IMOTHEP

GETTING HYBRID ELECTRIC

D6.4: NEED FOR INFRASTRUCTURES FOR THE DEVELOPMENT OF HEP

DISSEMINATION LEVEL: PUBLIC

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EXECUTIVE SUMMARY

This report analyses the potential need for additional testing infrastructures based on the review and proposal of key technology demonstrations required to pave the way of Hybrid Electric Propulsion (HEP) maturation. It also aims at identifying the existing facilities in Europe, and to some extent in the USA, which could support the development of HEP, in order to identify the need for new capabilities. The work performed provides inputs for the elaboration of IMOTHEP final roadmap on HEP.

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This deliverable report is public.

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Glossary

Acronym	Signification
D	Deliverable
HEP	Hybrid Electric Propulsion
EC	European Commission
EMC	Electro Magnetic Compatibility
EPU	Electrical Power Unit
HIRF	High Intensity Radiated Field
MRL	Manufacturing readiness level
MW	Megawatt
RI	Research Infrastructures
TRL	Technology Readiness Level
WP	Work Package

1. INTRODUCTION

1.1. IMOTHEP IN BRIEF

To pursue the goal of drastically reducing the greenhouse gas emissions of commercial aviation, the top-level objective of IMOTHEP is to achieve a key step in assessing the potential offered by hybrid electric propulsion (HEP) and, ultimately, to build the corresponding aviation sector-wide roadmap for the maturation of the technology.

The core of IMOTHEP is an integrated end-to-end investigation of hybrid-electric power trains for commercial aircraft, performed in close connection with the propulsion system and aircraft architecture. Aircraft configurations were selected based on their potential for fuel burn reduction and their representativeness of a variety of credible concepts, with a focus on regional and short-to-medium range missions. From the preliminary design of the aircraft, target specifications were defined for the architecture and components of the hybrid propulsion chain. Technological solutions and associated models were then investigated with a twenty-year timeframe perspective. In order to identify key technological enablers and technology gaps, the integrated performance of the electric components and power chain are synthesized by assessing the fuel burn of the selected aircraft configurations, compared to conventional technologies extrapolated to 2035.

The project also addresses the infrastructures and tools required for HEP development, as well as the need for technology demonstrations or regulatory evolutions. Eventually, all these elements will feed the research and technology roadmap of HEP, which will constitute the final synthesis of the project.

To achieve these ambitious goals, the four-year project is supported by seven R&D institutes, eleven industrial organisations (from aviation and electric systems), a service SME and seven universities from nine European countries, plus two RTD organizations from Canada.

1.2. SCOPE OF THE DELIVERABLE

Within IMOTHEP, WP6 is dedicated to the whole synthesis of the project, in particular through the elaboration of the roadmap for HEP development. The WP builds on the results of all the technical work packages of the project (WP1 to WP5) and carries additional specific studies in order to cover all aspects of the roadmap. A specific task, WP6.2 is dedicated to reviewing the needs for infrastructures and demonstrations for the maturation and development of HEP.

Considering the different levels of constituents in a hybrid propulsion chain, IMOTHEP first performed an analysis of the testing needs at each level: components, subsystems and systems. This is presented in section 1.

In parallel, the project performed a screening of existing facilities, mostly in Europe but also in the USA, which could support the development of HEP. Publicly released information on these facilities were collected. To the extent that relevant information were available, an attempt was done to analyse which testing requirements were covered or not by these facilities. This is presented in Section 2.

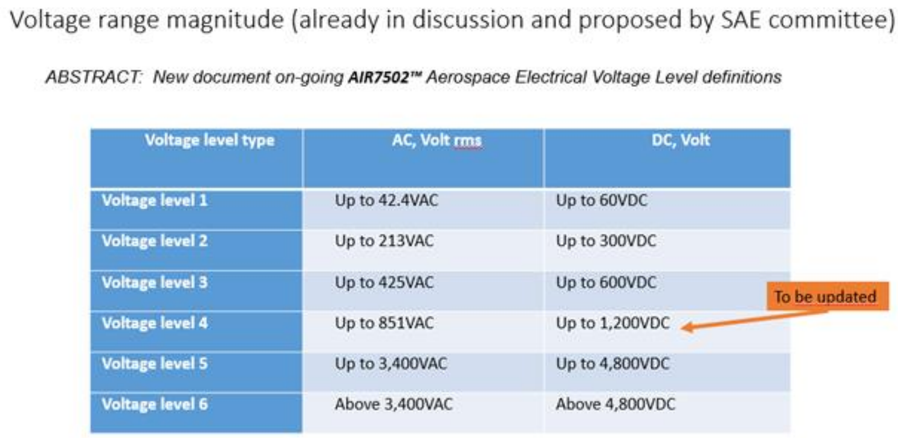
Last, the report presents, in Section 3, general considerations on the desirable characteristics for testing facilities to support the roadmap for HEP development.

1.3. NEEDS FOR ELECTRIC SYSTEMS TESTING

With a view to the development of HEP, testing and test requirements are to be considered at three different levels:

- Components,
- Subsystems,
- Integrated Systems.

IMOTHEP analysed the current state of the taxonomy for electric systems and decided to adopt as a reference the voltage range magnitude (1-6), as set by SAE committee, given in the Figure 1 below, for the development of the roadmap for testing facilities/demonstrations requirements.



Voltage range magnitude (already in discussion and proposed by SAE committee)

ABSTRACT: New document on-going ***AIR7502™*** *Aerospace Electrical Voltage Level definitions*

Voltage level type	AC, Volt rms	DC, Volt
Voltage level 1	Up to 42.4VAC	Up to 60VDC
Voltage level 2	Up to 213VAC	Up to 300VDC
Voltage level 3	Up to 425VAC	Up to 600VDC
Voltage level 4	Up to 851VAC	Up to 1,200VDC
Voltage level 5	Up to 3,400VAC	Up to 4,800VDC
Voltage level 6	Above 3,400VAC	Above 4,800VDC

To be updated

Figure 1: SAE AIR7502 Aerospace Electrical Voltage Level Definitions

(Voltage range magnitude is at the proposal stage will be updated when finalised by SAE).

However, the technical analysis showed that HEP applications studied in IMOTHEP do require a more precise classification of the areas to consider. Table 1 below defines in the rows the key features and performances of the critical electrical items supporting HEP propulsion, whilst the columns identify two relevant scopes of challenges for HEP propulsion.

Scope 1 includes the set of performances technically achievable at TRL6, at aircraft level, by 2030. They will be included in the regional aircraft HEP in flight demonstration planned in Clean Aviation or other global opportunities.

Scope 2 includes the set of performances required for a wide use of HEP propulsion in the regional segment up to 100 seat size and beyond in the SMR segment. At current pace of technology development, those performances will be probably achieved at TRL6 beyond 2030 or 2035 (high voltage distribution in particular) and then they may be ready for integration in low emission aircraft delivered in that timeframe.

Table 1: Additional classifications proposed

	Scope 1	**Scope 2**
Distribution	< 1 kV	~3 kV
Electric motor	0.3 to 1 MW	~1 to 10 MW
Generator	~1 MW	~5 MW / 10 MW

1.4. COMPONENTS TESTING

Many components under investigation within the IMOTHEP project are to be considered novel in the context of aircraft integration. Several parameters, such as voltage levels, electric power range or higher number of motors call for significantly adapted, changed or even new standards as a basis for an aligned set of component test requirements. With respect to power range, it is important to note that required tests at full power at TRL6 need to be taken into account for future infrastructure developments. Such TRL6 testing and facilities may also provide data relevant for the certification process depending on how “close” the tested solution is to the actual real solution going in revenue service and authority approval of relevance of tests against the actual solution features.

COMPONENTS CLASSIFICATION

The HEP components requiring testing are classified as follows:

- Generators,
- Motors,
- Power Electronic Converters (which will be found as interfaces for almost all energy sources and loads - generators, motors, batteries, fuel cells),
- Cables,
- Batteries,
- Fuel Cells,
- Solid-state power switches, circuit breakers,
- Connectors,
- Thermal system components.

COMPONENTS TESTING REQUIREMENTS

The specific **tests** required for the components are identified as follows.

[1] **Partial Discharge**
There has been discussion on partial discharge in aerospace AC cables [Christou 2010] as well as motors under altitude conditions and low-pressure environment. Partial discharge tests under these conditions would be required.

[2] **Short Circuit tests** (Figure 2)
These become more important due to larger amount of electric energy stored in the individual components.

[3] **Ageing tests** of high voltage, high power components and materials under relevant environmental conditions.

[4] **EMC tests**
EMC for conducted, radiated emissions as well as interference needs to be tested in dedicated chambers. This involves the need for low noise power sources and current bushings to access the test chambers. Standards need to define the test conditions (working points).

[5] **Performance tests**
Performance tests are component specific and need to be defined based on system needs. Especially for distributed DC generation and storage, a coordination of the power system needs to be reflected in the performance tests.

[6] **Environmental tests (DO160)**

[7] **Thermal management**

Figure 2 - Short circuit tests and pressure measurements and simulation performed at AIT Austrian Institute of Technology GmbH

COMPONENTS TEST REQUIREMENTS

Components are to be tested at full power for a TRL6 demonstration.

1.5. SUBSYSTEMS TESTING

SUBSYSTEMS CLASSIFICATION

The HEP subsystems (Propulsive and Non-Propulsive) requiring testing are classified as follows:

- Turbogenerator (control, thermal/electrical interfaces…),
- Battery + Power Electronic Converter + Control system+ Thermal Management System,
- Fuel cells + Power Electronic Converter + Control system+ Thermal Management System,
- Power distribution (power center),
- Power management,
- Electrical Power Unit (EPU),
- Hybrid TurboProp,
- Thermal Management System (oil cooling, heat exchanger…).

SUBSYSTEMS TESTING REQUIREMENTS

The specific tests required for High Voltage/High power subsystems are identified as:

[8] **Emergent Behaviours tests**

- ➢ System behaviours that emerge from the interaction of sub-systems can be difficult to pre-define and capture in a test setup. Typical challenges with current test practice include late detection of unwanted system behaviour, high cost of repetitive manual processes (required for testing), and risk of release delays because of late error detection [Kjeldaas 2021][1].

[9] **Fault insertion/coordination tests**

- Fault insertion is used to apply the kinds of electrical errors most likely to occur in an application when something goes wrong, especially in safety-critical applications.
- Coordination tests may be used to verify coordination of overcurrent protective devices within an electrical system and support assessments of all possible operating scenarios in case of faults.

[10] **Performance around operational envelope tests**

[11] **EMC tests**

[12] **Benchmark testing** – Tests to evaluate performance against established benchmark standards and solutions.

[13] **Tests to support development of standards/compliance means** to allow flexibility for disruptive "integrated subsystems" tests. This involves developing "non-traditional" test methods that are specific to several of the product's subsystems.

[14] **Environmental Qualification tests**
Components and subsystems required by HEP will require the environmental qualification to comply with certification and engineering standards applicable to aeronautics (i.e. DO 160, DO 178, ARINC). The qualification testing shall be able to manage the component and subsystem performance deriving from Table 1. Performance listed in Scope 2 of Table 1 are particularly severe compared to the current state of the art and may require a dedicated brand new testing facility.

SUBSYSTEMS TEST REQUIREMENTS

Subsystem testing can be performed by remotely connecting components test-benches located in different facilities. For this to be possible, these test benches need to have the ability to connect remotely in real-time, with compatible hardware and software.

As for the components, facilities need to allow testing subsystems at full power for TRL6 demonstration.

Subsystems are to be tested at:

- Full scale;
- Technology Readiness Level 6 (TRL6);
- Manufacturing readiness level MRL7 (the capability to produce systems, subsystems or components in a production representative environment).

1.6. INTEGRATED SYSTEMS TESTING

INTEGRATED SYSTEMS TESTING REQUIREMENTS

The Integrated Systems testing requirements are identified as follows.

[15] **MW class electric/hybrid propulsion**.
Referring to Table 1, the HEP propulsion requires an integrated test of electric and thermal contributors in the multi MW class. Testing requires a facility able to test at right size the thermal and electrical parts and their interaction because that is the critical feature for performance and safety. The option to test HEP in two separate facilities one for electric and one for thermal propulsion requires that data shall be

combined virtually in a simulation model that in any case will require a global validation. In alternative, a real-time connection and interaction shall be implemented between the thermal and electric facilities, which implies developing several critical solutions to allow a coordinated exchange of data.

[16] **High performance computing centre**.
The new technical challenges in Table 1 and the complexity of testing described above require a very powerful simulation capability, probably at real time. This requires a powerful high performance computing centre and the associated capability to easily combine and integrate heterogeneous simulation models (open simulation platform).

[17] **Certification virtual reality facility**.
Complexity of testing and technical challenges in Table 1 as well as the complementary issues on the thermal side, monitoring and control as well safety demonstration of a complex system will require a new approach to certification and acceptable means of compliance. The ability to combine real test data with simulation data to provide additional insight may require a specific facility able to provide a virtual reality of the HEP propulsion. This facility may be also useful to support the certification of maintenance and inspection processes

[18] **Full-scale crashworthiness and fire protection facility**.
Distribution and/or high power density batteries, probably based on metal-ion chemistry, providing the low emission energy source to HEP propulsion, are both quite sensitive to fire hazard. Therefore, a specific and suitable crashworthiness test facility shall be made available associated to a suitable fire testing capability able to manage Table 1 challenges.

[19] **Thermal bench**.
The new energy sources required by HEP (electrical storage in batteries) lead to low emissions but cause a thermal waste that has to be managed carefully. Unlike for traditional thermal engines, thermal waste is not discharged directly in the ambient atmosphere by means of hot combustion gases. There is a relatively low temperature waste that is emitted inside the aircraft, where those energy sources are integrated (fuselage, pod, nacelles). A thermal management system is required to drive such thermal waste (order of 10-100kW) outside. An appropriate test facility is required to validate those systems (aircraft size, full-scale climate chamber or alternatives?). It may be combined to the full-scale engine test cell or to the HEP thermal and electric test cell.

[20] **Full scale engine test cells**.
For certification and overall HEP validation, a global engine test cell fulfilling Table 1 features at full scale would be preferable. This will reduce risks and costs of flight-test and support it with proper data. The facility will also validate the simulation model of HEP discussed above.

[21] **Electromagnetic Compatibility (EMC) and High Intensity Radiated Field (HIRF) anechoic chambers**.
The high electrical power and high voltage required by HEP listed in Table 1 and Figure 1 from SAE cause unprecedented EMC and HIRF challenges at component, system and aircraft level. Current EMC chambers should be adapted to such new challenge and associated to suitable simulation tools validated at those power levels.

[22] **Hydrogen propulsion and liquid hydrogen storage facility**.
Although this was little studied in IMOTHEP, fuel cells are candidate energy sources for electrified power train. Hydrogen could also be envisaged as the fuel in Rankine

cycle thermal engines for the thermal part of HEP. Hydrogen will be very probably in liquid form because the weight and volume density ratio of compressed hydrogen for aeronautical applications studied in IMOTHEP is not enough for a sensible integration. Liquid hydrogen would also be necessary for the introduction of low temperature superconductive systems (in fully superconductive power train, the required hydrogen fuel flow would probably lead to use it as a fuel for the thermal engines also). If the potential interest of such systems were confirmed by future studies, a facility able to store and manage liquid hydrogen would also be required with capabilities in the range of power levels from Table 1. In case of developing propulsion systems using hydrogen, corresponding capabilities shall also be taken into account in full-scale crashworthiness and fire protection facility.

2.EXISTING TESTING INFRASTRUCTURES FOR HEP DEVELOPMENT

The screening performed during the project identified a total of 26 facilities, belonging to 17 different organisations, 6 being in the USA.

The description and characteristics that could be retrieved for these facilities are summarised in the following table. Unfortunately, for many of these facilities, it proved difficult to obtain detailed information about what they consist of and about their capabilities.

To the extent that relevant information were available, the table tries to provide the testing requirements that are covered by the facilities.

#	Organisation - Facility	Country	Capability	Testing requirement covered
1	**University of Nottingham**	United Kingdom	**UK Electric Aircraft Propulsion Test Facility (UK EAPF)** Megawatt level test facilities (up to 20MW, 6KVDC, 3.3KV/1.1 kVDC) Ability to emulate power systems, subsystems, components with altitude testing of motors, generators, drives. • High power propulsive motor drive test stands up to 2MW,30 krpm with torque and thrust emulation. • Reliability testing with environmental chambers up to +600ºC, Partial discharge test. • 100 kW dual channel drive as multi-shaft engine emulator. • Advanced thermal management and cooling systems (90kW, 420 l/min). • Small environmental chamber. ALEA - up to 75,000 ft, up to 60 kw and 12,000 rpm. • Large environmental chamber - up to 45,000 ft -100 degrees minimum temperature and maximum temperature 180 degrees. Up to 840kW up to 25,000 rpm. • Electrical Systems at High Altitude Research Facility (ELSA) – hybrid electric propulsion system with altitude chambers rated at 45000 ft for energy source and propulsion system up to 5 MW at 24000 rpm. • Digital twin lab with advanced real time simulation and emulation of hybrid electric propulsion systems (under construction). • Cryogenic propulsion lab capable of performing tests at altitude with cryogenic fuels sources including hydrogen. • EMC chamber – Semi Faraday's chamber - Conducted emissions measurements (9 kHz – 30 MHz) for AC and DC devices. https://www.nottingham.ac.uk/vision/world-leading-power-electronics-centre-at-forefront-of-zero-carbon-aviation	1,2,3,4,5,6,7,10,11,12,13,14,15,17,19,21,22 [6,14] except vibration tests
2	**University of Nottingham**	United Kingdom	**Nottingham Electrical System Test Bench (NEST)** • Copper bird designed lab (1.2 kV, 400 kW power generation facilities).	8,9,12,13

			- Energy management systems testing – advanced industry approved hardware in the loop systems (DSPACE, Typhoon, National Instruments). - Energy storage systems testing – high power battery emulation with programmable DC power supply.	
3	**University of Strathclyde**	United Kingdom	**PNDC (UST)** Systems and subsystems testing and TRL maturation facility for electrical power systems. Power capability in dedicated industry innovation centre up to MW, 11kV. - Whole systems testing for energy systems and electrified transport systems. - Charging system (inc. wireless charging) testing and derisking. - Power converter testing and derisking. - HV/LV fault testing and protection derisking. - Communications and cyber security systems testing and derisking. - Fuel cell/battery powertrain testing and derisking. - Thermal systems testing and derisking. - High fidelity real time simulation suite supporting power/control-hardware-in-the-loop (PHIL). - 5MVA motor-generator set: - 11kV/LV supply for test network - 1MW bi-directional power converter - High fidelity data acquisition PNDC@ANZIC opening 2024 provides additional integrated systems testing capability, including: - Hydrogen system testing bays. - Additional MW AC and MW DC testing rigs. - Integrated environmental chamber for component and systems testing - MW dyno rigs. https://www.pndc.co.uk/	2,3,5,7,8,9,10,12,13, 15,16,19 (partial), 22 (partial)
4	**University of Strathclyde**	United Kingdom	**Applied Superconductivity Laboratory (UST)** Cryogenic and superconductivity laboratory located in the Technology and Innovation Centre. - Advanced modelling suite for superconducting devices.	5,7,8,10,11,12, 13

			• Design and manufacturing tools for high power density superconducting machines and cryogenic power electronics converters/inverters. • Cryogenic propulsion testing and development rig. • Cryogenic testing facility for power electronic switches. • Superconducting in the loop experimental testing system. • Cooling systems for superconducting power component testing. https://cryogenicpropulsion.com/	
5	**University of Strathclyde**	United Kingdom	**Dynamic Power Systems Laboratory (UST)** The Dynamic Power Systems Laboratory (DPSL) and associated DC protection laboratory are located in the Technology and Innovation Centre and support dynamic and faulted performance and systems integration assessments. • 90 kVA three-phase power hardware-in-the-loop (PHIL) and control hardware-in-the-loop (CHIL) rig. • High fidelity real-time digital simulation suite incorporating multiple simulators. • DC protection development and testing suite incorporating fault throwers and arcing rigs. • AC protection testing rig. • CFRP composites testing rig. • Communications system emulator. • Energy storage emulator. • Fully-controllable Triphase power electronics and power amplification. • Geographically Distributed Laboratory functionality. • Adjacent laboratories supporting sensing and diagnostics. https://www.ulabequipment.com/facility/dynamicpowersystems	1,2,5,8,9,10,11, 12,13, 16
6	**CEA-LITEN**	France	**Batteries platform** Testing and qualification unit: • Test batteries in normal, degraded, and abusive conditions. • Instrument batteries to acquire physical data during electrical testing. • Control abuse tests. • Ensure the conformity of tests and results (no certification). https://liten.cea.fr/cea-tech/liten/english/Pages/Work-with-us/Technology-platforms/Batteries.aspx	

7	**ONERA**	France - Toulouse	**TROPHEA EMC test bench** • EM coupling, EM shielding, EM protection against electromagnetic interference of natural origin - indirect effects of electrostatic discharges and indirect effects of lightning (LIE) or of intentional origin (IEMI, AED-EM) or unintentional (HIRF). • Internal EMC. • EMC expertise (support for EM qualification and certification). • Development of numerical models for modeling and simulating EM coupling with systems. • Development of innovative experimental techniques for EMC characterization of systems. • Capabilities: +/- 500 V, 72 kW. https://www.onera.fr/en/phy-demr	4 , 11 (at small scale)
8	**Safran**	France- Niort	**Copper bird** - Characterization & Optimization of Power Plant & Equipment Rig • Electrical Systems Tests Centre. • Qualification Laboratories. • Material Laboratories. • EMI testing. • Power Drive. • Climatic chambers for thermal, altitude and humidity. • 120kN shaker. • A high voltage room for indirect lightning tests. • Several Mode-Stirred Reverberation Chambers, with the capacity to test a whole system. • Configurable electrical distribution centre up to 540HVDC. • Inverters & load of 100kVA (540V). • A programmable DC power supply of maximum 250kW. • 3x400VAC and 1x230VAC power networks.	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 14,21
9	**Safran**	France Bordes	Test facility for hybrid turbomachine. With a power rating of 300kW electrical and 700kW turbomachine.	8, 9, 10, 12, 13,
10	**Safran**	France Uzein	Test facility for ePropulsion up to 50kW by propeller.	5, 8, 9, 10, 12, 13,

<table>
<tr><td>11</td><td>Safran</td><td>France
Tarnos</td><td>Test facility for hybrid turbopropeller able to test hybrid engine up to 40kW electrical and 1300kW turbomachine. An upgrade is foreseen to get up to 500kW (electrical) and 1800kW (turbomachine).</td><td>10, 12, 13</td></tr>
<tr><td>12</td><td>Airbus</td><td>Germany
-Munich</td><td>E-Aircraft Systems test house Ottobrunn site
- Capability to test 2 hybrid electric propulsion systems, each with a power of up to 20 MW (3000 m^2).
- Integration of subsystems – batteries, gas turbines, energy distribution systems, electric drives.
https://www.aerospacetestinginternational.com/news/electric-hybrid/airbus-opens-electric-aircraft-test-facility.html</td><td>15, 20</td></tr>
<tr><td>13</td><td>DLR/AVL</td><td>Germany
-
Empfingen</td><td>BALIS test field - 1.5 MW composite testbed for fuel cells
Fuel cells, hydrogen tank, electrical motors, battery, cooling system, control systems.
- Fuel Cell: 1500 kWel.
- Electric Motor: 1500 kWel.
- Battery: 500 kW.
- Aviation Tank System: 200 kg H2(l).
- Hydrogen Storage: 3 t H2(l).
- Hydrogen Feed: 120 kg/h.
- Waste Heat Removal: 3 MW.
https://www.avl.com/en-gb/press/press-release/avl-contribution-dlr-project-15-megawatt-composite-testbed-fuel-cells</td><td>15, 20, 22</td></tr>
<tr><td>14</td><td>DLR</td><td>Germany
-
Göttingen</td><td>Next generation turbine test facility (NG-Turb test rig)
International test facilities for aircraft turbines / Business aircraft to A380
NG-Turb is used for aerothermo-dynamic investigations on high-efficiency high-, medium- or low pressure turbines of aero engines, gas and steam turbines.
<table>
<tr><td>Inlet pressure [kPa]</td><td>15-195</td><td>150-450</td></tr>
<tr><td>Inlet temperature [K]</td><td>290-540</td><td>263-320</td></tr>
<tr><td>Massflow [kg/s]</td><td>< 10</td><td>< 2</td></tr>
<tr><td>Pressure ratio [-]</td><td>< 10</td><td>< 4</td></tr>
<tr><td>Reynolds number [-]</td><td colspan="2">0,1-1 Mio.</td></tr>
</table>
</td><td>10,20</td></tr>
</table>

			https://www.dlr.de/at/en/desktopdefault.aspx/tabid-7393/#gallery/37160	
15	**DLR**	Germany - Stuttgart	**Hybrid-electric ground demonstrator (HeBO)** • For serial and parallel hybrid electric propulsion system. Using an electric generator coupled to a gas turbine with 300kW and a power density of 10kW/kg. • For load simulation there is a second (larger) electric engine. There is oil and water cooling for the device. The gasturbine will be also modified w.r.t its burn chamber. • Gas turbine model: Rolls-Royce M250-C20B (twin shaft). • Combustion chamber pressure: 7,2 bar(a). • Air mass flow @ nominal speed N1: 1,542 kg/s. • Maximum shaft power (5min): 313 kW. • Output voltage: 450 - 800 VDC. • Rated speed: N1max (gas generator): 50.970 1/min. • N2Nenn (load turbine): 33.290 1/min. https://www.dlr.de/en/vt/research-transfer/research-infrastructure/hybrid-electric-ground-demonstrator-hebo	2,5,8,9,10
16 a	**DLR**	Germany - Oberpfaffenhofen	**DO228 Flying Testbed** • The 'DO 228' D-CEFD was overhauled by the company General Atomics AeroTec Systems and was handed over to the DLR Flight Experiments Facility. The new DLR research aircraft will be used to test electric propulsion systems. • In a research project with MTU Aero Engines, a 600-kilowatt electric powertrain is to replace one of the conventional engines. • Fuel cells located in the fuselage will supply the electric propulsion system with power. https://aviationweek.com/aerospace/emerging-technologies/dlr-receives-do-228-use-electric-propulsion-testbed	8,14,20,22
16 b	**DLR**	Germany - Braunschweig	**UpLift Dornier 328-100 Flying Testbed** The Dornier 328-100 is being converted into a flying testbed for climate-friendly air transport technologies as part of the UpLift project. The aircraft will be used to measure and quantify the climate protection potential of various new technologies, such as fully synthetic fuels or hydrogen. The aircraft is stationed at the DLR site in Braunschweig, where it is part of the largest civilian research fleet in Europe.	8,14,20,22

			• Serves as Flying Testbed for disruptive H2 Technologies. • Testing of various technologies concerning propulsion, fuel-system and green on-board system. • The flying testbed shall be available openly to interested parties from industry and research. DLR acquires flying hydrogen laboratory and demonstrates whole-system solutions https://www.dlr.de/en/research-and-transfer/research-infrastructure/research-aircraft-fleet/uplift-dornier-328-100	
17	**Leonardo aircraft**	Italy - Naples	**Regional Integrated Aircraft Demonstration Platform** Regional Iron Bird Ground demonstrator	
18	**Rolls Royce**	Norway - Trondheim	**Electric propulsion for electric commuter aircraft and urban air mobility vehicles** ROLLS-ROYCE has assembled/mounted to test bench/spun its first 320 kW direct-drive electric motor demonstrator for commuter aircraft; testing can prove basic mechanical and electrical functionality of motor. https://aviationweek.com/aerospace/rolls-royce-68	
19	**AIT**	Austria Vienna	**Battery test facility** Electrical, thermal and mechanical tests for performance and safety at battery cell, module and system level, acc. to automotive and aeronautic test requirements. Cell level: • Cell testing units (AIT): 72 channels up to 6V, 100A charge, 120 A discharge. • Maccor testing unit with 96 channels up to 6V, 5A. • Impedance spectroscopy. Module-Testing-Units (AIT): 8 test benches with up to 140 V, max. 60 kW. System-Testing-Units (AIT): 2 test benches: 500 V / 1000 V, max. 300 kW. Climatic chambers (cell level): -45°C to +180°C, 4 K/min (modernized equipment could provide min. temp. of -70°C and higher temperature variation rates) [Acc. to DO-160A, -45° is operating low temperature for equipment intended for	

			installation in non-pressurized and non-controlled temperature locations on an aircraft (B2) and in the power plant compartment of an aircraft (B3) that is operated at altitudes up to 25,000 ft (7,620 m) MSL. -55°C is ground survival temperature for all categories and operating low temperature for equipment intended for installation in non-pressurized and non-controlled temperature locations on an aircraft (C-F2) and in the power plant compartment of an aircraft (C-F3) that is operated at altitudes up to 35,000 – 70,000 ft MSL.] Safety testing: • Thermal: Thermal stability (RT to >250°C), Storage at elevated temperature, Thermal cycling. • Mechanical: Internal short circuit (nail penetration), Crush, Drop, Corrosive environment / dust, Altitude simulation, Vibration / shock. • Electrical: Overcharge, Over-discharge / voltage reversal, External short circuit, Fast charge / discharge. Current accreditations: IEC62133-2, IEC 62281, IEC 62660-1&2, ISO 12405-4, UN 38.3	
20	**AIT**	**Austria** Vienna	**Power and Renewable Gas Systems** SmartEST, High Current, High Voltage labs Testing of components and systems with simulated grids and primary energy sources. • 1 MVA LV Connection. • 860 kVA grid Simulators. • 1500 A/1500 V DC sources. • Climate chamber -40 -> +120°C, up to 98% humidity. • Low pressure chamber 1 mbar to 1300 mbar (IEC 60068-2-13, IEC 60749, MIL-STD-810F). • Variable LVAC connection 120 MVA (max 40 kV). • Variable MVAC connection (max 40 kV, 120 MVA). • Variable MVDC connection (max 5 kV, 120 MVA). • Partial Discharge test facilities. • Short circuit test facilities for AC and DC	1, 2, 5, 6, 14
21	**NLR**	Netherlands	**Electric Systems Test Facilities**	2-14, 19-22

			NLR’s electric systems test facilities cover a wide field, including Vibration and Shock, Thermal Vacuum chamber, Climate chambers, and EMC. **Vibration and shock** These tests can be done in accordance with any applicable standard including the RTCA DO-160F, MIL-STD810F and IEC standards. Also dedicated test procedures can be applied. The VST laboratory is included in the Dutch Accredition Counsil (RvA) register of test laboratories under no. L220, for areas described in detail in the accreditation. The two larger shakers (V810, V875) are used for general purpose vibration and shock tests, the smaller shaker is especially suited for small items that have to be tested for a high level/high frequency environment (e.g. turbojet engine components). A sine vibration level of 60 g for a 3 kg load is feasible up to 5 kHz. Removable clean room (guaranteed up to Class 100,000, FED-STD-209B/ ISO 14644-1 Class 8), with contamination monitoring equipment. A temperature chamber which can be used in conjunction with the V810 shaker to create a temperature. A temperature controlled slip-table for thermal isolation. Laser-based vibrometers for vibration measurements without mass loading (Ometron VH300, MicroEpsilon NCDT1700 laser displacement sensors) Slip-table dimensions, loading: 75cm x 75 cm, max. 600kg. **Thermal Chamber** Chamber dimensions inside 1100 x 1200 x 1200 mm. Temperature range -80°C tot 300°C. (extension to -150°C). Positive gradient (heating ramp speed) up to +35°C/min. Negative gradient (cooling ramp speed up to -35°C/min. **Thermal Vacuum** Inner dimensions: 150 cm x Ø90 cm (length x diameter) Shroud temperature: • Temperature range: -175°C up to +150°C	

			• Temperature gradient: -3°C/min to +1.7°C/min Vacuum pressure: • Ultimate vacuum: 2 x 10-7 mbar (= 2 x 10-5 Pa) @ 20°C • Pump down period to 10-5 mbar: 9-30 hours, depending on test item outgassing and pump down temperature • As altitude chamber: 1-950 mbar (>100.000 ft/32 km) **Small heat sink/cold plate** Specifications (single plate): • Temperature range: -150°C up to +120°C • Temperature gradient: -10°C/min to +7°C/min **Large heat sink/cold plate** Specifications (one low power (LP), one high power (HP) available). Both can be used together: • Temperature range: -175°C up to +200°C • LP sink: Temperature gradient: -18°C/min to +4.7°C/ min • HP sink: Temperature gradient: -18°C/min to +9.0°C/ min • Heat sink/cold plate dimensions: 610x504 mm • Aluminium adapter plate dimensions: 610x504x8 mm **EMC Test facility** EMC anechoic chamber dimensions: 12.0 m (L) x 6.6 m (W) x 6.1 m (H). The EMC tests are performed in accordance with most applicable aerospace standards including Eurocae ED-14 / RTCA DO-160, MIL-STD-461 and OEM standards such as Boeing D6-15050 and Airbus ABD-0100. Other standards (e.g. FCC, IEC, DEF-STAN) and dedicated test procedures can also be supported. The NLR EMC test laboratory is included in the Dutch Accreditation Council (RvA) register of test laboratories under no. L220, for areas described in detail in the accreditation. The NLR EMC facility operates test equipment to perform Lightning Induced Transient Susceptibility tests according ED-14 / DO-160 section 22. The NLR EMC facility operates test equipment to perform Lightning Induced Transient Susceptibility tests according ED-14 / DO-160 section 22 and MIL-STD 461G section CS117.	

			Waveforms: 1, 2, 3, 4, 5A, 5B, 6 Level 1 to level 5 Single Stroke, Multiple Stroke, Multiple Burst Pin Injection, Cable Induction, Ground Injection. Other capabilities of the NLR EMC facility are: - In-situ EMI tests to customer specifications - Helicopter platform annex Open Area Test Site (OATS) for emission measurements and antenna calibrations. - Variable frequency AC power source for power quality tests. - Wiring and cable shielding measurements (crosstalk and transfer impedance) In addition to measurements the EMC laboratory is also involved in modelling and analysis of the EMC characteristics of cables (crosstalk and transfer impedance) and is involved in the analysis of potential electromagnetic interference on aircraft and airports. **Energy Management** Wide range of thermal control solutions and testing, focused at two phase MPL, and heat pipes. Development, simulation, modelling, testing and validation of thermal control solutions up to MW. **Open Test Facility** For large size and high power electric and hydrogen equipment testing. Currently under development	
21	**NASA**	USA - Ohio	**Electric Aircraft Testbed (NEAT)** Being developed to enable end-to-end development and testing of the electric portion of MW-scale electric aircraft powertrain systems - Power up to 12 MW (more if regenerating). - Cooling tower with 950 kW cooling capacity (additional chillers, etc. can be used as well). - Altitude (up to 60,000 feet pressure). https://ntrs.nasa.gov/api/citations/20200001643/downloads/20200001643.pdf	14, 15, 20

22	**Collins Aerospace**	USA - Illinois Rockford	**The GRID – electric power system lab** High power, high voltage facility Design and test 1MW motor for project 804 HE flight demonstrator https://www.collinsaerospace.com/news/news/2019/04/collins-unveils-plans-redefine-future-electric-flight-the-grid	5
23	**Boeing**	USA	**Test & Evaluation (T&E) Airplane Zero Lab** Integration Test Vehicle Lab • Lab testing for integrated aircraft systems • To test 777X in a virtual environment before first flight, Hardware in the Loop https://www.aerospacetestinginternational.com/features/laboratory-testing.html	
24	**Crane Aerospace and Electronics**	USA Fort Walton Beach	**High power lab** • 1 MW Power Availability • Discrete/Systems • Three Overhead Power Rails • 277/480 Vac • 120/208 Vac • Variable Voltage, Variable Frequency • Static/Pulsed Loads • Environmental Capability • Multiple Workstations https://www.craneae.com/news/welcome-powerhouse-crane-aes-new-high-power-lab	
25	**BAE Systems**	USA New York	**Aircraft Electrification Lab** Maturing energy storage, controls, and power conversion systems for aviation applications https://www.baesystems.com/en/feature/bae-systems-makes-multi-million-dollar-facility-investment-to-support-aircraft-electrification	
26	**General Electric**	USA Winnipeg	**Aircraft engine facility** – Winnipeg Testing Research and Development Centre • 11-fan wind tunnel	

			- It allows testing of the industry-leading GE9X engine, which will power Boeing’s 777X aircraft. https://www.economicdevelopmentwinnipeg.com/newsroom/read,post/710/ge-opens-upgraded-aircraft-engine-testing-facility	

The table, although lacking information for some facilities, shows that, at first sight, many testing needs are already covered by existing facilities in Europe. In particular, facilities of the University of Nottingham cover a broad scope of tests, from components to integrated systems, even for high power testing. NLR also has a broad scope of testing means, including some for integrated systems, but mainly for low power systems. In addition, the University of Strathclyde have significant experience with integrated systems testing facilities incorporating dynamic loading and fault testing across facilities up to the MW scale. The SAFRAN Group have a large panel of facilities for components and subsystems, while a large facilities is available at Airbus for high power integrated tests (20 MW). Facilities also exist at DLR for fuel cells and at AIT or CEA for battery testing. Applicability of some facilities may depend on the targeted range of power and would need a more detailed analysis on a case-by-case basis for a given project.

Available facilities belong to different types of actors: universities, research centres and industry. Generally, facilities of research centres and universities are open to industry, which might not be the case for industrial facilities. Industry, in the context of an industrial development, may also favour internal facilities.

A deeper analysis would certainly be required to identify precisely the gaps, which would also require a more precise identification of the targets that will be pursued on hybridization by industry players in the coming years. Yet, a capability that seems to be lacking is the ability to connect remotely testing means to combine available capabilities for subsystem or system testing.

As a complement to the information collected in the previous table, the RINGO[1] project shall be mentioned here. RINGO (Research Infrastructures - Needs, Gaps, and Overlaps) was a Coordination and Support Action funded by the European Commission (EC) under Horizon 2020. The RINGO project was tasked to provide an analysis of Needs, Gaps and Overlaps of European Research Infrastructures in order to reach Flightpath 2050 goals, as well as to provide concepts and ideas for sustainable operating and business models for such RIs. It detected needs for aviation research infrastructures in Europe and concepts and ideas for sustainable operating and business models for their management. A catalogue containing about 350 RIs operated mostly by research organisations and universities, but also by private companies, was compiled and delivered to the European Commission. Research infrastructure were classified as “strategic”, “key” and “common” and clustered in eight classes (wind tunnels, propulsion bench, flight test bed, structures, material, simulator, supercomputers and “others”). Needs for HEP were considered within RINGO Project[2]. However, related facilities cannot be easily identified from the interactive catalogue on RINGO website and the description of facilities' capabilities is lacking.

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[1] http://www.ringo-project.eu

[2] RINGO Final Report - Results by research fields - *RINGO Project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 724102*.

RINGO final reports indicates that: "*In the field of electric and hybrid propulsion RINGO collected 24 needs for aviation research infrastructures. From the analysis of those needs, 12 asset gaps*[3]*, 5 capability gaps*[4] *and 7 identities*[5] *were identified.*" The gaps covered a wide range of facilities including flying test beds, climate chambers for battery packs and fuel cell, gas turbine test bench with attached electric machines, test rigs for battery safety, power train test rigs and facilities for hydrogen. It would be certainly worthwhile to update RINGO analysis and catalogue in light of the most recent results, developments and perspectives for HEP. Therefore, it is suggested that the EC supports an update of RINGO effort including HEP needs described in IMOTHEP deliverable as well as the test facilities needed to demonstrate fuel cells, ground infrastructure for refilling and recharging new energy sources at airports, logistics of supply, environmental and safety conditions. Considering some facilities currently not used for aeronautics (for instance high voltage and current test facilities used for civil electrical network qualification) could also be a way to cover some of the needs.

3.GENERAL CONSIDERATION FOR TESTING FACILITIES

IMOTHEP discussion and workshop results suggest that the preferred option is that the testing infrastructures listed in section 2 would be available in Europe to preserve its technical and scientific sovereignty, simplify the access of European stakeholders and limit cost. Often, as per the list in section 2, they are available in the EU but they may need a relevant refurbishment or they should be made accessible being private. In other cases, like the full-scale engine test cell suitable to HEP or the hydrogen test facility, they may require a deep redesign thus implying a brand new facility. In all cases, and namely in case of new facilities, several parameters have to be considered in the decision to build a new test facility, including the following ones.

- Use for applications other than aerospace for economic viability. It is in theory a very relevant option but the performance targets of the facility required by HEP and aeronautics in general may be more severe than other applications. A detailed feasibility study is required to design correctly the facility size, its performance and test instrumentation.

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[3] An "Asset Gap" shows a research infrastructure need, which cannot be met by the existing research infrastructure landscape.

[4] A "Capability Gap" indicates that existing research infrastructure facilities could be modified or upgraded to meet presented requirements, thereby providing a short cut towards the FP2050 goals.

[5] An "Identity" indicates that today's available research infrastructure will also meet forthcoming demands, and should therefore continue to be maintained in the future.

- Cost infrastructure/maintenance/skilled persons. To run such very peculiar and "frontier" test facilities require personnel with exceptional skills and know-how and their continuous update to follow technology evolution. This suggests that a public support is paramount at least to the continuous improvement.

- National or European facility. In most cases those facilities, either only for HEP validation and testing or for other application too, are meaningful only at the EU level because the size and frequency of use is justified only at the EU level, and maybe if open also to other applications having similar testing needs.

In alternative to testing facilities, IMOTHEP partners identified three options.

- **Use Model + Validated tool + Link among partial tests + extrapolate tests from subsystem tests**.
  This seems the simplest solution to limit the cost and have an immediate return to EU stakeholders. The option simply divides the complete testing "all included" in separate parts then linked each other. Each of the steps will require a separate validation probably using smaller and simpler facilities. Yet, strong limitations arise that will probably limit the scope of this option only to support preliminary design phases and not for the validation of final HEP propulsion and configuration or maturing data for certification and permit to flight test because models and design tools may not be validated at the right scale and performance range. The missing step here is a suitable test facility or a reliable tool to extrapolate smaller scale results to the HEP actual size. Another weakness, considering the complexity of tests and the number of interactions, is that often the relevant interactions (reason for the full scale test actually) are not known in advance so interactions of data sets from two separate facilities or steps may concern only a subset of parameters and not real time interaction. In conclusion, this "partial test patchwork" may not see hidden and secondary effects not evident in the available models and tools and caused by the new performance required by HEP often orders of magnitude different from existing systems at the edge of technology.

- **Fly test bed.**
  Flight test bed will provide data at real scale, in real environment about HEP performance and features. Yet they are expensive, time consuming and not flexible to adapt test configuration to on-going results. A suitable and flexible aerial platform to perform them is required with the ability to modify it to integrate properly the HEP items. The testing will require anyhow the support of relevant ground test results to allow certification authority to issue the permit to fly. In addition, for some hybrid configuration, the strong interrelation between the propulsion system and the aircraft architecture (e.g. for distributed propulsion) may not allow to test a full or fully representative propulsion system on available platforms. Flight test shall then maximise the investigation of criticalities and extrapolation approach may be required for the future aircraft product.

- **Test benches plug-in capabilities.**
  This option concerns a test bench with a plug-in capability from another separate test bench running in parallel on its own but exchanging real time data on a large bandwidth channel. This is possible when a proved simulation is available providing the major data interactions in quantity and quality. However, the risk to miss unknown but relevant interactions is real.

4.CONCLUSIONS AND PROSPECTS

This deliverable D6.4 has reviewed the needs for infrastructures for the maturation and development of HEP.

Considering the different levels of constituents in a hybrid propulsion chain, IMOTHEP performed an analysis of the testing needs at three levels: components, subsystems and integrated systems.

Nine HEP components requiring testing were classified: generators, motors, power electronic converters, cables, batteries, fuel cells, solid-state power switches, circuit breakers, connectors, thermal system components. Seven specific tests required for the components were identified: partial discharge, short circuit tests, ageing tests, EMC tests, performance tests, environmental tests (DO160), thermal management. Components are to be tested at full power for a TRL6 demonstration.

Eight HEP subsystems requiring testing were classified: turbogenerator, battery/ fuel cells with power electronic converter, control system, thermal management system, power distribution, power management, electrical power unit, hybrid turboprop, thermal management system. Seven specific tests required for High Voltage/High power subsystems were identified: emergent behaviours tests, fault insertion/coordination tests, EMC tests, performance around operational envelope tests, benchmark testing, tests to support development of standards/compliance, environmental qualification tests. Subsystems are to be tested at full scale, TRL6, MRL7.

Eight integrated systems testing requirements were identified: MW class electric/hybrid propulsion, high performance computing centre, certification virtual reality facility, full-scale crashworthiness and fire protection facility, thermal bench, full scale engine test cells, Electromagnetic Compatibility (EMC) and High Intensity Radiated Field (HIRF) anechoic chambers, hydrogen propulsion and liquid hydrogen storage facility.

The project also performed a screening of existing facilities, mostly in Europe but also in the USA, which could support the development of HEP. The screening performed during the project identified a total of 27 facilities, belonging to 18 different organisations, 6 being in the USA. To the extent that relevant information were available, data on the testing capabilities of these facilities were recorded. It is suggested that the EC supports an update of the work performed during the RINGO project to take into account recent developments on HEP and include HEP needs described in IMOTHEP deliverable, as well as the test facilities needed fuel cells, ground infrastructure for refilling and recharging new energy sources at airports, logistics of supply, environmental and safety conditions.

IMOTHEP discussion and workshop results suggest that the preferred option is that the testing infrastructures listed in section 2 would be available in Europe to preserve its technical and scientific sovereignty, simplify the access of European stakeholders and limit cost. Often, as per the list in section 2, they are available in Europe but they may need a relevant refurbishment or they should be made accessible, being private. In other cases, like the full-scale engine test cell suitable to HEP or the hydrogen test facility, they may require a deep redesign thus implying a brand new facility. In case of new facilities, several parameters have to be considered in the decision to build a new test facility such as the possibility to use alternative approaches such as model and validated tools, link among partial tests, extrapolation from subsystem tests, fly test bed and test benches plug-in capabilities.

5.References

- [1] Kjeldaas, Kent Aleksander, Rune André Haugen, and Elisabet Syverud. "Challenges in detecting emergent behavior in system testing." *INCOSE International Symposium*. Vol. 31. No. 1. 2021.
- [2] *WP6.3 Report* "Demonstrators for the development of HEP"
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