# MARANDA – Marine application of a new fuel cell powertrain validated in demanding arctic conditions
# Grant agreement no: 735717

# D2.4 Preliminary safety analysis for integrated fuel cell system and hydrogen storage

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**Summary**

In the MARANDA EU project, a 165 kW (AC) power scale proton exchange membrane (PEM) fuel cell (FC) system is installed on-board the Aranda naval research vessel. Attached to the fuel cell system there will be a hydrogen (H2) fuel storage (350 bar) and dispensing system.

The IGF Code entered into force in the beginning of 2017, and it is mandatory for ships fueled by gases or other low-flashpoint fuels. The current version of the IGF Code includes detailed regulations to meet the functional requirements only for natural gas as fuel and internal combustion engine as fuel consumer.

Until regulations for other low-flashpoint fuels will be added to the IGF Code, compliance with the functional requirements of the IGF Code must be demonstrated through alternative design. The main principle of the alternative design is that design solution deviating from prescriptive regulations/rules may be approved provided it is demonstrated to be at least as effective and safe as that required by the regulations.

Risk assessment is an essential part of alternative design procedure and its approval. This deliverable introduces the set requirements and existing guidelines for risk assessment concerning use of fuel cell and hydrogen systems in marine use. Plan for preliminary risk analysis and risk assessment for research vessel Aranda's fuel cell system is presented.

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## Contents

# 1. Introduction

In the MARANDA EU project, a 165 kW (AC) power scale proton exchange membrane (PEM) fuel cell (FC) system is installed on-board the Aranda naval research vessel. Attached to the fuel cell system there will be a hydrogen ($H_2$) fuel storage (350 bar) and dispensing system. Together these systems will comprise a complete hydrogen-fueled PEMFC power plant, which can supply power to the Aranda electricity system, for example during research operation when minimal emissions and vibration levels on the ship are desired to guarantee measurement quality.

Both of the subsystems - the PEMFC system and the $H_2$ storage system - are installed in 10-foot sea containers, attached on the deck of Aranda. The $H_2$ storage system can be detached from the fuel cell system as well as from the ship, and be lifted to/from shore by using Aranda's own lift crane. The purpose is to enable re-filling of the $H_2$ storage in a maximal variety of locations and in particular, at standard 350 bar automotive hydrogen refueling stations (HRS).

As Aranda is an ice-going vessel, the ship and the fuel cell plant on-board will be subject to the harshest marine and winter conditions during its operation. Whatever the conditions, the safety of the equipment and especially the personnel (and other people) on-board must be guaranteed at all times. To this end, dedicated safety considerations, abiding to the normal sea-going vessel design and classification processes shall be undertaken. Furthermore, as part of the classification process of the Aranda ship, also the fuel cell plant shall be put into class by the class authority DNV GL.

Because the MARANDA fuel cell plant is not a critical/single power source of the Aranda vessel, the requirements for operative reliability - typically a substantial part of marine power system safety - may be relaxed. Nevertheless, as the fuel cell system and the hydrogen fuel storage are systems containing highly flammable hydrogen gas, particular safety procedures must be followed in the design and construction of these systems.

# 2. Requirements and approval procedure for integrated fuel cell system and hydrogen storage on-board a ship

## 2.1 IMO Conventions and Codes

### 2.1.1 SOLAS Convention

International Convention for the Safety of Life at Sea (SOLAS) is the most important of all international treaties concerning the safety of merchant ships. The Convention in force today is referred to as SOLAS (1974), as amended. The main objective of the SOLAS Convention is to specify minimum standards for the construction, equipment and operation of ships, compatible with their safety.

SOLAS (1974) contains prescriptive requirements concerning e.g. structure, subdivision and stability, machinery and electrical installations (Chapter II-1), fire protection, fire detection and fire extinction (Chapter II-2), life-saving appliances and arrangements (Chapter III). Flag States are responsible for ensuring that ships under their flag comply with its requirements.

### 2.1.2 International Code of safety for ships using gases or other low-flashpoint fuels (IGF Code)

The IGF Code was adopted in 2015 and it entered into force 1 January 2017. It is mandatory for ships fueled by gases or other low-flashpoint fuels under the International Convention for the Safety of Life at Sea, SOLAS (IMO 2015 a). The purpose of the IGF Code is to provide an international standard for ships using low-flashpoint fuel, other than ships covered by the IGC Code (Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk).

The goal of the IGF Code (IMO 2015 b) is to provide for safe and environmentally friendly design, construction and operation of ships and in particular, their installations of systems for propulsion machinery, auxiliary power generation machinery and/or other purpose machinery using gas or low-flashpoint fuel as fuel.

**The functional requirements** that all ships using gases or other low-flashpoint fuels must meet are described in Chapter 3 of the IGF Code:

1. The safety, reliability and dependability of the systems shall be equivalent to that achieved with new and comparable conventional oil-fueled main and auxiliary machinery.
2. The probability and consequences of fuel-related hazards shall be limited to a minimum through arrangement and system design, such as ventilation, detection and safety actions. In the event of gas leakage or failure of the risk reducing measures, necessary safety actions shall be initiated.
3. The design philosophy shall ensure that risk reducing measures and safety actions for the gas fuel installation do not lead to an unacceptable loss of power.
4. Hazardous areas shall be restricted, as far as practicable, to minimize the potential risks that might affect the safety of the ship, persons on board, and equipment.
5. Equipment installed in hazardous areas shall be minimized to that required for operational purposes and shall be certified suitably and appropriately.
6. Unintended accumulation of explosive, flammable or toxic gas concentrations shall be prevented.
7. System components shall be protected against external damages.
8. Sources of ignition in hazardous areas shall be minimized to reduce the probability of explosions.

Requirements for **limitation of explosion consequences** concern also all low-flashpoint fuels. According to them, an explosion in any space containing any potential sources of release and potential ignition sources shall not:

1. cause damage to or disrupt the proper functioning of equipment/systems located in any space other than that in which the incident occurs;
2. damage the ship in such a way that flooding of water below the main deck or any progressive flooding occur;
3. damage work areas or accommodation in such a way that persons who stay in such areas under normal operating conditions are injured;
4. disrupt the proper functioning of control stations and switchboard rooms necessary for power distribution;
5. damage life-saving equipment or associated launching arrangements;

6. disrupt the proper functioning of firefighting equipment located outside the explosion-damaged space;
7. affect other areas of the ship in such a way that chain reactions involving, inter alia, cargo, gas and bunker oil may arise; or
8. prevent persons' access to life-saving appliances or impede escape routes.

The current version of the IGF Code includes detailed regulations to meet the functional requirements only for natural gas fuel. Regulations for other low-flashpoint fuels will be added to the IGF Code as the International Maritime Organization (IMO) develops them. In the meantime, for other low-flashpoint fuels, compliance with the functional requirements of the IGF Code must be demonstrated through alternative design.

## 2.2 Alternative design and arrangements

Traditional prescriptive regulatory approach, based on experience, is not adapted to breakthrough innovations. That is why SOLAS regulations II-1/55 and III/38 concerning alternative design were adopted in 2006.

Alternative design and arrangements mean measures, which deviate from the prescriptive requirement(s) of SOLAS chapters II-1 or III, but are suitable to satisfy the intent of that chapter. The term includes a wide range of measures, including alternative shipboard structures and systems based on novel or unique designs, as well as traditional shipboard structures and systems that are installed in alternative arrangements or configurations. (IMO 2006).

The main principle is that design solution deviating from prescriptive regulations/rules may be approved provided it is demonstrated to be at least as effective and safe as that required by the regulations. The approval of an equivalent design is in the hands of the Flag State and the approval should be reported to IMO by the approval authority.

### 2.2.1 IMO guidelines for alternative design

In many IMO conventions, there are provisions for acceptance of alternatives and/or equivalents to prescriptive requirements in many areas of ship design and construction. In this context, IMO has issued guidelines e.g.

- Guidelines on alternative design and arrangements for fire safety (MSC/Circ.1002, 2001)
- Guidelines on alternative design and arrangements for SOLAS chapters II-1 and III (MSC.1/Circ.1212, 2006).

These Guidelines are intended for application of fire safety engineering design and safe engineering design to provide technical justification for alternative design and arrangements. The Guidelines are not intended to serve as a stand-alone document, but should be used in conjunction with the appropriate engineering design guides and other literature.

According to the Guidelines MSC.1/Circ.1212 the engineering analysis used to show that the alternative design and arrangements provide the equivalent level of safety to the prescriptive requirements of SOLAS chapters II-1, II-2 and III should follow an established approach to safety design. This approach should be based on sound science and engineering practice incorporating widely accepted methods, empirical data, calculations, correlations and computer models as contained in engineering textbooks and technical literature.

In 2013, the Maritime Safety Committee approved the *Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments (MSC.1/Circ. 1455, 2013).* The Guidelines provide a consistent process (figure 1) for the coordination, review and approval of alternatives and equivalents with regard to ship and system design as allowed by the SOLAS Convention and other mandatory IMO instruments.

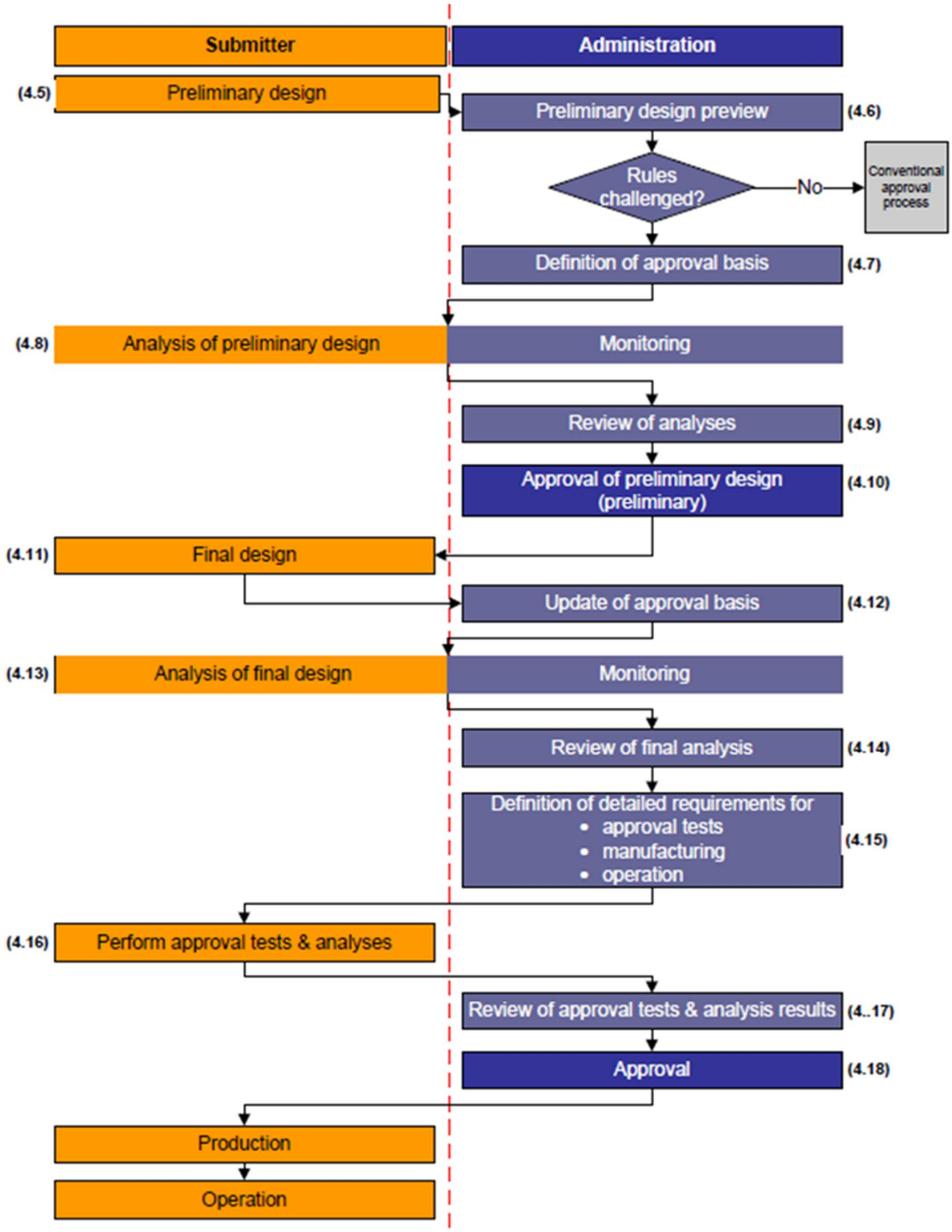



*Figure 1. Process for alternative design approval according to MSC.1/Circ. 1455 (IMO 2013a). (Numbers in figure refer to chapters in MSC.1/Circ. 1455)*

The Guidelines MSC.1/Circ. 1455 are intended for use of both Administrations and Submitters when dealing with an approval request for an alternative and/or equivalent design. The process in figure 1 describes the procedure for obtaining and maintaining approval of an alternative and/or equivalency taking into account the Submitter and the Administration.

The details performed in each phase of the process may vary on a case-by-case basis depending on the design being considered. However, the basic process should be generally applicable to the approval of most alternatives and/or equivalencies. Guidelines MSC.1/Circ. 1455 contain detailed instructions for each phase of the process.

### 2.2.2 Other guidelines for IGF Code and alternative design

In addition to IMO, also other organisations like Classification Societies have published rules and guidelines for fuel cells, IGF Code and alternative design and arrangements e.g. ABS (2010), DNVGL (2017), GL (2009), IACS (2016), Lloyd's Register (2016) and Lloyd's Register (2017).

# 3. Preliminary design of research vessel Aranda's fuel cell and hydrogen storage system

Preliminary design of the fuel cell and hydrogen subsystems, including their process diagrams are presented in *Deliverable 2.1 Specification report*. This preliminary design will be updated and modified based on the findings of the systems' safety evaluation work.

The complete fuel cell plant is structurally divided into two modules: the fuel cell system module and the hydrogen storage and dispensing system module. These modules are installed in modified sea containers, one dedicated per module. Those two containers will be placed on Aranda's deck (Figure 2).

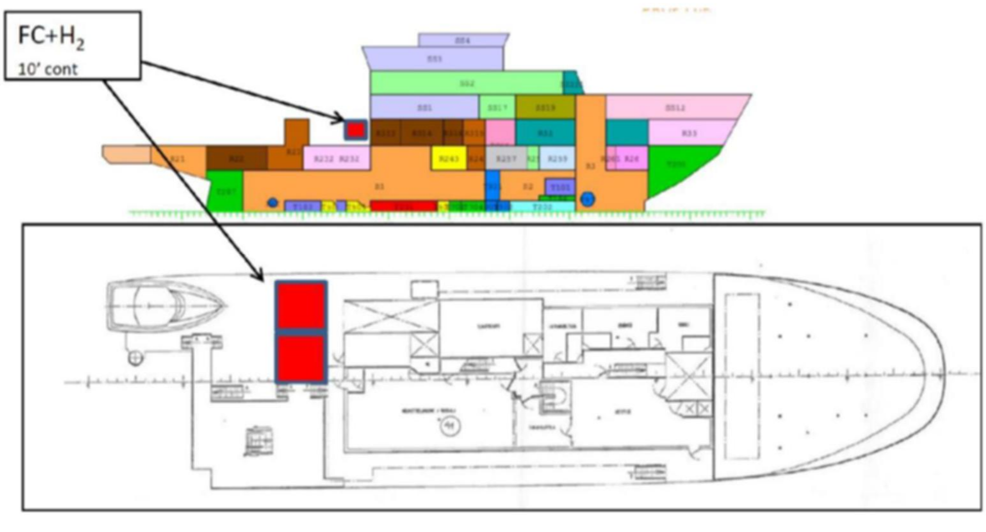



*Figure 2. Planned fuel cell and hydrogen storage installation on the deck of Aranda (after overhaul).*

For the fuel cell system and the hydrogen storage and dispensing system, the containers will be modified:

- Fire and hydrogen safety mechanisms are integrated into the containers.
- Air inlet and outlet ports for the FC system and container ventilation are made.

- Fire-insulated through-holes for hydrogen and data signal passage between the containers are made
- Necessary utility power inlet ports are included in both containers.

The general safety philosophy of the fuel cell system as well as the hydrogen storage follows an emergency shutdown (ESD) approach meaning the system is fully powered off if hydrogen is detected elsewhere than where it is supposed to be. This is feasible, because the FC plant is not an operationally critical power source of the Aranda vessel.

During its operation, the fuel cell system is ventilated to ensure hydrogen concentration remains within safe limits even in case of leakage. Hydrogen concentration of the air is continuously monitored in the ventilated fuel cell space as well as in the ventilation air duct. When not in operation, the fuel cell system is always purged of hydrogen gas. Therefore, the fuel cell system is considered a safe zone when not in operation (hazardous zone 1 when in operation).

The hydrogen storage system is always considered hazardous zone 1 and continuous ATEX-rated, redundant ventilation and hydrogen monitoring are therefore applied to this part. In addition, explosion relief hatches for controlled impact direction in case of pressure build up or even explosion are installed to the hydrogen storage module container.

On behalf of safety regarding fire outside the containers, A60 level fire insulation is installed where necessary. Furthermore, thermally activated pressure relief devices (TPRDs) are included in the hydrogen storage system to assure a controlled hydrogen release in the case of long-enduring fire. For the case of fire inside systems, the amount of flammable material is kept to minimum. Smoke detectors, fire dampers at ventilation air inlets and a fire extinction system are included in the fuel cell system as well as the hydrogen storage system.

# 4. Alternative design and approval process for Aranda’s fuel cell plant and hydrogen storage

As the amendment to the IGF Code regarding fuel cells is not yet approved, the compliance of Aranda’s fuel cell system with the functional requirements of the IGF Code must be demonstrated through alternative design (see chapter 2). The approval procedure for the alternative design is presented in chapter 2.2 figure 1 (IMO 2013 a).

Based on this, a plan for alternative design and approval process for Aranda’s fuel cell system and $H_2$ storage is developed (see figure 3). Submitter is Finnish Environment Institute (SYKE), who owns research vessel Aranda and Administration is Finnish Transport Safety Agency (Trafi). In addition, DNVGL is involved because it will do the classification of Aranda.

According to the timeline in figure 3, the preliminary design of the Aranda fuel cell system has been finalized and the preliminary design description including general structure of the fuel cell system and $H_2$ storage (Deliverable 2.1 Specification report) has been submitted to Finnish Transport Safety Agency (Trafi) in June 2017. Trafi authorities previewed the preliminary design of the fuel cell system and the decision to apply alternative design procedure was made in a meeting arranged June 27. 2017.

Plan for the preliminary risk analysis of Aranda´s fuel cell system and hydrogen storage is in Chapter 5. This Deliverable deals only with the preliminary design phase and related risk analyses, which shall be conducted before the preliminary approval.

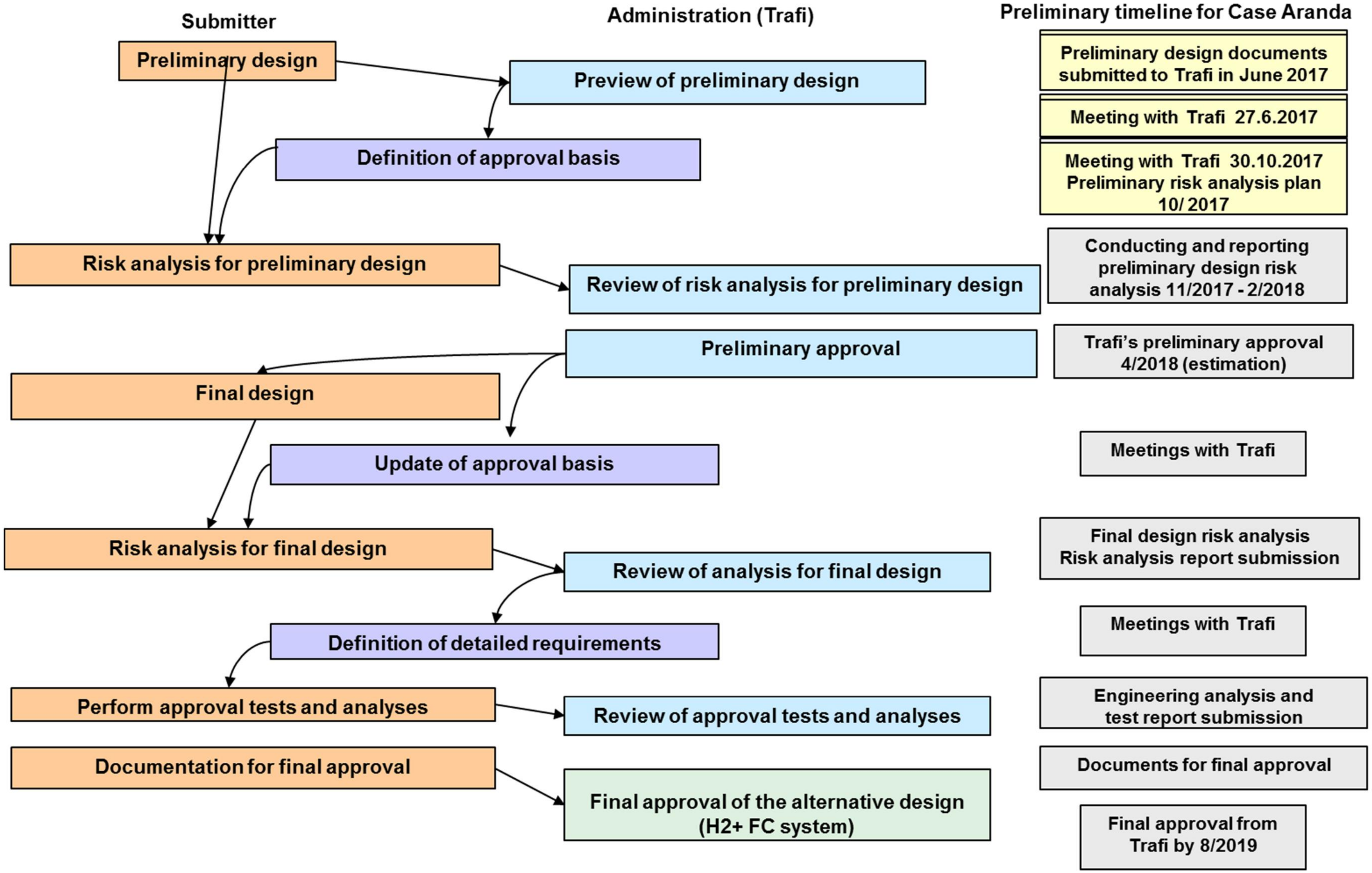



*Figure 3. Plan for alternative design and approval process for Aranda's fuel cell system and H2 storage.*

# 5. Plan for preliminary risk analysis and assessment

## 5.1 Definition of the approval basis

According to *Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments* (IMO 2013 a) the phase following the preliminary design preview is definition of the approval basis. The Submitter and the Administration will agree on the approval basis and on the evaluation criteria.

The approval basis was discussed in the end of October 2017. Participants from Finnish Environment Institute (SYKE), VTT, Finnish Transport Safety Agency (Trafi) and DNVGL took part this meeting.

## 5.2 Steps for preliminary risk analysis and assessment

IMO guidelines (IMO 2006, IMO 2013 a) contain general requirements and procedures for preliminary risk analysis. The steps defined are 1) identification of hazards 2) enumeration of hazards 3) selection of hazards for more detailed analysis 4) specification of design accident/casualty scenarios.

IACS (International Association of Classification Societies) produces recommendations and guidelines related to adopted resolutions that are not necessarily matters of class but which IACS considers would be helpful to offer some advice to the marine industry. One of those recommendations is *"Recommendation 146 Risk assessment as required by the IGF Code"* (IACS 2016). This recommendation complies with the general requirements of the IMO guidelines. IACS Recommendation 146 will be used as basis for Aranda's risk assessment as this recommendation is specifically intended to be used in risk assessment required by the IGF Code.

### 5.2.1 Hazard identification

The aim is systematically identify unwanted events that could result in, for example, major injuries or fatality, damage to the environment, and/or loss of structural strength or integrity of the ship. For Aranda's hazard identification, the entirety of the fuel cell power plant will be divided to appropriate parts. Apparent parts would be the fuel cell system module and the hydrogen storage and dispensing system module. All conceivable and relevant hazards of those modules shall be identified.

Hazard identification will be done in a structured brainstorming with the purpose of identifying all relevant hazards, their causes, possible consequences and mitigating measures already included in the design. The identification work should be done with an open mind and the people taking part in it should have expertise in various fields (fuel cells, chemicals, materials, consequences of leaks, flammability risks etc.). There are guidewords and check-list, which can be used to help hazard identification (IMO 2006, IACS 2016). The results of the identification phase shall be documented.

Hazard identification session or sessions will take place in November-December 2017.

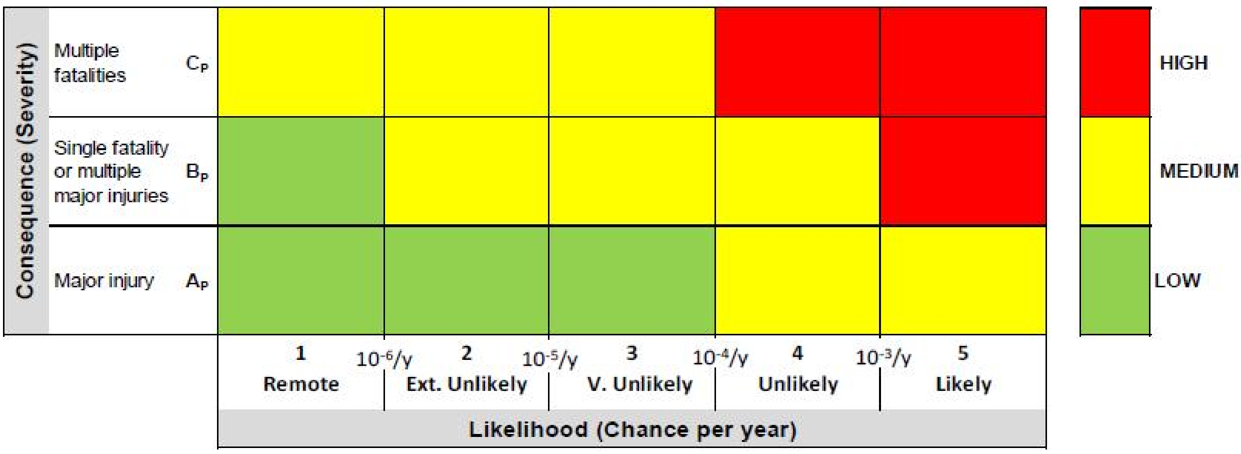
### 5.2.2 Consequence and likelihood analyses

For each identified cause and following hazard, an estimation of potential consequences shall be made. The harmful consequences can be, for example, major injuries, single and multiple fatalities, adverse environmental impact and damage sufficient to compromise safe operations. The risk analysis team can estimate the potential consequences by using judgement and reference to: (a) the fuel's properties/hazards; (b) the release location; (c) dispersion/leak pathways; (d) location and 'strength' of ignition sources; (e) proximity of vulnerable receptors; (f) generic or (if commissioned) specific fire and explosion modelling; and (f) expected effectiveness of existing/planned mitigation measures.

In addition, to estimating the potential consequences also the likelihood of occurrence of 'cause and consequence' shall be estimated. Likelihood can be estimated by the risk analysis team for each 'cause-consequence' pair or a grouping of causes with the same consequence. The estimation can be informed by reference to accident and near-miss reports, accident and equipment release data, analogy to accidents in similar or other industries and consideration of the reliability and effectiveness of mitigation measures.

It is not always apparent if the likelihood of a 'cause-consequence' combination is credible (i.e. reasonably foreseeable). There are guidelines, for example, in IACS Recommendation 146 how to evaluate if an unwanted event may be considered credible or not.

Both the potential consequences and the likelihood estimates of certain 'cause-consequence' combination can be categorised in a risk matrix. One example of the risk matrix for persons on board is given in figure 4 (IACS 2016).




**Consequence Category Examples**

$A_P$ Major injury - *long-term disability / health effect*
$B_P$ Single fatality or multiple major injuries - *one death or multiple individuals suffering long-term disability / health effects*
$C_P$ Multiple fatalities - *two or more deaths*

**Likelihood Category Examples**

1. Remote - *1 in a million or less per year*
2. Extremely Unlikely - *between 1 in a million and 1 in 100,000 per year*
3. Very Unlikely - *between 1 in 100,000 and 1 in 10,000 per year*
4. Unlikely - *between 1 in 10,000 and 1 in 1,000 per year*
5. Likely - *between 1 in 1,000 and 1 in 100 per year*

The likelihood categories can be related to a ship life. For example, assuming a ship lifetime is 25 years, then for a scenario with an annual likelihood of 1 in a million (i.e. rating 1 Remote) the probability of occurrence in the ship's lifetime is 1 in 40,000 (i.e. $1/(10^{-6} \times 25)$).

*Figure 4. Example of risk matrix concerning persons on board (IACS 2016).*

Prioritization of risks as well as measures and tolerability of risks is also discussed in IMO's *"Revised guidelines for formal safety assessment"* (IMO 2013 b). Proper way to define the consequence and likelihood categories will be discussed with the authority. Whatever the categorisation system will be, it is done by the same team as hazard identification.

### 5.2.3 Risk analysis and assessment

Risk can be estimated by combining the consequence and likelihood categories to provide a risk rating. For example in figure 4, if a 'cause-consequence' pair is categorised as, say '$A_p$', and associated 'likelihood' as, say '1', then the risk rating is '$A_p$1'.

The estimated risk can be compared against risk criteria embedded within a risk matrix. The matrix shows the risk rating (with respects to consequence and likelihood) and the criteria illustrate whether the risk has been 'mitigated as necessary'. The ratings have been defined (IACS 2016).

Green - Low Risk: The risk can be accepted as 'mitigated as necessary'. Where practical and cost-effective good practice is to implement mitigation measures that would further reduce the risk.

Yellow - Medium Risk: The risk is tolerable and considered 'mitigated as necessary'. This assumes that all reasonably practicable mitigation measures have been implemented. That is, additional or alternative mitigation measures have been identified and implemented unless judged impractical or the cost of implementation would be disproportionate to the reduction in risk.

Red - High Risk: The risk is unacceptable and is not 'mitigated as necessary'. Additional or alternative mitigation measures must be identified and implemented before operation, and these must reduce the risk to medium or low.

There are no universally agreed risk rating schemes or risk criteria: there are differences between governments, regulators and organisations. Therefore, prior to the commencement of the risk assessment, risk rating/criteria should be agreed with appropriate stakeholders (e.g. the Administration).

Practically, the risk rating is an indication that additional or alternative mitigation measures:

- must be provided; or
- must be considered and implemented if practical and cost effective; or
- need not be considered further, beyond accepted good practice of reducing risk where practicable.

The phrase 'Mitigated as necessary' is used in the IGF Code and means the same as the phrase 'As Low as Reasonably Practicable', commonly referred to as ALARP. Essentially, a risk is considered ALARP if all reasonably practicable mitigation measures have been implemented. This means that additional or alternative measures have been identified and implemented unless they are demonstrated as impractical or the cost of implementation is disproportionate to the reduction in risk.

### 5.2.4 Documentation

Documentation of the preliminary risk analysis and assessment of Aranda's fuel cell and hydrogen storage system will follow the good practices described in IMO Guidelines (IMO2013 a), IACS Recommendations (IACS 2016) and in standard EN 31010 *Risk management. Risk assessment techniques*. The aim is to conduct the preliminary risk analysis for Aranda's fuel cell and hydrogen system by the end of February 2018.

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