



D2.2

Test Plan

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List of abbreviations

ABBREVIATION	DESCRIPTION
MECS	MARPOWER Energy Conversion System
HBK-S	High-pressure Combustor Rig Stuttgart
ATM	Atmospheric Combustion Test Rig Stuttgart

WHRS	Waste Heat Recovery System
HP	High-pressure
LP	Low-pressure
AMB	Active Magnet Bearing
RMR	Risk Management Register

1. INTRODUCTION

1.1. General overview of the objective of the testing

Most of the technological innovation within the MARPOWER project is developed through digital methodologies, including modelling and simulation. However, selected design approaches, modelling techniques, and key components of the MARPOWER Energy Conversion System (MECS) technology will be experimentally verified through prototype development and physical testing to ensure validation.

The scope of testing within the MARPOWER project focuses specifically on critical technologies at the component level. These include:

- the combustion chamber,
- recuperator, and
- the high-pressure (HP) shaft system (for both stationary and moving platforms).

The feasibility of other components, such as the Waste Heat Recovery (WHR) system and the low-pressure (LP) shaft system, will be assessed exclusively through numerical simulations.

Consequently, these components are excluded from the experimental testing programme and from the scope of this deliverable.

1.2. Document structure

The remainder of this document is structured into chapters organized according to the critical components under investigation, namely the combustion chamber, the recuperator, and the HP shaft system. Each chapter provides a comprehensive description of the respective testing activities, including:

- testing objectives
- test setup
- instrumentation and measurement details
- test procedures and standards
- expected outcomes
- risk assessment and mitigation plans
- safety considerations.

2. COMBUSTION CHAMBER TESTING

2.1. Objectives

The combustion chamber is responsible for mixing the incoming compressed hot air with fuel and initiating combustion. To ensure safe, stable, and low-emission operation, it is essential to accurately define and control the boundary conditions and to design the combustor accordingly.

The main objectives of the combustion chamber testing are:

- To investigate the performance of different combustion chamber prototypes regarding the emissions characteristics and flame stability with respect to:
 - Fuel (hydrogen, natural gas)
 - Air inlet temperature
 - Air mass flow (load point)

- Air split
- Fuel split
- To experimentally validate the Computational Fluid Dynamics (CFD) simulation results.

2.2. Test setup

2.2.1. Combustor testing at ATM combustor test rig, DLR Stuttgart

Testing will take place in an atmospheric test rig in the DLR facility in Stuttgart. The test rig is supplied with air from an external compressor and consists of:

- An electrical heater (to control the temperature of the combustion chamber air)
- The combustion chamber prototype (including temperature and pressure sensors)
- Fuel supply system, with mass flow controllers for pilot and main stage (to enable an exact fuel split)
- Exhaust gas analyzer (for exhaust gas measurement)
- Exhaust gas quench (to cool down the exhaust gas)
- Piping

The boundary conditions include:

- Air mass flow: 0...440 g/s
- Air inlet temperature: 0... 650 °C
- Fuel mass flow controller:
 - MFC1: 0.016...0.8 g/s
 - MFC2: 0.12...6 g/s
 - MFC3: 1.2...60 g/s
- Max. exhaust gas temperature: 600 °C

2.2.2. Machine testing at Aurelia test site, Lappeenranta

- Test the fully built setup in Lappeenranta Aurelia site testing tent
- Energy supply with the external container
- Fuel line from regulator to testing tent
- Fuel regulator at the testing site

2.2.3. High pressure section testing at HBK-S, DLR Stuttgart

- Testing will take place in a high-pressure test rig in the DLR facility in Stuttgart. The test rig consists of:
 - Two external compressors, which allow for 1.2 kg/s air at up to 40 bar
 - An electrical heater (to control the temperature of the combustion chamber air – up to 1000 K)
 - Optical accessible chamber for a combustor section
 - Optical and laser-based measurement techniques
 - Exhaust gas analyzer

2.3. Instrumentation and measurements

2.3.1. ATM combustor test rig (at DLR test site)

Table 1. List of sensors and required instrumentation for combustion chamber testing

LOCATION	SENSOR	QUANTITY
Air supply	Mass flow controller	2
	Thermocouple	6
	Pressure sensor	5
Fuel supply	Mass flow controller	3
	Thermocouple	1
	Pressure sensor	3
Combustion chamber	Thermocouple	16
Piping	Thermocouple	13
	Pressure Sensor	3
	Exhaust gas Analyzer	1

- Data collection with 1 Hz frequency
- Averaging of stable points over 5 minutes

2.3.2. Machine testing (at Aurelia test site)

- Temperature measurements
- Pressure measurements
- Fuel mass flow measurements
- Exhaust gas measurements
- Air mass flow measurements
- Electricity variables measurements

2.3.3. High pressure test rig (at DLR test site)

- Optical and laser-based measurement techniques
- Conventional diagnostics
 - Exhaust gas measurements with various types of sampling
 - Gas chromatography
 - Fast pressure sensors (10 kHz)

2.4. Test procedures and standards

- Standard test preparation using checklists, including checking of the key components
- Measurement of stationary points --> thermal equilibrium must be achieved before measurement
- Sensors generally are externally calibrated before the testing campaign, exhaust gas analyzer is calibrated before each test day
- The conducted tests will investigate the influence of a variation of the boundary conditions of the combustion chamber (such as air inlet temperature, air mass flow, air split, fuel, fuel split, ...) on the combustion itself (stability, emissions)

2.5. Expected outcomes

The testing activities will initially focus on evaluating the performance of the baseline combustion chamber. The experimental results, combined with complementary CFD simulations, will be used to design improved combustor prototypes with enhanced performance, particularly for hydrogen combustion. The results of these tests, combined with additional CFD simulations, will support additional prototype iterations. These iterations are expected to achieve stable and low-emission combustion across a wider operating range, thereby improving fuel flexibility. The primary evaluation criteria for the combustion chamber performance are flame stability and emission guidelines.

2.6. Risk assessment and mitigation (RMR-related)

Potential risks for the combustion chamber are:

- Bad combustion properties leading to high emissions and flame instabilities
 - CFD simulations to optimize the design
 - combustion chamber iterations to ensure good combustion behavior
- Strong thermoacoustics, which hinder the testing
 - A silencer is designed to mitigate the thermoacoustic impact
- Infrastructural problems (e.g. fuel supply)
 - Time buffer in the planning to be able to handle these problems
- Damage to key elements (e.g. heater, exhaust gas analyzer)
 - Careful and eligible operation under admissible conditions
- Time delay
 - Time buffer

2.7. Safety considerations

To mitigate risks associated with high-temperature equipment and fuel combustion, the following safety measures are implemented:

- To mitigate risks associated with high-temperature equipment and fuel combustion, the following safety measures are implemented:
- Access is strictly limited to certified and trained staff
- A comprehensive safety breakdown of the test rig to identify and mitigate potential technical
- Complete structural separation between the between the test rig and the control room

3. RECUPERATOR TESTING

3.1. Objectives

The role of the recuperator is to preheat supply air to the combustor. Testing aims to confirm the heat transfer power of the recuperator and validate the analytical calculations as well as the CFD studies of the recuperator. Recuperator prototype power, efficiency and effectiveness are to be determined, and the data is to be analyzed to validate the sizing of the full-scale recuperator in the testing.

3.2. Test setup

The recuperator tests are conducted at Alfa Laval's in-house testing facilities, which have been adapted to accommodate recuperator performance measurements. The test setup comprises the recuperator

prototype, a burner and combustion chamber, a combustion air fan, a supply air compressor, and a dedicated casing for the recuperator prototype.

Testing is performed under representative summer conditions for the supply air. The inlet air properties are controlled using the compressor and a heat exchanger to achieve the required reference conditions. Stable operating conditions and flow rates are verified through sensors and thermocouples installed at multiple locations throughout the system. Measurement data from instrumentation and sampling probes are acquired in real time using a data logging system for subsequent analysis.

3.3. Instrumentation and measurements

Data will be collected throughout the whole testing with high frequency. Data will be analyzed and combined to show the trends of the results.

Table 2. List of sensors and required instrumentation for recuperator testing

LOCATION	SENSOR	QUANTITY
Combustion air	Temperature transmitter	1
	Temperature indicator	1
	Pressure difference transmitter	1
	Pressure transmitter	1
Combustion air duct before recuperator	Temperature indicator	1
	Thermocouples	6
	Temperature transmitter	4
	Pressure difference transmitter	1
Combustion air duct after recuperator	Temperature indicator	1
	Thermocouples	6
	Temperature transmitter	5
	Pressure difference transmitter	1
Supply air in	Mass flow meter	1
	Temperature indicator	1
	Temperature transmitter	1
	Pressure indicator	1
Supply air out	Pressure transmitter	1
	Mass flow meter	1
	Temperature indicator	1
	Temperature transmitter	1
	Pressure indicator	1

	Pressure transmitter	1
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Planned testing duration is 1 month, and the tests are done with test runs taking 1 working day per run to ensure a balanced environment.

3.4. Test procedures and standards

Test procedures are done according to the test process and instrumentation diagram and by following EN 308 standard guidelines for air-to-air heat exchanger test procedures. Testing is to be done according to the highest precision level (P1) of the standard as viable.

3.5. Expected outcomes

The objective of the tests is to verify that the recuperator with the new fin geometry achieves thermal performance equal to or better than the baseline design, demonstrating that the new manufacturing processes do not negatively affect recuperator efficiency or effectiveness. The measured efficiency and effectiveness are therefore expected to be consistent with the original design calculations.

The recuperator test will be considered successful if the acquired data are reproducible and the measurement uncertainty complies with the relevant standards.

Potential risks for the recuperator testing are unbalanced test mass flows and delays in time schedule. To mitigate the risk of unbalanced air flows during testing, several test runs are to be done before the prototype testing. Possible leakages can also delay testing.

3.6. Safety considerations

Safety measures for personnel and equipment are related to working with hot equipment. Test facility safety is controlled by Alfa Laval’s safety procedures, such as with safety walks, operating instructions, and reporting. Safe working environments are ensured in test runs before the prototype testing. Testing is to be done under constant supervision.

4. HP SHAFT SYSTEM

4.1. Objectives

The HP shaft testing is subcategorized as tests conducted on stationary setup, and tests conducted on moving platform.

The objective of the stationary test of the HP shaft system is to check the feasibility from rotordynamics, AMB control, and generator performance and cooling viewpoints at operational speed using the full-scale prototype.

For the moving platform tests, the key objective is to test and validate an Active Magnetic Bearing (AMB)-suspended prototype machine on moving platforms as part of the experimental verification of rotordynamic behavior and control performance under base motion, replicating the dynamic forces experienced on a marine vessel due to ship maneuvering, waves and wind.

4.2. Test setup

Both stationary and moving platform tests will be conducted in the bunker of the Electrical Drives Laboratory at LUT University, Lappeenranta, Finland. The physical configuration of the test rig, including

boundary conditions, environmental conditions, and system interfaces, is described below. The stationary test bench setup requires a 690 V grid connection capable supporting a 2.7 MW generator driven through a 3 kHz MVA-class frequency converter. The setup also includes a ≥ 2 MW load machine drive with 1.5 times overload capability and an integrated power analyzer for electrical measurements. Although the full-scale HP shaft system itself measures approximately $1.5 \times 1.5 \times 1.5 \text{ m}^3$, the total installation footprint depends on the dimensions of the load machine, converter, and gearbox. The dedicated highspeed, high-power test bunker at LUT has internal dimensions of $2.7 \times 2.7 \times 4.5 \text{ m}^3$ and 20 cm thick concrete walls for safe operation. The 2.7 MW, 15 krpm generator, along with its sensors, torque transducer, and gearbox, will be installed inside this bunker for testing.

The rotor-AMB system includes inbuilt radial and axial inductive position sensors connected to the magnetic bearing controller (MBC). The electrical machine is equipped with a rotor speed measurement device (encoder), which is also connected to the magnetic bearing controller. Temperature sensors are integrated into the AMB actuators to monitor temperature for safety functions. Optional sensors may be required, such as acceleration sensors for vibration monitoring

For the stationary tests, the Low-pressure compressor (LPC) is planned to load the motor. The LPC setup will follow the layout requirements defined in ASME PTC 10-2022. The compressor stage will be arranged with designated inlet and outlet sections to accommodate the airflow. The test piping will include the possibility to integrate temperature and pressure sensors. In addition, the mass flow rate is measured at the compressor inlet or outlet.

The main elements of the test bench are shown in figure below.

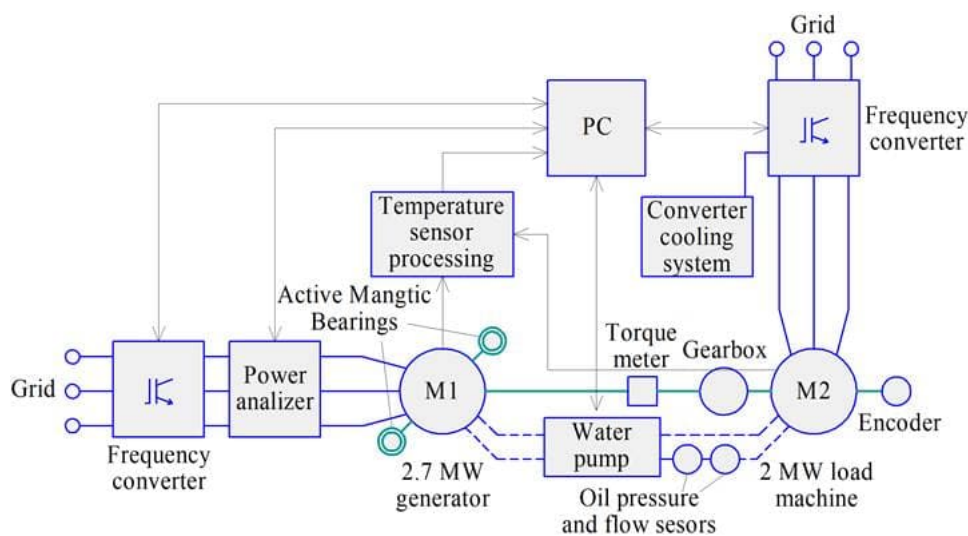


Figure 1. Simplified schematic view of the testbench assembly for stationary tests

Due to safety considerations, the experimental moving-platform campaign will be conducted using a medium-scale AMB-supported test rig installed in the bunker facility at LUT University. At LUT, the test rig will be mounted on a moving platform capable of reproducing representative ship motions in accordance with relevant standards. In parallel, a small-scale test rig at DTU will be employed to develop and validate scalability methodologies based on similarity principles. This work includes the development of approaches for scaling safety-bearing contact forces and other key dynamic responses. Initial experimental findings from the DTU test rig have been accepted for publication in the Proceedings

of the 13th Conference on Vibrations in Rotating Machinery (VIRM 13), confirming the relevance of the experimental methodology and dynamic modelling approach. A video of the DTU moving-platform experiment is available at [Experiments on a moving platform propel MARPOWER's magnetic bearing innovation](#).

4.3. Instrumentation and measurements

A comprehensive list of sensors, instruments and their measurement location for both stationary and moving platform tests combined is listed in the table below:

Table 3. List of Sensors and required instrumentation for HP shaft system testing

LOCATION	SENSOR	QUANTITY
Stator	Temperature sensor (PT-100)	10
Load machine rotor (outside bunker)	Encoder	1
Outside bunker	Multimeter	1
Outside bunker	Three-phase power analyzer	1
Outside bunker	oscilloscope	1
Between generator and gearbox	torque transducer	1
Generator cooling system	Water pressure sensor	2
Generator cooling system	Water flow sensor	2
Outside bunker	PC with Dewsoft and Labview software	1
AMB actuators	Temperature sensor (PT-100)	8-10
AMB actuators	Displacement sensors	2
Moving platform	acceleration sensors	2
Moving platform	Gyroscope	1
Rotor shaft	Encoder	1
Acceleration sensors	Accelerometers	2
Compressor inlet	Temperature sensor (PT-100)	4
Compressor inlet	Pressure sensor	1
Compressor outlet	Temperature sensor (PT-100)	4
Compressor outlet	Pressure sensor	1
Compressor inlet or outlet	Mass flow measurement	1

4.4. Test procedures and standards

All test procedures will be conducted based on the following standards:

- Electrical standards (relevant for both stationary and moving platform tests)
 - IEC 60034-1 (pretest checks and no-load test)
 - IEC 60034-2-1 (efficiency and loss estimation)
 - IEC 60034-1 (temperature rise test)
 - IEC 60034-14 (Vibration acceptance)
 - IEC 60034-9 (Noise measurement)
 - IEC TS 60034-25:2022 (converter integration)
 - IEC 60034-18-41 (converter qualification test)

- AMB and mechanical standards (relevant for both stationary and moving platform tests)
 - ISO 14839-2:2004(E) (Mechanical vibration)
 - ASME Y14.5 (Geometric Dimensioning & Tolerancing – GD&T)
 - ASME Y14.24 (Engineering Drawing Practices)
 - ASME Y14.1 (Engineering Drawing Format)
 - ISO 1101 (GD&T – Form, Orientation, Location)
 - ISO 2768 (General Tolerancing – Linear/Angular/Geometric)
 - ISO 286 (Fits & Tolerance Grades)

- Standard for low pressure compressor (relevant for stationary test)
 - ASME PTC 10 -2022 (centrifugal compressor performance)

- Standard for Ship motion (relevant for moving platform test)
 - DNVGL Rules Part 4 - Ch.1 – Sec. 3 - § 2.2 “Environmental conditions”. July 2022. (accelerations, pitch and roll test parameters)

The test sequence for stationary tests will begin with checks of all electrical connections, mechanical assembly, and cooling circuits, followed by static electrical tests and the setup of the converter. The machine will then undergo levitation and low-speed operation, before its speed is gradually increased up to the rated value. After reaching rated speed, tests will be carried out under load conditions ranging from no-load to rated torque, and the procedure will conclude with an overspeed test to verify safe operation beyond the rated speed. The main measured parameters from electrical aspects will include resistance, inductance, induced voltage rms and waveform, load currents rms and waveform, losses, efficiency, temperature in the targeted generator parts.

For the control design and verification, the ISO 14839-2:2004(E) standard will be followed. In the first stage, the test procedure will involve evaluating the AMB control system without base movement and will validate its performance using identification tests. These tests will be used to refine the model and retune the controller, after which rotational tests will follow. At different operating points, an identification run will also be performed, and the controller will be tuned accordingly. Once the controller is properly tuned, the test will continue with base movement, during which the performance will be re-evaluated. The platform feedback signals, including acceleration and gyroscope signals, will be scaled and incorporated into the feedforward control path.

4.5. Expected outcomes

The expected outcome of stationary test of the HP-shaft system at LUT will be the validation of the design and analysis methods developed in the project covering generator cooling, rotordynamic behavior, control performance, and similarity theory, through experimental evaluation of AMB-supported full scale prototype machine.

With moving platform tests, the expected outcome is the validation of the design and analysis methods developed within the MARPOWER project about rotordynamic behavior, feasibility under dynamic load, control performance, and similarity theory of scalability of the developed methods with medium scale and small-scale test rig at LUT and DTU respectively.

4.6. Risk assessment and mitigation

The potential risks reported in the Risk Management Register (RMR) involve:

- **Stationary tests**
 - **Generator failure:** malfunction of the generator may interrupt testing
 - **AMB failure:** insufficient current in the Active Magnetic Bearings (AMB) could limit rotor vibration control.
 - **Simulation inaccuracies (vibrations):** discrepancies between simulated and measured vibration levels may occur. To mitigate this risk, rotational speed will be increased incrementally to closely monitor vibration evolution.
 - **Simulation inaccuracies (electric machine performance):** the rated power may not be achievable. In this case, testing will be performed at the maximum attainable power level and results will be assessed accordingly.
- **Moving platform test**
 - Same risks as stationary tests
 - Moving platform failure to generate required motion: Base motions will be tested within the test capability of the platforms

Schedule delays: Delays in procurement, redesign, or manufacturing may impact the planned testing schedule for both stationary and moving platform tests. The timeline is monitored through monthly progress meetings. Any delays are communicated to all stakeholders, and the schedule is reassessed and, if required, updated and reported to the Project Officer.

4.7. Safety considerations

Safety measures for personnel and equipment are of high importance due to the high rotational speeds of the test rigs. Test facility safety is ensured at LUT by using the LUT Bunker for the testing procedures. Rotational speeds will be increased incrementally to perceive any potential issue when the vibrations are minimal. Testing will be conducted with trained personal only with at least one member of the electrical lab present.

5. Conclusion

In summary, the "Test plan" report outlines the comprehensive strategy and methodologies employed to ensure the quality and functionality of the project's experimental activities. The detailed test cases, along with the defined objectives and scope, provide a clear roadmap for the testing process. By adhering to this plan, we aim to identify and address potential issues early, ensuring a robust and reliable final product. The collaborative efforts of the team, combined with the systematic approach detailed in this report, will contribute significantly to the project's success. Moving forward, continuous monitoring and iterative testing will be crucial in maintaining the integrity and performance of the system.