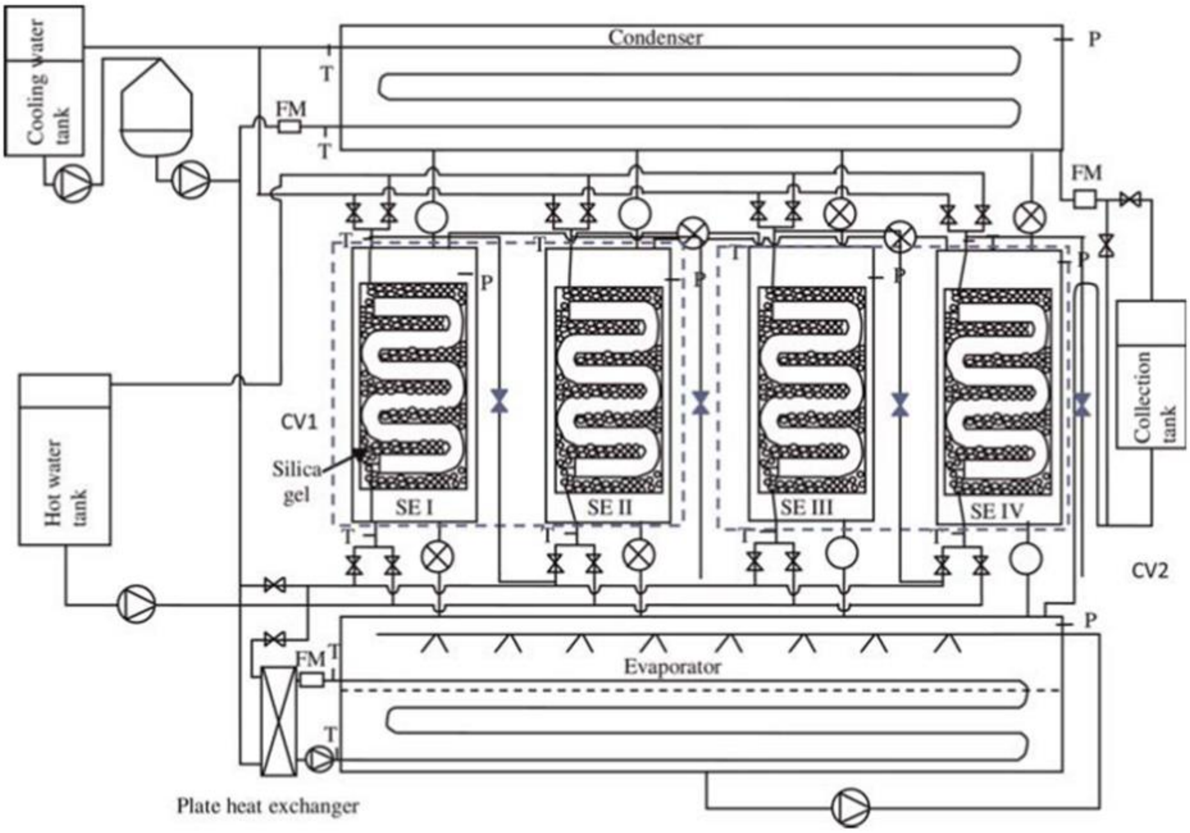

Figure 7.9: Schematic representation of a four-bed adsorption & desalination system [42].

Adsorption desalination system is a thermodynamic cycle based on two main processes, the adsorption-evaporation process and the desorption-condensation process [43,44], and relies on three main components: evaporator providing the cooling output, reactor consisting of silica gel packed heat exchanger tubes and condenser for pure water vapor condensation [45]. Specifically, where adsorption desalination systems are concerned, thermal energy necessary for the desorption phase of the adsorber can be supplied by renewable energy sources as well as by low temperature (i.e., <100°C) waste heat from industrial processes or prime movers, thus primary energy fuel consumption is minimized and carbon dioxide emissions are significantly reduced with respect to other desalination technologies.

Reduced amount of electrical energy is required by auxiliaries (e.g., pumps) to control adsorption desalination circuits (around 1.4 kWh/m^3), hence low cost to produce 1 m^3 of freshwater is achieved (around 0.3 $\$/m^3$). Economic competitiveness of adsorption desalination may be further enhanced by adopting configurations allowing for the co-generation of potable water and cooling through multi-bed arrangement [46,47].

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Technology	Thermal energy (kWh/m³)	Electrical energy (kWh/m³)	Total energy (kWh/m³)	CO_2 emission[a] (kg/m³)	Unit production cost of water ($/m³)
AD[b]	0[c]	1.38	1.38	0.32	0.46–0.81
MED	4–7	1.5–2	5.5–9	0.72–2.08	1.4[d]
MSF	7.5–12	2.5–4	10–16	2.31–3.69	2.3[d]

[a] It assumes that the primary fuel used is natural gas whose emission rate of CO_2 is 64.2 tonne/TJ.
[b] The data refers to the experimental and calculation results of a 4-bed AD system using Type RD silica gel that was reported by Thu et al. [17] (T_{hw} = 80 °C, T_{cw} = 30 °C, T_{eva} = 40 °C and T_{cond} = 48 °C).
[c] The thermal energy of AD systems is considered to be 0 since it could be driven by the free energy from waste heat or solar energy lower than 80 °C.
[d] The water production of the related plants is 1000 m³/d.

Figure 7.10: Comparisons between different desalination technologies (AD= adsorption desalination; MED= Multiple Effect Desalination; MSF= multistage flash distillation) [46].

Typically, an adsorption desalination cycle containing 1000 kg of silica gel manages to generate 12.5 m^3/day of fresh water and 24 refrigeration tonnes of cooling rate [48,49]. Similarly, due to their simple design as well as reduced corrosion and fouling issues inside the tubes, low maintenance costs are required in a life-cycle perspective [46].

Furthermore, among benefits of adsorption desalination systems, their operating conditions can be flexibly adapted to desalinate high salinity water and brackish water containing organic compounds, owing to their double distillation process taking place in evaporator-reactor and reactor-condenser thermodynamic transformations. This guarantees high efficiencies of desalination (up to 80%), i.e. large amount of pure water produced from unitary mass of seawater, and nearly null waste water to be discharged in the sea.

Many types of working fluids suitable for adsorption desalination cycles have been developed in recent decades: chars, biochars, activated carbons and coals [50]; chitin and chitosan derived materials [51]; biosorbents [52]; zeolites, hydroxides and geopolymers [53]; metal-organic frameworks [54]; silica-based materials [55]. Generally, the main challenges of adsorption desalination plants include:

- High efficiency: the presence of residual contaminants in the desalinated water produced should be carefully avoided, to ensure the desired standard quality is achieved. This point gains even more importance considering that both pure water and cooling demands in passengers ships are relevant also at berth for hotel services, when sea water quality and types of contaminants are different from those available during navigation
- Flammability, corrosion and toxicity: non-flammable, noncorrosive and non-toxic working fluids should be considered for adsorption desalination cycles. Specifically, corrosion should be avoided within a wide range of working temperatures and non-flammable behavior should be ensured even in presence of ignition sources

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- Chemical stability: performances of adsorbent materials can be negatively affected by changes in water composition and properties (e.g., pH, ionic strength, conductivity, …), which deteriorate chemical stability and correct functionality of the system
- Mechanical stability: since multi-bed arrangement is assumed, any pressure drops, obstructions and generation of preferential pathways which are possibly caused by the adsorbent should be avoided to ensure the continuous water treatment
- Physico-chemical characteristics: the physico-chemical characteristics of adsorbent should guarantee high surface area and large amount of functional groups on the surface, which need to interact with the contaminants. Additionally, adsorption should take place with fast kinetics to shorten the time required for the full treatment of saline water as well as to reduce volumes related to the installation of adsorption desalination systems onboard
- High adsorption capacity: in order to lower the quantity of adsorbent necessary to cover specific pure water and cooling demands onboard, large amount of contaminant should be adsorbed per gram of adsorbent. This also allows for a reduced physically active surface area necessary to operation
- Regeneration and reuse: to lower operational costs and distance the dates at which it is necessary to stop the system for maintenance, the adsorbent should be easily regenerated to reuse it many times
- Low environmental impact: environmentally friendly adsorbent/adsorbate pairs (i.e., silica gel/water) should be considered

Finally, since 70% of the operational costs of an adsorption desalination cycle is driven by the large amount of adsorbent material required, mature production and transport chains are needed to ensure availability and economic viability [56].

Overall, adsorption systems for cooling and desalination purposes should be designed according to the following RINA Rules:

- auxiliary machineries: RINA Rules Pt C, Ch 1
- electrical machineries: RINA Rules Pt C, Ch 2, Sec 1, 3, 12
- piping: RINA Rules Pt C, Ch 1, Sec 10

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- heat exchangers: RINA Rules Pt C, Ch 1, Sec 3
- refrigerating units: RINA Rules Pt C, Ch 1, Sec 13

Additionally, the design process should guarantee that adsorption plant performances as well as fitness-for-service are not negatively affected by marine environment operation. Towards this end, the design shall account for vibrations levels, ambient conditions (salt-bearing, wet and possibly very hot) and inclination angles reported in the RINA Rules Pt C, Ch 1, Sec 1.

Furthermore, integration of adsorption systems onboard shall not cause negative effects on the other ship systems, thus ensuring fitness-for-service and safety. E.g., pressure losses caused by heat exchangers used for waste heat recovery from the prime mover discharge manifold should not negatively affect the safe operation of prime movers as well as related auxiliaries (e.g., cooling circuits, steam and freshwater generators, safety monitoring and control systems, etc.). No negative effect on other ship systems shall be guaranteed on design, off-design and transient operation as well as during emergency shut down of the adsorption system. Furthermore, the working fluid of adsorption systems should be safe (e.g., no issues of corrosion, toxicity, flammability,…) as well as environmentally friendly, according to HSE principles. Details on the corrosion allowance for steel and non-ferrous metallic pipes are reported in the RINA Rules Pt C, Ch 1, Sec 10 [2.2.4].

Finally, to give evidence that no negative effects are triggered by the integration of adsorption systems onboard, the Manufacturer shall provide installation guidelines and system schematics reporting the structural, mechanical, hydraulic, thermal and electrical interfaces of adsorption plant with other systems present on the vessel as well as relevant connection/segregation criteria.

7.5 Wind Assisted Propulsion Systems

Wind assisted ship propulsion is receiving major attention in recent years owing to its potential benefits in reducing fuel consumption and environmental impact of the shipping field. Many devices were developed to effectively capture wind energy and transfer it to the ship. Among all of them, wingsails based on airfoil know-how appear to optimize aerodynamic performances against Flettner rotors and kite sails.

However, some technical challenges affect wind assisted ship propulsion, especially for existing vessels, since hydrodynamics of hull and propulsion systems as well as deck structure are not designed and built accounting for possible additional thrust, stresses and side forces generated by wingsails installed

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onboard. Thus, the hull forms and propeller geometry should be optimized with respect to hydrodynamic performance in realistic sea and weather conditions. Additionally, wingsail technology can also present challenges with respect to obstruction of cranes, ship intrinsic stability, wind direction constraints, maintenance and crew training.

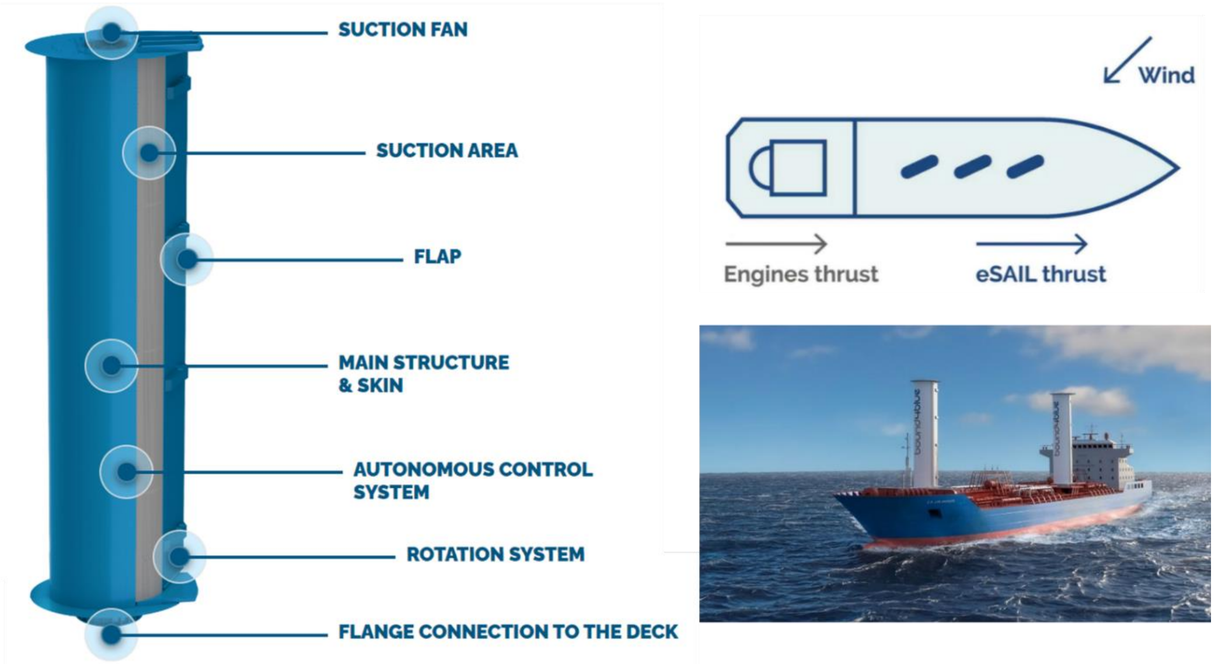

Figure 7.11: 3D model for the eSail technology (left side) [12] together with real application onboard ship (bottom right side) and operating principle (top right side) [12,13].

Overall, a wing rig consists of a 3D structure relying on an airfoil, which aims to generate thrust by means of lift and drag aerodynamic forces as occurs for conventional sails. Both rigid or morphing elements can span the Wind Assisted Propulsion System (WAPS), with variable camber allowed by the latter by means of adjustable flaps. The sail is typically only supported by its cantilevered foundation and mounted around a spar, hence it can rotate for the purpose to adapt angle of attack to the apparent wind direction.

The resultant force F_r generated by wind on the sail is applied into the center of pressure of the wing. Specifically, the component of F_r aligned along the ship longitudinal direction is the driving force (i.e. the thrust contribution), whereas the component orthogonal to this direction consists of a side force generating heeling and, possibly, also yawing moments, depending on the arrangement of the WAPS on board.

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Furthermore, suction sails for wind assisted ship propulsion use active suction boundary layer control to change aerodynamic forces acting on the airfoil, other than possibly adapting its geometry by morphing actuators or rotating to the pertinent wind direction by means of a spar mechanism. The eSail technology from B4B considered into the ZHENIT project belongs to this category of WAPS (see Figure 7.11). In detail, the eSail consists of a nearly-symmetric airfoil coupled with a fan, which aims at sucking the boundary layer on a specific side of the wing (i.e. suction side), thus generating high lift forces with minimum cambered geometry. Therefore, the wingsail is possibly not required to rotate on a spar to adjust the angle of attack and a flap is used to provide slightly positive camber to the airfoil. Both mass flow rate imposed by the fan and the angle of the flap can be changed depending on the actual wind conditions (i.e., magnitude and direction) as well as thrust demand, with reduced advantages gained in poor wind conditions. Of coarse, vessels are required by shipowners to keep a schedule regardless of the weather. Therefore, WAPS technologies able to generate acceptable levels of thrust independently from the wind magnitude and direction (within a certain operating range) reveal more reliable. A detailed schematic view of the eSail system and its operating principle is shown in Figure 7.12.

In particular, the suction sail eSail from Bounded4Blue consists of a 18.892 m height wing dealing with a nearly elliptical airfoil equipped with a flap (see the general arrangement of eSail reported in Figure 7.12). The pressure center is located at 9.314 m above the deck foundation and 0.388 m from the leading edge, whereas gravimetric point is positioned at 6.636 m height and 1.479 m from the leading edge. The height of the wing and the position of pressure center as well as gravimetric point should be carefully considered when assessing stability of ships equipped with the eSail and structural strength of wing foundations, according to the RINA Rules Pt B, Ch 3 and RINA "Rules for Loading and Unloading Arrangements and for other Lifting Appliances on Board Ships", Ch 14 (see paragraphs below for more

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details). A suction surface is present in the rear part of the airfoil, aiming at accelerating the flow fieldon the profile and generating pressure drop on the suction side of the airfoil. In this way, pressure gap between pressure and suction sides of the airfoil causes lift production. Suction is enabled by a fan

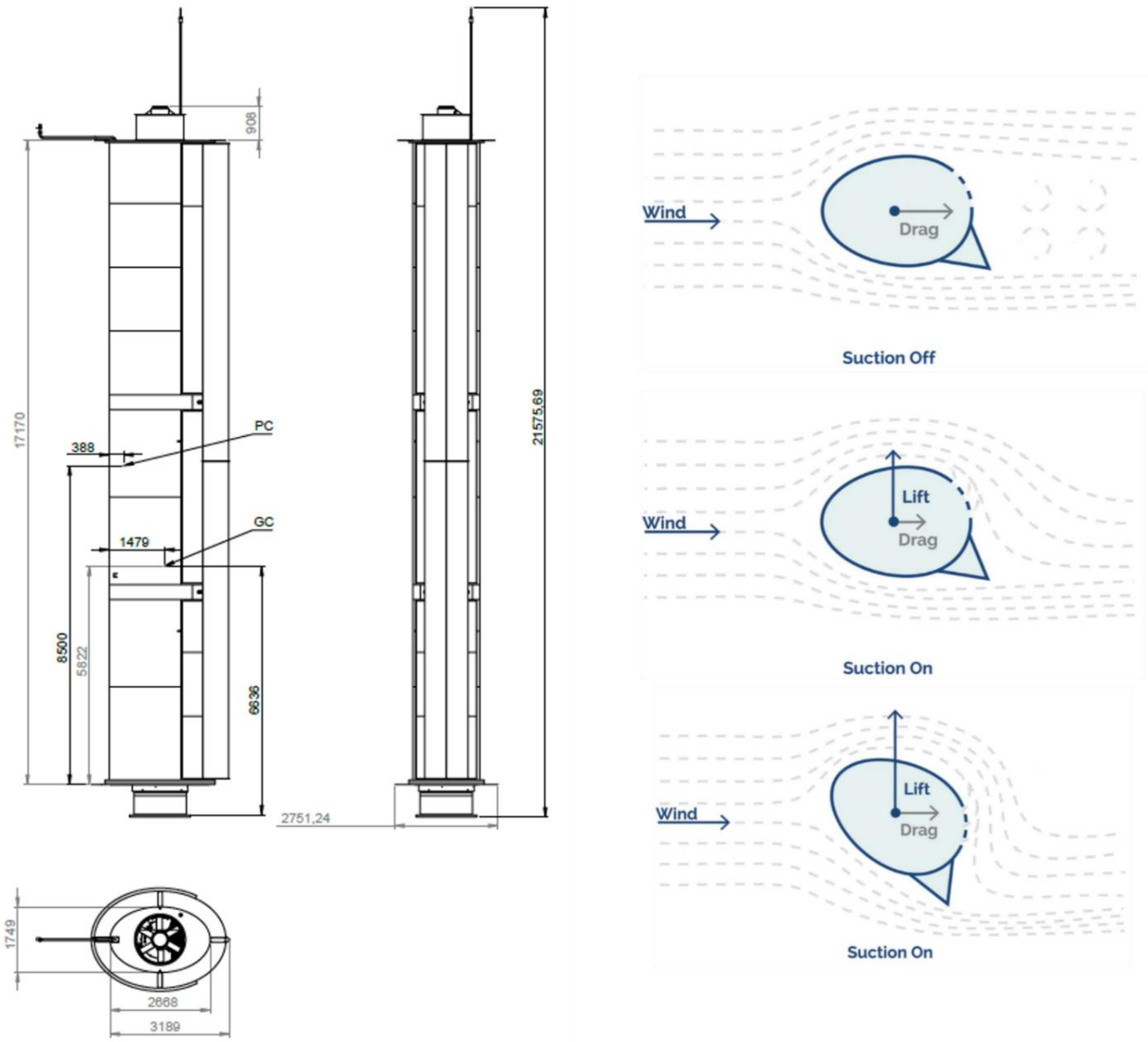

Figure 7.12: general arrangement of eSail (courtesy of Bound4Blue), on the left side, and 2D view of its suction airfoil operating principle [12], on the right side. Where general arrangement is concerned, PC stands for pressure center, while GC indicates gravimetric center.

positioned at the top of the eSail wing (i.e., at 17.984 m height) and driven by electrical motor by means of electrical power generated by the engine room installed onboard. As visible from Figure 7.12, in order

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to further increase lift force exchanged by eSail with the wind by increasing flow field deflection, a flap mechanism is installed in the rear part of the profile.

When the flap does not increase curvature and suction devices are switched off, the profile is symmetric, hence no lift is generated and only drag force acts on the eSail. In order to align the leading edge of the airfoil with respect to relative wind speed in each wind and ship operating condition, yaw control is actuated by an electrical motor.

Finally, in case of excessive wind speed, eSail suction fan and flap are switched off and the wingsail trim is changed by a suitable control system (i.e., tilting system) to reduce the drag forces and stresses on the foundations. Analogously, the trim of eSail is similarly changed when the ship enters into port or passes below bridge, for safety reasons.

Overall, detailed information regarding reliability and maintainability of all the control and actuation systems mentioned above (i.e., suction fan, flap and yaw actuation, tilting mechanism) shall be provided, to ensure compliance with safety regulations. Specifically, evidence that safety is guaranteed must be provided in case of possible failure of control and actuation systems or components (e.g., gears, bearing, electric motors, etc). In this case, the worst possible conditions for multiple failures and extreme weather conditions should be accounted for to verify structural integrity of all the eSail parts (flap, fan, wing,…) as well as foundations.

7.5.1 Design procedure and requirements

The design process of WAPS needs to account for the weather conditions statistically present on the ship route, humidity, dust, salt-bearing air, hot exhaust gases from prime movers possibly impacting on it, vibrations generated by wind and those originally present in the deck. Details on the environmental conditions to be considered during WAPS design can be found in RINA Rules Part C, Ch 1, Sec 1, whereas auxiliary machinery, electrical installations and piping are to be set up according to RINA Rules Pt C, Ch 1; Pt C, Ch 2, Sec 1, 3, 12 and Pt C, Ch 1, Sec 10, respectively.

Where the structural design is concerned, all the forces and moments acting on the WAPS both in operation and when generating no auxiliary propulsion power (i.e., in port mode or in extreme weather conditions) must be accounted for to guarantee safe conditions.

Overall, loads applied to the structure of WAPS may be divided into two classes:

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- regular service loads, i.e. aerodynamic forces and moments acting on the WAPS during normal wind operating conditions and supporting vessel propulsion. These constitute the design loads and the maximum wind speed allowed in normal operation should be defined at design stage. Furthermore, technical evidence that aerodynamic relations used to evaluate lift and drag forces (and corresponding structural loads) are pertinent to the particular type of WAPS considered is required. The effects of wind gusts dealing with higher magnitude (e.g., 25%) with respect to the maximum wind speed allowed in normal operation are to be taken into account. Overall, aerodynamic forces generated by wind on the WAPS can be computed as prescribed in MEPC.1/Circ.896 "2021 Guidance on treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI and EEXI" and MSC.1/Circ.1200 "Interim Guidelines for Alternative Assessment of the Weather Criterion". On the other hand, inertia loads generated on the WAPS by means of acceleration related to ship motions or other applicable loads related to specific vessels must be accounted for additionally. In particular, acceleration loads due to the ship motion in the longitudinal, vertical and transversal directions shall be assessed according to RINA Rules Part B, Ch 5, Sec 3 and applicable navigation notation according to RINA Rules Part A, Ch 1, Sec 2, [5].
- extreme loads: loads acting on the WAPS during extremely adverse weather conditions and exceeding the regular ones. In case of extreme weather conditions, reliable mechanism for the shutdown of the WAPS is to be enabled to prevent unnecessary or possibly dangerous strains. Possible solutions include tilting systems (as eSail has) or folding/unfolding mechanisms, whose reliability is to be demonstrated. Thus, extreme wind loads occur when the WAPS system is out of service and are to be computed based on the wing height and maximum true wind speed, i.e. wind speed beyond which structural damage may be achieved. When the WAPS is out of service, the wind load consists of only drag force, significantly depending on the shape of the sail. Increase in pressure forces on WAPS caused by spray water may be additionally considered as extreme loads. Finally, weights caused by snow and ice accretion on the WAPS may be eventually accounted for, depending on the vessel operating conditions targeted by the shipowner (see the RINA "Rules for Loading and Unloading Arrangements and for other Lifting Appliances on Board Ships", Ch 6 for more information).

Combinations of the WAPS loads reported above should be considered cautiously.

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Overall, evidence on compliance of the structural stresses with the permissible ones is required, depending on the materials (steels or aluminum alloys) adopted by the Manufacturer for the WAPS. In detail, the structural analyses listed below need to be carried out:

- Structural stresses: structural stresses caused by single load type and relevant load combinations are to be assessed, paying attention that both global and local (stress concentration) levels do not exceed permissible ones.
- Stability: buckling analysis is to be conducted according to well-established calculation methods, i.e. geometrically nonlinear Finite Element Analysis (FEA).
- Fatigue: fatigue analysis is necessary to ensure that vibrations pertaining to WAPS do not compromise structural strength of the base plate or auxiliary systems used for control purposes. Additionally, frequency resonance of the WAPS must be avoided to preserve its integrity and ship safety. The main excitation sources of vibration for the WAPS are:
    - ship induced sources: propulsion systems, hydraulic or electric energy production equipment, equipment related to WAPS (e.g., fan,…).
    - external sources: instantaneous variations of wind speed, induced vibratory phenomena caused by the release of the von Karman vortex street, sea effects on the ship motion.

Further information on the strength verifications required for the main components of the WAPS is available in the RINA “Rules for Loading and Unloading Arrangements and for other Lifting Appliances on Board Ships”, Ch 14 (e.g., welded connections refer to [2.2.5]), whereas the properties of the steel or aluminum materials used in the construction of WAPS components (e.g. masts, booms, wings, rotors) shall follow the requirements available in RINA Rules Part B, Ch 4, Sec 1.

Multiple WAPSs can be installed onboard a ship, in order to generate more thrust. However, each WAPS forms a wake, i.e. a flow region characterized by low wind speed and high turbulence, which may impact on other sails positioned downstream. This wake effect determines a reduction of aerodynamic forces exchanged by downstream WAPSs with the wind and, consequently, a negative effect on the thrust generated.

Thus, if components are arranged in such a way that they shelter one another, the effect of wind load reductions on areas arranged one behind another is to be represented by sheltering coefficient, since overall thrust does not simply coincide with multiplication of single WAPS thrust.

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Additional relevant points for the safety assessment and regulation compliance of the WAPS are listed in the following:

- Intact stability: the resultant aerodynamic force acting on the center of pressure is characterized by non-null side force, which in turn generates heeling moment on the vessel. Therefore, intact stability of the vessel must be guaranteed also in case permanent heel is provided by the WAPS, according to the RINA Rules Pt B, Ch 3, Sec 2 and IMO Resolution A.562(14) "Recommendation on a severe wind and rolling criterion (Weather Criterion) for the intact stability of passenger and cargo ships of 24 meters in length and over". Specifically, the ability of the ship to withstand the combined effects of beam wind

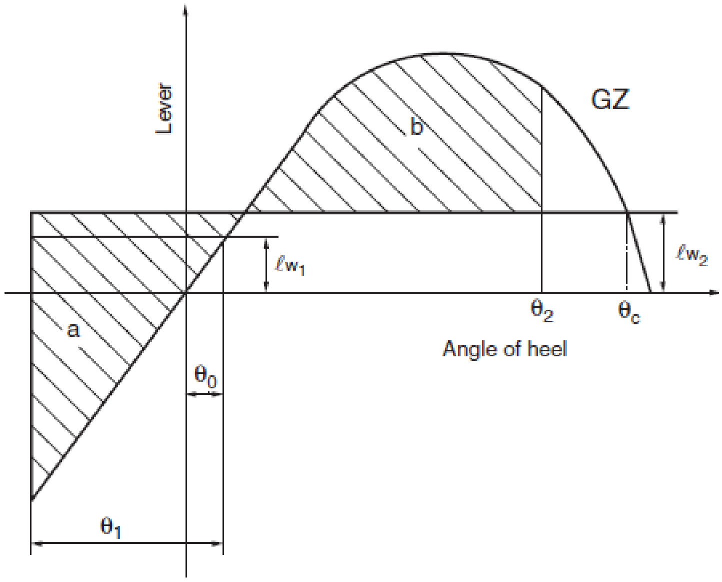

Figure 7.13: Severe wind and rolling criterion for intact stability verification [14].

and rolling is to be demonstrated for each loading condition by assessing the severe wind and rolling criterion, as shown in Figure 7.13.

Where l_{w1} is the heeling lever caused by steady lateral wind (i.e. whose direction is orthogonal to the ship centerline), l_{w2} is gust wind heeling lever (i.e., additional heeling lever caused by gust wind), θ_0 is the resultant angle of equilibrium, θ_1 is the angle of roll to windward due to waves, θ_2 is the angle of down flooding. The angle θ_2 can be evaluated in three distinct ways:

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- $\theta_2 = \theta_f$ with θ_f being the heeling angle provoking the immersion of openings in the hull, superstructures or deckhouses. In this case, small openings which are unable to cause progressive flooding should be neglected.
- $\theta_2 = \theta_c$, with θ_c being the angle corresponding to the second intercept of the gust wind heeling lever l_{w2} and the GZ curve.
- $\theta_2 = 50°$

Under these circumstances (i.e., combined effects of beam wind and rolling), the angle of heel θ_0 shall not exceed the minimum values between 16° or 80% of the angle of deck edge immersion and, in addition, the area inequality $b \geq a$ shall be valid.

The wind heeling levers l_{w1} and l_{w2} remain constant independently from the ship angle of inclination and are computed as (see Part A, Sec 2.3 of the International Code on Intact Stability, 2008, for more details):

$$l_{w1} = \frac{PAZ}{1000g\Delta} \tag{1}$$

$$l_{w2} = 1.5\, l_{w1} \tag{2}$$

Where $P = 504\ N/m^2$ (lower values for P can be imposed by Class for ships with restricted navigation notation), A is the projected lateral area of the vessel above the waterline, Z the distance between the center of A and the center of the underwater lateral area (or, alternatively, a point at one half the mean draught), Δ is ship displacement and g is the gravitational acceleration of $9.81\ m/s^2$. It must be remarked that the contribution of WAPSs to the heeling lever should be accounted for into l_{w1}. Nevertheless, Class Society may provide specific corrections of the eq. (1) reported above to explicitly include WAPS contribution to l_{w1} (e.g., by means of correction coefficients).

Alternative methods to compute the wind heeling lever may be eventually used, subjected to the approval of the Classification Society.

- Maneuverability: as a direct consequence of the aforementioned point on intact stability, WAPS can positively or negatively contribute to ship maneuverability. For this reason, documentation proving that WAPS installation onboard does not compromise maneuverability is requested and maneuvering characteristics of WAPSs are to be included into the operational manual. Specifically, the rudders, appendages and main propulsion

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systems need to counteract all WAPS effects on sailing and maneuvering conditions. Acceptable level of maneuverability is to be demonstrated by sea trials and evidence that the anchoring arrangements of the vessel are adequate is to be proved.

- Obstruction view: since WAPSs usually deal with large surfaces, they may obstruct view from the navigation deck. On this point, relevant IMO and national regulations shall be considered.
- Structural strength of foundations: the WAPS foundation aims at transferring the wind forces generated on the sails to the supporting ship structure. Therefore, foundations shall provide sufficient structural strength under all the possible operating conditions, in presence of static and dynamic loads. Towards this end, deck structure is to be reinforced and stiffened locally to ensure adequate resistance to plate buckling. The foundations of the WAPS on the outer hull plating or other relevant connections are to comply with the requirements of RINA Rules Part B, Ch.7, taking also into account the local and hull girder loads described in RINA Rules Part B, Ch 5.

Finally, the WAPSs shall enable cargo handling and sufficient bridge clearance without any physical interference. Towards this end, tilting systems or alternative mechanisms for folding sails or reducing wing surface shall be included and their reliability is to be assessed. Hydraulic systems used for WAPS element actuation are required to comply with RINA Rules Pt C, Ch 1, Sec 10 and Pt C, Ch 1, Sec 3.

In general, where design and construction of WAPS are concerned, the following documentation needs to be submitted for approval:

- Description of operating principle and limitations (e.g., wind speed and sea state)
- Regular and extreme load calculations
- General arrangement of WAPS installation onboard
- Conceptual design documentation
- Engineering design documentation including Finite Element Analyses, resonance and buckling analyses
- Risk and safety assessment. Risk assessment is necessary to ensure that the risks arising from the use of WAPS and potentially affecting persons, environment, structural strength or the integrity of the ship are addressed. Generally, aspects to be accounted for in the risk assessment are severe weather conditions (storm, snow, ice), overspeed and overload,

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vibrations and resonance, control system failure, component failure, fire, human error,… Particularly, FMEA analysis may be required by the Classification Society to deeply investigate the WAPS effects on ship maneuverability. The assumptions underlying the risk assessment are to be agreed by a team of experts including a representative of Class, Flag Administration, owner, builder or designer and consultants.

- Operational manual. Specifically, instructions enabling the safe and reliable handling of WAPS should be included, with specific attention focused on operational range and constraints.
- WAPS specifications (i.e. sizes, weights, center of gravity, center of pressure, materials). Particularly, details on components and equipment (e.g., bearings) are necessary.
- Detailed design drawings of parts being relevant by structural and safety points of view. Specifically, details on each wingsail foundation (drawings, welding, position,…) and its integration with the deck as well as below structures are necessary.
- Report on loads including definitions, aerodynamic loads, inertia loads,…
- Detailed description of the driving unit integration onboard, together with its interfaces with the power supply as well as other ship systems
- Drawings and specifications of the electrical engine unit as well as details on any hydraulic actuating mechanisms (e.g., pipe design pressure, inner and outer diameters, thickness, material, design and working temperature, etc.)
- Electrical and/or hydraulic circuit diagrams
- Description and specifications of control systems, including their arrangement and, possibly, redundancy
- Documentation on the user interface is additionally required
- Driving unit shut down system description for emergency conditions
- In case no automated solutions for WAPS control are present, information on the crew training courses ensuring safe ship operation is necessary
- Maintenance information for all the WAPS systems (mechanical, electrical, hydraulic,…)
- Report on Harbour Acceptance Test (HAT)
- Report on sea trials

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Further documentation may be requested by Classification society as supporting evidence of compliance with standards, functional specifications as well as safety requirements.

Where integration onboard is concerned, evidence that the wingsail have no adverse effects on ship essential services (i.e., propulsion and safety) as well as on crew health during normal operation and in the event of a WAPS failure shall be provided. By a classification point of view, WAPSs are considered not essential for the safe operation of the ship, i.e. sufficient propulsion power can be supplied by conventional power generating set in case of wingsail failure. In other words, the WAPS installation is considered as an auxiliary propulsion system, hence the vessel shall be fully operable with main propulsion equipment only. Nevertheless, safety considerations associated with the WAPS installation and operation onboard require detailed investigation through risk assessment. In particular, it must be underlined here that if WAPS tilting system results from the risk assessment essential for ensuring vessel safe operation under the worst scenario, redundancy should be adopted for both hydraulic control systems and motors. Additionally, the interfaces between the wingsail and the ship shall be reviewed and accepted by the Classification Society, including the connection to the deck, the electrical power supply, electrical control circuits and any other connection (e.g., hydraulic circuits). E.g., all the structural parts of WAPS exposed to the atmosphere need to be protected against corrosion by means of coatings or alternative protective measures (e.g. corrosion addition), according to RINA Rules Part B, Ch 10, Sec 4, [3.1.3]. Similarly, evidence will be required to ensure that the vessel has appropriate stability and maneuverability when the WAPS is integrated onboard and that propulsion machinery is capable of operating in all conditions of heel and trim which may result from the WAPS operation. Furthermore, the suitability of WAPSs to hazardous areas and explosive atmospheres is to be assessed carefully for specific types of vessel (e.g., tanker ships).

Overall, further details on the requirements for vessels equipped with WAPS will be available into specific RINA Rules, which will be published in the next future.

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8 Concluding remarks and future perspectives on ZHENIT technologies

In the previous sections, the inventory of Rules and Regulations applicable to novel technologies developed in the ZHENIT project has been presented to guide the design, from the concept to the engineering phases, in a system-by-system approach. In addition, an overview of the certifications required for approval by Class Societies has been provided. Generally, each novel technology investigated in ZHENIT appears to possibly contribute to the reduction of environmental impact of the waterborne transport.

However, despite some general information concerning the integration onboard and possible challenges arising from it has been included, it must be underlined that the impact of novel technologies on the actual ships on which they are planned to be installed is missing here, since it requires a case-by-case approach. Indeed, a tailored assessment of the impact of new technologies when installed onboard should be carried out carefully and independently for each specific vessel, aiming at guaranteeing compliance with the statutory aspects (IMO) to be verified directly by the Flag Administration or, in replacement, by a RO appointed by it.

Examples of codes regulating statutory aspects are the International Convention for the Safety of Life at Sea (SOLAS), the International Convention for the Prevention of Pollution from Ships (MARPOL), Seafarers' Training, Certification and Watchkeeping (STCW) code, High-Speed Craft (HSC) code, … whose validity and restrictions depend on the type and size of vessel considered. E.g., it should be recalled here that the statutory requirements for safety are more stringent and detailed for passenger ships, thus making the assessment even more complicated.

In general, by adopting a compartment or space-by-space based approach, statutory aspects concerning safety include the following points, but not limited to:

- identify candidate positions to set up the novel systems, taking into account the general layout of the ship, its services (including those required by the new technology) and possible interferences
- classify spaces according to their criticality for safety, i.e. based on which systems and services are contained and/or pass through them. Specifically, this point should consider the arrangement of compartments limited by watertight or "A" class boundaries as well as location of active/passive fire protection systems

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- evaluate the existence of possible constraints and requirements for the arrangement and operation of systems used for fire/flooding detection, system monitoring and safety
- define ventilation requirements for spaces where novel technologies are installed onboard and evaluate the impact of ventilation duct routing as well as inlet/outlet locations on the general layout of the ship
- assess the level of automation and remote-control functionality required for governing novel technologies and ensuring their safe operation
- guarantee safe access to components or equipment requiring manual actions for restoration or maintenance
- verify power supply to the novel technologies and routing of related cables
- assess protections, piping systems of sea chest, valves, provision for shut down/start, air vents and air intakes necessary to ensure both safe and correct operation of the systems
- suggest training programs for seafarers aimed at increasing competence on novel systems

More details on statutory aspects concerning safety are available in the SOLAS convention.

In conclusion, since the verification of compliance with all the statutory aspects requires a detailed analysis and is different for each vessel considered, it cannot be reported exhaustively in this deliverable. However, it must be assessed very carefully on a case-by-case basis by the Flag Administration or RO appointed by it.

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