Publishable Summary

Background
The EU funded technology programme ENOVAL (ENgine mOdule VALidators) significantly contributes to a cleaner and quieter aviation future. It provides the next step of engine technologies to achieve or surpass the ACARE 2020 goals on the way towards Flightpath 2050. ENOVAL completes the EIMG roadmap of Level 2 aero engine projects within the European 7th Framework Programme (FP7). ENOVAL runs in conjunction with the EU projects LEMCOTEC, considering core engine technologies, as well as E-BREAK, investigating system technologies for enabling ultra-high overall pressure ratio engines. ENOVAL focuses on the low-pressure system of geared and direct-driven ducted turbofan engines with Ultra-High Bypass Ratios (UHBR) from 12:1 up to 20:1 and Ultra-High Overall Pressure Ratios (UHOPR) from 50:1 up to 70:1. Resultant engine configurations, with fan diameters being 20% to 35% larger than the year 2000 reference engine, can still be installed within the limits of a conventional aircraft configuration and, thus, are fully in line with the SRIA roadmap for 2020. These engines are amongst the best candidates for the next generation of short/medium and long range commercial aircraft applications with an entry into service date of 2025 onward.

After the ramp up and conceptual definition phase the ENOVAL programme has now finalised its second reporting period (M19 – M36) with the design and manufacturing of the relevant rig test hardware as well as the definition and preparation for the final test activities. Some tests have already been started or even finalised.

Overall ambition
The global project objectives remain the same since the project start: to reduce CO₂ emissions and perceived noise of future aero engines and successfully validate innovative technologies at component level (i.e. up to TRL5) through 18 rig tests.

The overall targets of ENOVAL are:
- CO₂ reduction by 5% within the project alone achieving a cumulated CO₂ reduction of 26% for long range applications compared to technologies representative of year 2000. For short/medium range turbofans the CO₂ reduction will be 3% alone achieving a cumulated CO₂ reduction of 24%.
- Overall reduction of engine noise emission by 1.3 EPNdB alone achieving a cumulated reduction in the range of 9 EPNdB.

The 5% reduction in fuel burn will result from 5% higher propulsive efficiency and 1.5% better module efficiencies compensating the 1.5% increase due to weight and drag. The noise reduction results from a 1.1 EPNdB jet and fan noise improvement complemented by LP turbine noise reductions. This will have significant economic and societal impacts for an Emission Trading System and for the public acceptance of the necessary infrastructure development.

Relevance
At the Aerodays 2015 in London and the Greener Aviation Conference 2016 in Brussels the conference presentations and discussions solidified the relevance of UHBR and UHOPR aero engines as the next step for commercial aircraft applications. Already during the preparation phase of the ENOVAL project the market for new commercial aircraft had evolved significantly with high volume orders for aircraft with new engine technologies (PW1000G or LEAP X) and requests for further developments in fuel burn and noise reductions. Current market forecasts from Airbus or Boeing state the growth of passenger traffic at 4.5% and the need for some 33,000 new aircraft over the next 20 years. There are strong indications and activities providing evidence that the trend for new engine architectures follows the SRIA outline for UHBR ducted turbofans (BPR >12): Rolls Royce promotes the “Ultrafan” engine concept, and CleanSky 2 Engine ITD work packages include UHBR and UHOPR engine concepts. Therefore the technology work which is performed within the ENOVAL project is considered to be highly relevant for the definition of the next generation of commercial aircraft engines.
Progress and main results achieved in the second period (M19 – M36)
The following main achievements were made in the five sub-projects:

Integration and Assessment (SP1)
After the initial engine and reference aircraft specification in the first project period the overall objective within the second reporting period was to complete the respective specifications to support the component technology work packages and to prepare for an initial evaluation of the technical results and environmental benefits of the ENOVAL project. The final engine platforms are now finally defined in line with the modelling and the sizing of the three reference aircraft and including a revision of the power gearbox design for the Large Turbofan engine platform. A matrix of the technologies being developed in ENOVAL was created and updated to be the basis for the initial technology assessment. Also the Future Propulsor Concept Studies were continued and the main portion of the development of models and evaluation of the studied technologies was performed. The results of these studies and the initial technology assessment are expected to be presented at the 2nd Contractual Review Meeting in January 2017.

Medium Fan & Nacelle (SP2)
The main objective of SP2 is to mature innovative fan module, VAFN and acoustic liner technologies that will be included in fan and nacelle modules of UHBR engines dedicated to short and medium range aircrafts applications up to TRL 4-5. Within this second reporting period the progress towards technology targets of SP2 has been followed and reported to SP1 for overall assessment.

Design works of the fan module have been performed during the second period including aerodynamic, aero mechanics and acoustics optimization where the CDR was successfully passed. The main geometric parameters of the casing treatment affecting the margin and the efficiency of the fan were identified. For the OGV serration technology, CFD calculations of the fan-OGV stage have been performed to check the aerodynamic performance (pressure losses) of the serrated OGVs at the fan nominal speed. The full scale fan blade design has been frozen in February 2016. Consequently to the freezing of the design, drawing and procurement of the necessary material and manufacturing of the fan module and adaptation parts are now in progress, and iterations with the fan blade manufacturer are ongoing. A metallic additive manufacturing test on a scaled OGV has been carried out in order to accelerate getting the OGV with such a complex shape. The preparation of the fan rig test at the test bench facility PHARE 2 at ECL is still in progress and focuses on the definition of the instrumentation including localization of the instrumentation and design of specific rakes and sensors for the optimization of the test matrix.

Concerning the acoustic concepts, the assembly of a prototype electrodynamic panel made up of 30 cells that will be tested in the NLR facility has been performed, and the test in the NLR facility including material validation prepared. The electrodynamic panel is ready and has been tested in a wooden duct (without grazing flow) with the same cross section to de-risk the tests at NLR which were scheduled for September 2016. For the “soft wall” concept, acoustic measurements have been conducted in the CEVAA (Rouen, France) facility at the end of 2015. In addition ECL has developed an acoustic impedance eduction method for the identification of the impedance characteristics of the acoustic liner in a duct under a grazing flow.

After the evaluation of several VAFN concepts, the hardware for the mechanical test of the chosen VAFN door mechanism concept was built and the test has been performed with some tuning in order to properly simulate the aero loads. The test campaign has been completed with 60 tests performed, which demonstrate the global stability of the door kinematics.

The numerical investigations for the 3D optimization of an air intake to assess the aero lines have been completed. Several configurations were studied to find the optimum of the air flow behaviour with the Integrated Particle Separator in ON and OFF mode. All aero lines and interfaces were released to complete the design of the air intake module.

Fan and Nacelle for Large Engine (SP3)
SP3 is about to develop technologies to improve the efficiency and reduce noise of the large fan engine including an advanced large low pressure ratio fan module and a novel intermediate case with optimized OGV and a VAFN in the nacelle.

In the second period the fan system has been designed after full specification of the Large Engine Platform considering the integration with the airframe. This was based on conceptual fan design studies applying automated optimization strategies in combination with 3D-CFD and FEM analysis, where 50 variable design parameters were used in the design optimization process and 3 operating conditions were considered simultaneously.

A scaled fan system aerodynamic test for the Anecom modular fan rig facility was specified to validate analytical methods to allow the design of more efficient low speed fan systems. This includes a detailed list of instrumentation to allow high
quality noise and performance measurements. Various microphone/sensor configurations in the interstage section have been analysed, with respect to their performance as beamforming arrays. The manufacture of all of the new rig hardware has been completed and components are currently undergoing instrumentation prior to assembly into the rig modules.

An intermediate case (IMC) structure is being designed according to the specification, which covers the functional and structural requirements. This design includes two types of OGVs: primary structural metallic OGV and a general composite/metal hybrid OGV based on a polymer composite material, a light weight core and advanced joint. RTM manufacturing process simulations were developed to predict shape distortions due to curing of the thermoset resin.

A full scale demonstrator with a titanium hub frame, single configuration OGVs and an aluminium fan case ring was built and tested in several component test setups for ice impact, bird impact and joint strength and damage tolerance. The tests were successful and validated both the design’s capability to cope with the requirements and at the same time provided important data for verifying predictive models.

A rig setup to simulate engine loads in the full frame has been designed and built, which contains all six degrees of freedom of global loading. The full frame mechanical testing has been started and currently the data collection and post-processing is ongoing. A total of 6 load cases have been performed.

From the various design concepts of a VAFN that were carried out in the first project period, a down selection to meet the requirements for area change, rate of actuation and accuracy was performed to an aft door VAFN with a segregated actuation system. This configuration needs to be validated with respect to aerodynamic performance and mechanical behaviour for the actuation powertrain. The validation strategy of a half or a 360° model for the aerodynamic test is still in discussion. For the one door mechanical test the facility is selected and the design, validation and manufacturing of the test model and the test bench are completed.

**Low Pressure spool (SP4)**

SP4 activities continue to concentrate on the low pressure spool technologies separated into the different components of the low pressure spool: transmission system, low pressure compressor (LPC), and low pressure turbine (LPT).

All three ENOVAL platform engines, which were specified in the first project phase, have a transmission system through a gearbox. Due to a change in the boundary conditions on the large turbofan engine – long range mission platform, the gearbox trade-off analysis detailed in D4.1.1 was repeated for the above platform.

For the intended rig test the epicyclic gear test article reference design is completed. Several design iterations were necessary in order to complete the reference design respecting project objectives and budget constraints. The main improvements of this redesign activity are weight reduction, oil network improvement, and optical access optimization by means of a CFD assessment. The test matrix for the test campaign was defined and activities were carried out to measure oil jet and windage losses on single and paired representative gears. The rig was upgraded to handle test conditions representative of the epicyclical test article. These activities are preparatory to measure windage losses on the final epicyclical test article rig.

A CFD model to analyse the fluid dynamic losses in planetary gear trains was developed together with a strategy for decoupling the losses in order to limit computational effort.

The methodology for improved modelling capabilities to expand its applicability to different epicyclical gearbox configurations was developed as well as the dynamic transient capability with sub-reduced models.

In the work package for the low pressure compressor (LPC) one objective is the design and test of an advanced high load speed booster, for which the CDR to freeze the aerodynamic and mechanical design has been passed followed by the integration of more than 900 sensors to the test vehicle. Final iterations on aerodynamic and mechanical interactions were carried out to establish the booster map, and partial testing of some critical components has been performed to ensure the fit of numerical analysis to the real behaviour of the parts. After the design and manufacturing most of the tooling is available to continue assembly. At the test site the adaptation parts interfaces have been frozen to ensure the correct installation of the test vehicle to the test rig.

The second objective is to investigate the boundary layer aspiration technology to increase the compressor surge margin and to enhance the engine operability. After the design phase the parts in concern were manufactured, however for the compressor casing aft the deposit of the black layer has failed. The part was largely damaged and had to be scrapped. Therefore a new one was ordered resulting in an increased lead time of the test module. As a result of the numerical flow analysis the slots have been manufactured close to the vane suction side in the shroud and the hub corner. Following the delivery of all parts and the instrumentation phase, the compressor test module was finally built, delivered and installed on the test rig ready for testing.

Following the high speed requirement for the geared very large turbofan engine platform an integrated ITC / LPT design was carried out to achieve an aerodynamic optimization taking into account HPT and LPT interaction to generate an optimal inlet flow for the first vane of the LPT. The detailed design of the new parts has been finished and procurement
started. An instrumentation plan has been developed. In addition enhanced material modelling capabilities for integral structural parts in the ITC are developed for a nickel cast alloy and therefore fatigue and deformation tests are carried out on standard specimens to identify the most accurate lifting concepts with respect to multiaxial fatigue and fatigue in notches. Up to now, notched LCF testing (70%), thermo-mechanical fatigue testing (80%) and CLCF testing (100%) is almost done.

For the integrated LPT/TEC the design of the TEC has been performed considering the LPT/TEC interaction effects on module level. The acoustic liner design and manufacturing approach has been validated through coupon tests and modelling. The results are in excellent agreement giving confidence in the noise reduction potential of the 3D printed liners. The TEC is assembled for further integration to the test rig to be tested at a high altitude test facility in two phases with and without acoustic liners between the TEC-struts.

In the first reporting period a state-of-the-art TEC was experimentally investigated as reference in the high speed cascade wind tunnel. Now a new highly loaded profile was designed which includes active flow control by fluidic oscillators, and a cascade for wind tunnel testing was manufactured and tested. The experiments demonstrate that active flow control with the fluidic oscillators is a highly efficient concept to avoid open flow separation in the low Reynolds number regime.

Further tests are in preparation.

For the low speed low weight/noise and high efficiency LPT one objective is to run the test for the noise reduction technologies and perform an acoustic validation of middle & rear LPT stages in a first test campaign. The first rig was a multistage rig redesign where clocking and complex 3D optimized geometries were introduced. The tests for the multistage rig were run successfully and the new noise module performed as expected. The final post-test review and analysis of the results confirmed the expected behaviour. Meanwhile design, manufacturing and assembly are ongoing for the second test rig which is going to provide an aerodynamic validation in a middle & rear LPT stages environment. The second rig was also a redesign of a 181/2 stages rig for the evaluation of trailing edge (TE) and 3D design within a multistage environment on the NGV performance. The actual status is that the manufacturing of casings and vanes has been completed and instrumentation and assembly activities are ongoing.

A second objective is the introduction of novel disk materials through an integrated design-manufacturing process allowing higher cycle temperatures and higher disk life requirements. First specimens for fatigue testing and determination of initiation of cracks were provided and an early crack detection method with thermography imaging was successfully determined. Fatigue testing including thermography imaging has been successfully implemented to detect crack initiation. Samples were tested in the as-machined and after shot-peening conditions. Analytical models have been used for the analysis of back-propagation from critical crack size to first cycle. Also the setting-up of a finite element model able to predict the surface integrity conditions depending on the working conditions, tool wear and work-piece material was done for the nose turning process. In line with the modelling activities the identification of the material constitutive law for Inconel 718 was started.

To improve the interaction between the ITC and the low speed LPT, an integrated design approach and a split into two different aerodynamic rigs was necessary, completed by a grazing flow rig for liner characterisation. The main activities in this reporting period were focused on progressing and finalizing the design of the aerodynamic and acoustic rigs, along with launching manufacturing and procurement phases.

The aerodynamic design on aggressive inter-duct module was completed and respective reviews were passed. The test rig has been modified to meet all the requirements for the experiments. The HP turbine is already manufactured and installed in the rig and the HP turbine shaft balanced and commissioned. The turbine has been instrumented with a tip clearance measurement system. A secondary air system has been designed and built up from scratch in order to provide the different independent purge flows to the two turbine stages with correct mass flow rates and temperature.

For the two stage rig, 3D unsteady CFD analyses supported defining final geometries to be tested. CAD models of the different parts have been generated and feasibility studies aimed to define best solutions for manufacturability have been launched and completed. The manufacturing activity has been launched and is in completion. The rear frame together with other parts manufactured has been already delivered to the test site.

Also the detailed design of the grazing flow acoustic rig has been finalized and first liner samples are produced and verified. Currently the rig manufacturing is ongoing.

**Management, Dissemination and Innovation (SP5)**

The main objective for SP5 in the second reporting period was to further maintain the project infrastructure, continue to carry out the financial and contractual management, plan and support dissemination activities and manage the foreground generated and its exploitation.

Based on the recommendations of the Reviewers during the 1st Contractual Review Meeting the deliverable review process has been streamlined including an update of the deliverable template. The deliverable performance has significantly improved. Also a strict and condensed monitoring of the main rig tests has been established.
The EC Project Officer and the Reviewers were regularly informed about news, major events or dissemination activities and the coordinator provided a progress report including slides and photos for the second Internal Review Meeting covering the period M19-M28.

As a basis for this report the fourth amendment request to the Grant Agreement was submitted to the EC in July 2016 and approved on 30th September 2016.

For dissemination purposes a project flyer has been published in 2015, which provides information on the project’s objectives, the ENOVAL engine illustrations and the consortium. To improve the dissemination of ENOVAL research and development at universities and to facilitate the education and later recruitment of engineers, 10 ENOVAL learning modules with specific scientific/technical topics were provided and are available for download on the ENOVAL website.

ENOVAL attended the Aerodays in October 2015 in London, UK where it shared a booth together with its sister projects E-BREAK and LEMCOTEC, and gave a presentation at one of the event’s parallel sessions. At the DLR Congress 2016 which took place mid-September in Braunschweig, Germany ENOVAL had a shared booth with MTU. Within the second reporting period preparations commenced for a workshop dedicated to the supply chain and SMEs at the AIRTEC 2016 in Munich which will take place in late October 2016.

The project main technological achievements and their innovation potential was summarized and presented at the end of the 1st Contractual Review Meeting as well at the 2nd Internal Review Meeting by the ENOVAL Chief Engineer.

**Deliverable Status**

The status of deliverables at the end on the second contractual reporting period end of September 2016 has significantly improved compared to P1. Out of a cumulated total of 64 deliverables planned until the end of the reporting period (M36) 53 deliverables were provided and uploaded into the ECAS system, whereas 3 reports are already drafted and currently in the approval process. Unfortunately, 8 deliverables are slightly delayed, half of which being the results of WP1.3 studies on future propulsor concepts, closing by the end of the year 2016. Hence, the delay, although regrettable, has no consequence on SP1 and the overall project.

**Conclusion**

In the second reporting period, between M19 and M36, the ENOVAL project progressed significantly with the finalisation of concepts followed by the design activities for the respective modules and the intended validation tests. Manufacturing and procurement for most of the required test hardware is launched or even completed and the test preparation in terms of modifications or instrumentation has started. Some testing activities have already been performed, but the major part of validation tests is still to come, which will be challenging to finalize within the planned project duration. The deliverable performance has significantly improved. The technical contents are still highly relevant and the interim assessment of the investigated technologies indicates that the overall project objectives can be met.