FINAL PROJECT REPORT

OPEN ROTOR ENGINES ADVANCED TECHNOLOGY II

PITCH CONTROL MECHANISM

DELIVERABLE REF: D1.6

JTI-CS-2011-1-SAGE-02-006

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Table of Contents

Table of Figures

1 ABBREVIATIONS

CDR	Critical Design Review
CROR	Counter Rotating Open Rotor
CS&DAQ	Control System and Data Acquisition
EHS	Environmental Health and Safety
FICD	Functional Interface Control Document
FWD	Forward
MTB	Modular Test Bench
MTB SI	Modular Test Bench System Integration
OREAT	Open Rotor Engine Advanced Technology
PCM	Pitch Change Mechanism
SAGE	Sustainable and Green Engine
TRR	Test Readiness Review

2 INTRODUCTION

The contents of this report were prepared for the OREAT 2 project that is part funded by the European Commission under the Clean Sky Joint Technology Initiative.

Clean Sky Reference *OREAT* – JTI-CS-2011-1-SAGE-02-006

3 Final Publishable summary report

3.1 Executive Summary

Environmental considerations defined by Clean Sky objectives such as reduced aviation carbon footprint, reduction of nitrogen emissions and noise, demand significant fuel burn reduction over current state of the art aviation propulsion systems. An Open Rotor propulsion system has higher propulsive efficiency than the current technology by virtue of its much higher By-Pass Ratio (BPR), a major contributor in achieving significant fuel burn savings. In order to maintain each propeller in a contra-rotating propeller at its correct and efficient operating point, its blade pitch must be controlled to absorb the supplied power and achieve the required rotational speed. The most effective systems in use today have independent hydraulically actuated pitch-change mechanisms (PCM) driven by a single turbo-propeller engine through a differential epicyclical gearbox. A Counter Rotating Open Rotor (CROR) in a Pusher configuration, such as the SAGE2, adds additional elements of technical difficulty i.e. blades that are situated at large diameters, severe thermal conditions and extreme loads. A novel pitch control mechanism is required for actuation and control of the blade pitch of an Open Rotor engine. Furthermore, robust and accurate PCM control system is crucial for exact control of the blade pitch and thus for frictionless operation of CROR engine. This project was aimed to address PCM technology maturation and development challenges required for reliable Pitch Change Mechanism operation in SAGE2 Counter Rotating Open Rotor engine.

Two main deliverables were foreseen as part of this program:

1. A preliminary design of the forward and aft pitch change mechanisms for the SAGE2 Open Rotor
2. A pitch change mechanism architecture with a Technology Readiness Level of 5

Both of these objectives were successfully met within this program. The first was through the delivery of both 3D models and successful completion of Preliminary Design Reviews for both FWD and AFT PCMs with the Topic Leader. The novel designs were able to meet all of the difficult integrational and functional requirements.

The second, and much more involved subject, was to ensure that the main PCM architecture was verified in a laboratory environment. In support of this point, a new test facility was developed to perform full scale system integration testing of a PCM. The testing was successfully carried out with the Topic Leader in the first quarter of 2016. The testing was broken down into two main areas; verification of PCM characteristics and endurance testing. Several key conclusions were made regarding the PCM as part of this testing:

- on the whole modelling of PCM characteristics was validated
- the PCM architecture did not undergo any unforeseen failure or wear as a result of the test campaign
- several novel solutions (lubrication and kinematics) worked successfully

The overall conclusion is that the PCM architecture that was tested as part of the OREAT II project could be used for the SAGE2 GTD testing.

3.2 Summary description of project context and objectives

The OREAT II (**O**pen **R**otor **E**ngines **A**dvanced **T**echnologies) program, a follow-up to OREAT I, whose main goal was to mature Open Rotor PCM concepts, defined in the latter. The OREAT Consortium was made up of three different partners; General Electric Company Polska (GECP), General Electric Aviation Systems (GEAS) and the Institute of Aviation in Warsaw (WIA). The project started in December 2011 and lasted 52 months, finishing in March of 2016.

3.2.1 Background

Open Rotor blade pitch change mechanisms add a great deal of unavoidable dynamic mechanical complexity to aircraft propulsion systems, particularly with pusher-configuration engines. It will be one of the greatest challenges to the eventual introduction of the undoubted open rotor efficiency benefits into commercial aviation to overcome the unreliability burden that comes with this complexity, particularly in the especially difficult environment of the pusher configuration.

During the OREAT I Program, several Key Technologies were identified for comprehensive testing to assess and improve their reliability and durability in the PCM and Open Rotor environment.

3.2.2 Objectives

The program of design, testing and dynamic modelling was to have a strong positive impact on the verification of component reliability, durability and system interaction which would then lead to a reduced risk for the SAGE2 program as a whole. Specifically the full scale testing of the main PCM architecture was to provide a very good insight into high risk areas such as:

- Assembly
- Balancing of a rotating structure with translating features
- Large diameter actuation and sealing capability
- Complex PCM kinematics
- Hydro-mechanical system interaction
- Durability of components in an Open Rotor environment

3.3 *Description of main S&T results/foregrounds*

Based on the first objective of providing preliminary FWD and AFT PCM designs, two unique approaches were taken for the SAGE2 GTD. The FWD PCM design was based on the principles of minimizing complexity by having a minimum part count and relying on mature standard components. The design was prepared so that it would not vary greatly from that which was already conceived as part the System Integration testing being planned (Modular Test Bench) in Warsaw.

The main PCM architecture that was created for the GTD was based on the following concept (US Patent 20140294585; EP2763893A1):

- Single static annular actuator
- Load Transfer Bearing
- Multiple Crank Rods

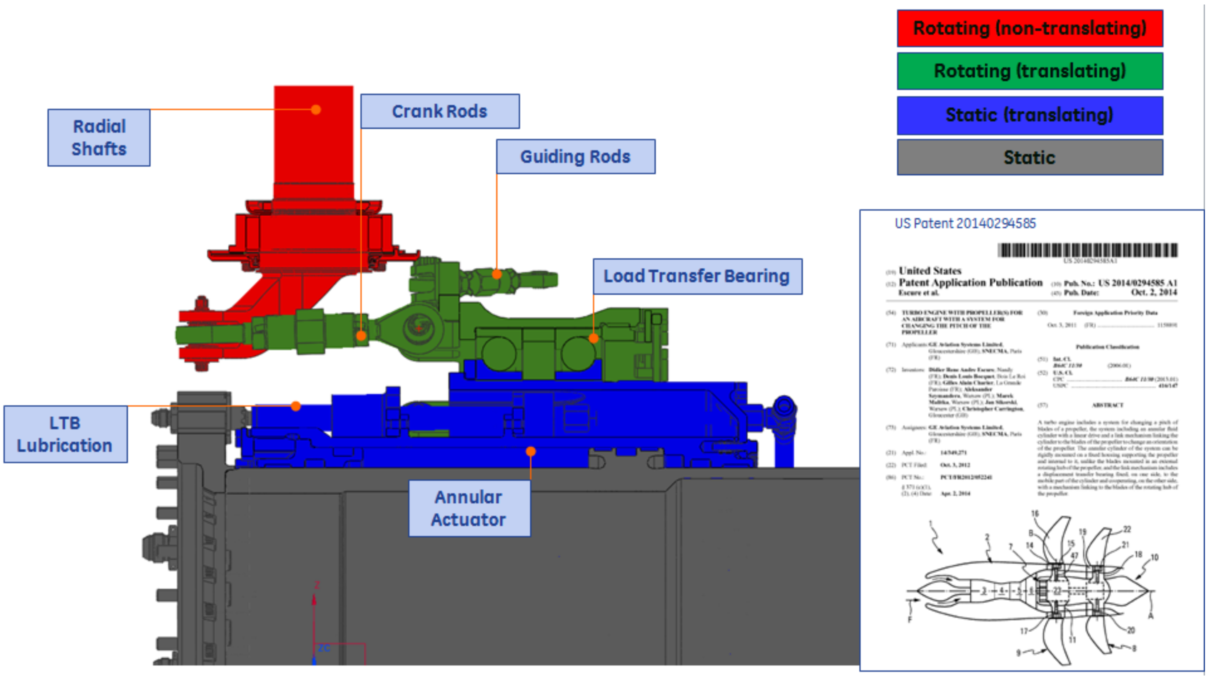


Figure 1: Forward Pitch Change Mechanism

For the AFT PCM, two key factors drove the design that was developed within OREAT II; specific technical requirements and a need to test to differentiate the PCM architectures. As such, the AFT PCM resulted in a design that varied greatly from that of the FWD design. Ultimately, to reduce overall SAGE2 risk a decision was made by the Topic Leader to unify the design of the two PCMs and base both on the design of the FWD PCM.

The second objective necessitated the design and construction of a new test facility located at the Institute of Aviation in Warsaw. The test facility, built from the ground, included the following:

- a hydraulics system with separate low and high pressure and temperature configurations
- a test cell room with a modular test plate
- an electric drive system
- a control and data acquisition system
- full instrumentation of the facility and test article

The test vehicle itself, known as the Modular Test Bench, is a full-scale rotating test bench capable of testing PCMs under CTM (Centrifugal Twisting Moment) loads. The test facility allowed for the validation of the integration of the PCM control system (Topic Leader) with the PCM (OREAT) itself.

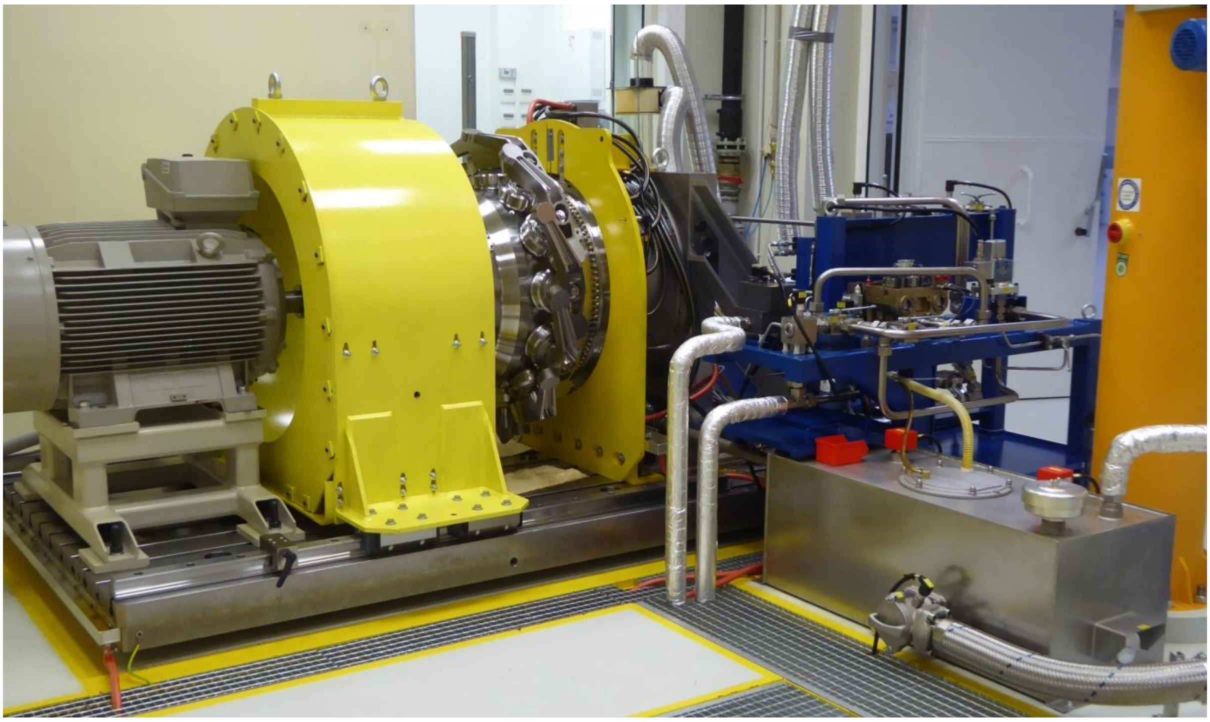


Figure 2: Modular Test Bench used for System Integration Testing in Warsaw

Key findings, for the PCM, from the testing were as follows:

- the PCM architecture did not undergo any unforeseen failure or wear as a result of the test campaign – see Figure 3.
- several novel solutions (lubrication and kinematics) worked successfully
- on the whole analytical modelling of the PCM was validated

Figure 3: Piston surface following test campaign

3.4 Potential impact and main dissemination activities and exploitation results

3.4.1 Potential Impact

With the undeniable performance gain of a variable pitch blade (whether it be a fan blade or propeller), pitch change mechanisms will be part of engine architectures in the near future. Thus it is of utmost importance to begin the task of realizing a PCM configuration that will be robust enough to survive the harsh environment of the Open Rotor. A substantial amount of work was done in the 1980s to this point but with the change in oil prices all momentum was lost. The new Clean Sky initiative has once again allowed aerospace companies to explore this challenging design space.

With this in mind, a new PCM configuration has been proposed and validated to TRL 5 within this program. This should allow the Topic Leader to lead a successful SAGE2 GTD testing campaign in 2016.

3.4.2 Main dissemination activities and exploitation results

The project developed the following type of results:

- Knowledge and capabilities in the form of large actuator design, lubrication design and kinematic and dynamic modelling
- Data from test campaign

The data from this project will not be disseminated outside of the project group and thus has a dissemination level of Confidential (CO).

4 Core of the report

4.1 *Project objectives*

Effective and sustaining pitch control is one of key enablers for the efficient and safe operation of the Open Rotor engine. OREATII Project addresses technical risk related to pitch control of the Counter Rotating Open Rotor Engine blades through maturation of the novel PCM technology addressing the needs and constraints of the engine architecture. The program will bring the CROR PCM Technology up to TRL5 level. The program should yield detail design of the PCM for CROR, detail design of the test benches required for PCM technologies maturation, instrumentation and test plan. All that should have been followed by dedicated sourcing, manufacturing, assembly and, eventually, full scale PCM prototype testing.

The objective of the project was as follows:

1. Prepare a preliminary design of the forward and aft pitch change mechanisms for the SAGE2 Open Rotor
2. Drive the main pitch change mechanism architecture to a Technology Readiness Level of 5

4.2 *Work progress and achievements*

All of the planned Work Packages were completed within the frame work of the OREAT II program. The deviations between the actual and planned end months are explained in a brief summary of each of the Work Packages below in Table 1:

WP Number	WP Title	Start Month	End Month – *Planned*	End Month - *Actual*
WP 1	Program Management	1	52	52
WP 2	Sourcing	14	41	43
WP 3	Test Bench Detailed Design	1	38	37
WP 4	Test Bench Instrumentation	1	35	37
WP 5	Key Technologies Detailed Test Plan	1	50	50
WP 6	Test Bench Manufacturing	16	41	41
WP 7	Key Technologies Detailed Design	1	38	40
WP 8	Key Technologies Manufacturing	16	41	42
WP 9	Test Bench Assembly	38	45	44
WP 10	Test Bench Controls	16	49	47
WP 11	Test Support	43	50	51
WP 12	Test Data Post Processing	49	51	51
WP 13	Dynamic and kinematic response analysis	2	51	52
WP 14	Support of engine demonstrator preliminary design	1	32	32

Table 1: Work Packages Summary

WP1 *Program Management*

The output of this package was the creation of a development plan to ensure the effective progress and eventual completion of the project. The success of this package was measured by the progress of the project and as such it can be said that this Work Package was successfully completed.

WP2 *Sourcing*

All of the necessary parts and installations for the Test Bench and Test Facility were purchased. A summary of all the components that were purchased within the sourcing Work Package is shown below (Table 2):

Type of component	Total quantity	Machined	Catalogue
MTB parts	247	123	124
Tooling	71	71	-
Instrumentation	79	-	79
Laboratory Equipment	161	-	161
SUM	558		

Table 2: Summary of purchased items

There was some deviation from the original schedule (~ 2 months) in terms of finishing the sourcing activities due to issues in the Manufacturing WP 8 (highlighted later in the report). There were some purchases made towards the end of 2015 to allow for the simplified (borescope) inspection of the Test Bench following testing but this is not included as a deviation.

Key highlights of this Work Package during this phase were the completion of large orders such as the Hydraulic System, Controls System and Data Acquisition and Electric Drive. This allowed the on time delivery of the Test Facility.

WP3 *Test Bench Detailed Design*

The output of this Work Package was not only the design of the Modular Test Bench but as well the Oil Transfer Bearing Test Bench and the 1P Test Bench. Only the Modular Test Bench was built. Technical reviews for all of the test benches were passed with auditors from the Topic Leader.

WP04 *Test Bench Instrumentation*

The output of this Work Package was the selection of specific sensors (and vendors) for the MTB, 1P and OTB Test Benches. Furthermore, calibration plans for sensors were prepared with the result being either relying on manufacturer’s data or performing further calibration in-house.

WP5 *Key Technologies Detailed Test Plan*

The output of this Work Package changed during the project phase as it was decided that the Topic Leader would prepare the test plan. Nonetheless, the OREAT Engineering Team prepared several deliverables as part of this package, namely identification of tests required to characterize the PCM and validate the PCM Kinematic Model. Furthermore, as part of the commissioning of the Test Facility, specific test plans were prepared to ensure that the Test Facility met the functional requirements in a safe manner. This included components associated with the Key Technologies, in other words the PCM. All of the test plans were reviewed during the Critical Design and Test Readiness Reviews.

WP6 *Test Bench Manufacturing*

The output of this Work Package included the manufacturing of the following major components:

- Test Plate
- Mounting Plates
- Rotor frames
- Counterweights
- Cranks
- Containment Case

The Test Bench components were produced in various countries within Europe, mainly Germany and Poland with some examples shown in the next three figures (Figure 4, Figure 5, Figure 6).

Figure 4: Rotor frames undergoing final machining process @ Germany machining plant

Figure 5: Cranks following initial turning before milling @ Germany machining plant

Figure 6: Containment Case undergoing inspection following welding @ Poland welding plant

WP7 *Key Technologies Detailed Design*

This Work Package was completed with the final results being validated through the 1P, Oil Transfer Bearing and Modular Test Bench CDRs. This also included the detailed design drawings, for the Modular Test Bench, which necessary for manufacturing.

WP8 *Key Technologies Manufacturing*

This Work Package proved to be difficult to complete according to the schedule. There were several reasons for this:

- one-off prototypes (low priority for supplier)
- relative inexperience of supplier leading to rework and poor lead time estimates
- no buffer in the schedule for any changes

These risks were highlighted early on in the project phase and some risk abatements were introduced beforehand:

- Inspection of machining facility, quality system, etc.
- RFQs sent to multiple suppliers for each part
- supplier experience as a key driver in selection process

- contact with supplier at an early stage of manufacturing
- release of preliminary drawings to the suppliers before final issue of drawings
- face-to-face meetings to ensure supplier understands key features and design intent

Even with all of these various actions in place, a two month delay was incurred. The main components that had a delay were:

- Annular Actuator Piston and Cylinder
- Load Transfer Bearing Pedestal

This delay had an impact on the next key Work Package of the project (WP9) which was the Test Bench Assembly phase. Some examples of the parts during manufacturing are shown below in Figure 7 and Figure 8:

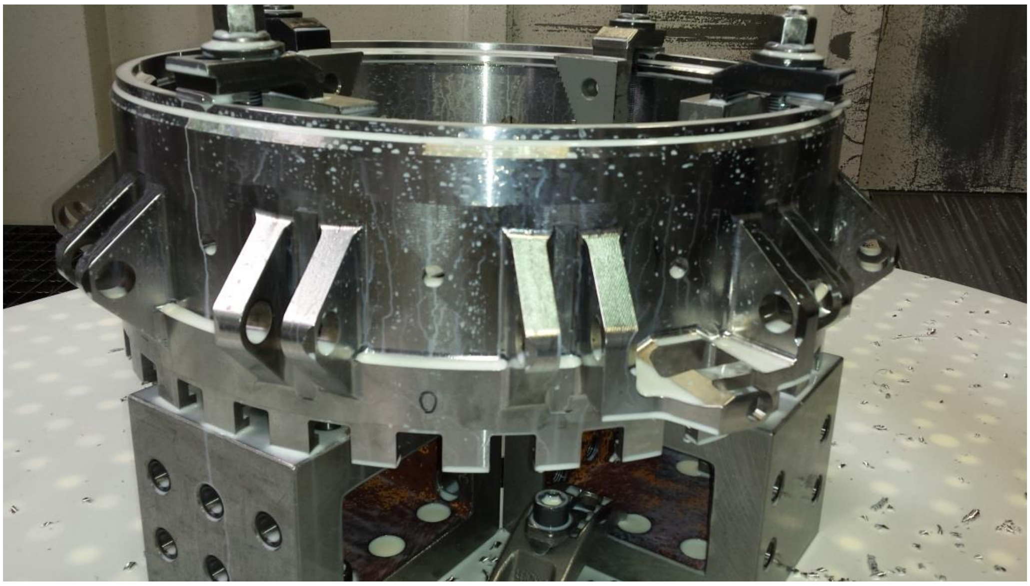


Figure 7: LTB Outer Guide during milling @ Germany machining plant

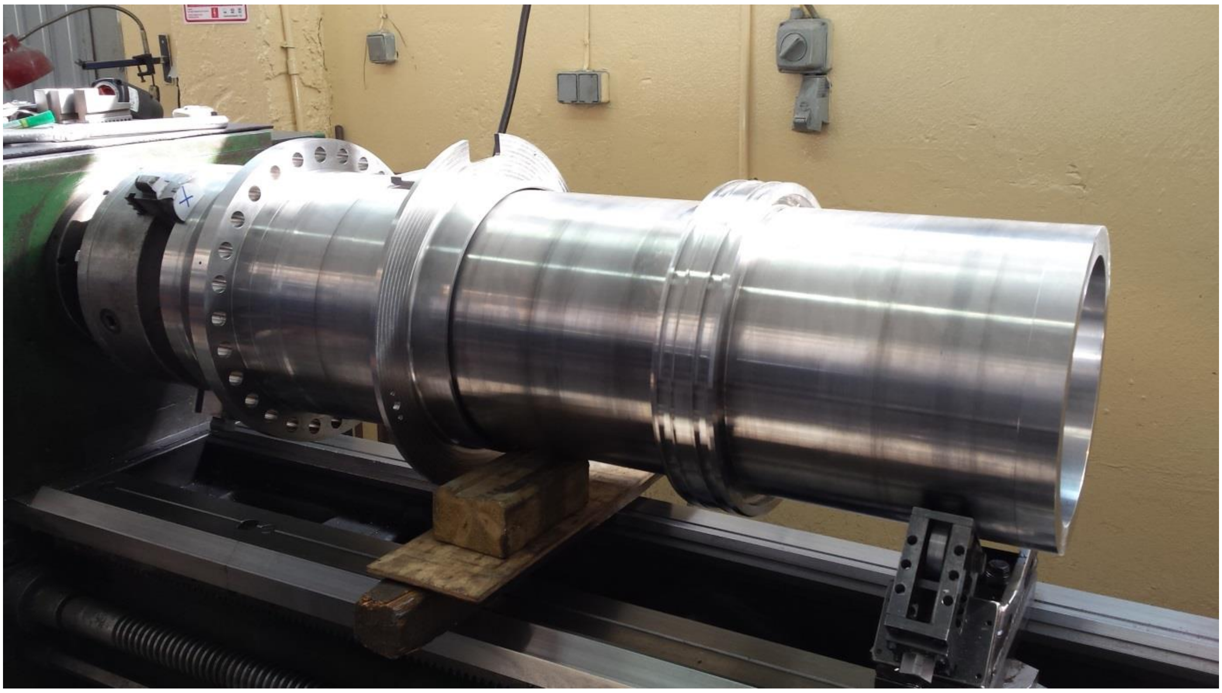


Figure 8: Static Frame and Piston undergoing final assembly machining @ Germany machining plant

WP9 *Test Bench Assembly*

The Test Bench Assembly Work Package had to be completed in a shorter amount of time due to the delay in manufacturing of some components. The assembly team was able to bring back 1.5 months of this delay due to several key points:

- 95% of assembly process was done in house
- Split of assembly into several parallel tasks (10 tasks in total)
- Planning of assembly tasks prior to their completion (300+ pages of procedures)
- Evaluation of high-risk assembly procedures through the use of special software tools
- Extended working hours
- Engineers overseeing assembly process

The total process lasted approximately 4.5 months (non-continuous work) with several delays due to the non-availability of components as mentioned. The only task that was outsourced was the assembly of the Annular Actuator which required specific tooling and experience in the field of hydraulic equipment. Several pictures from the assembly process are shown below in Figure 9 to Figure 13:

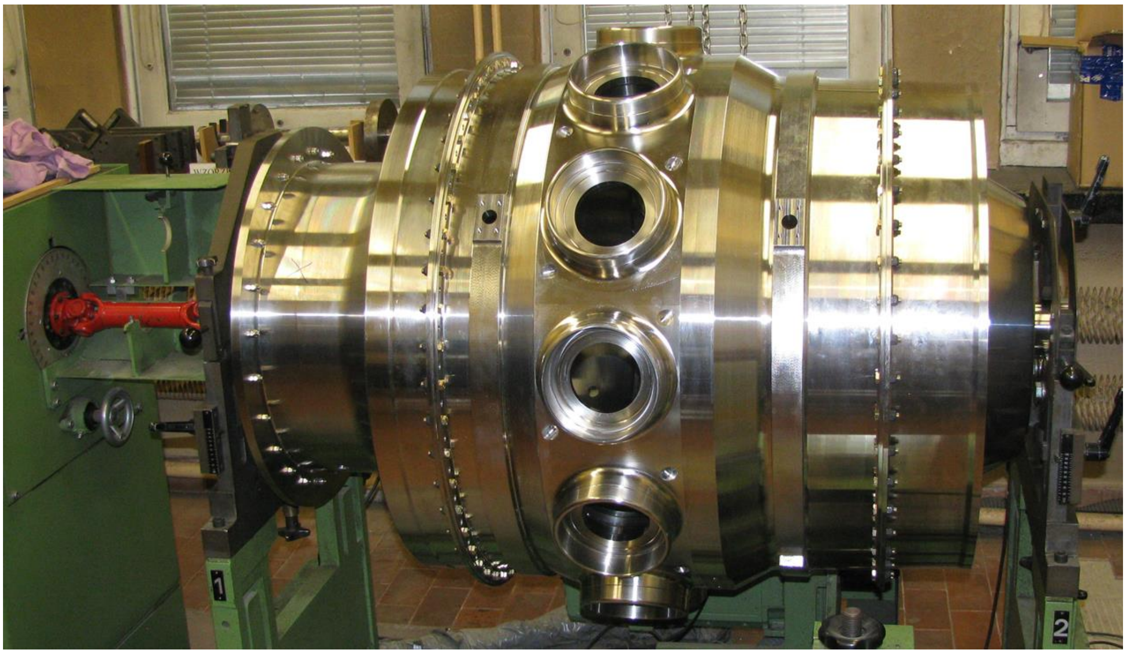


Figure 9: Rotor frame balancing (prior to module assembly) in the WIA facility

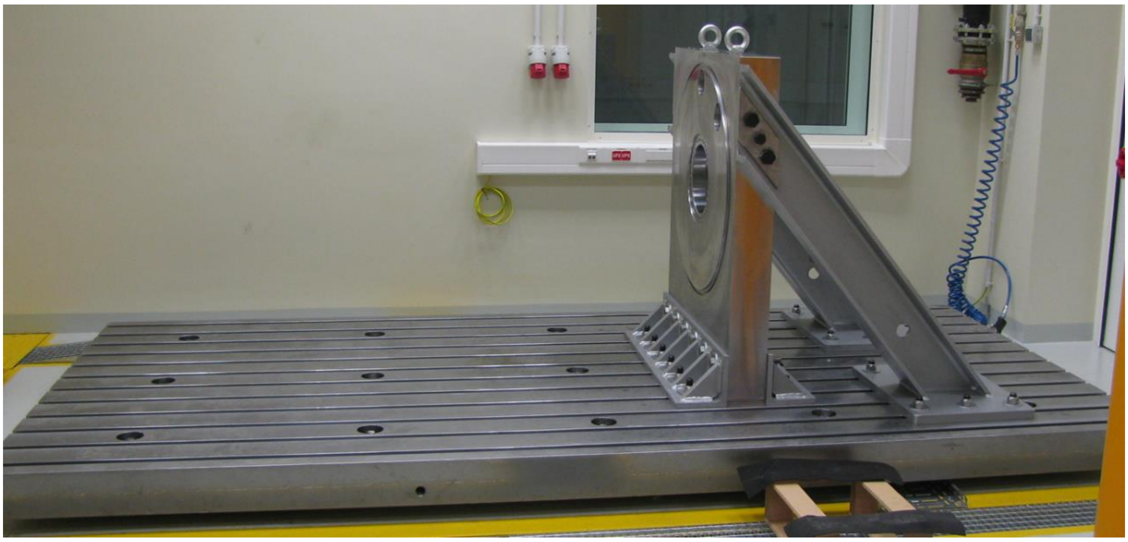


Figure 10: Test and Vertical plate assembly

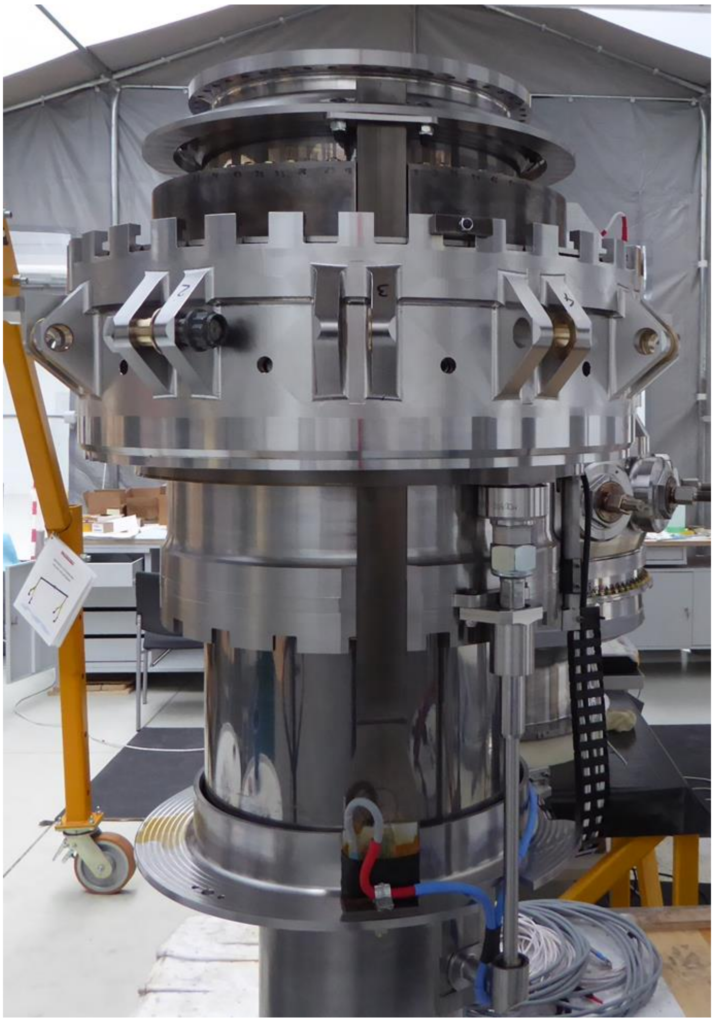


Figure 11: Main test article assembly

Figure 12: Assembly of two main modules

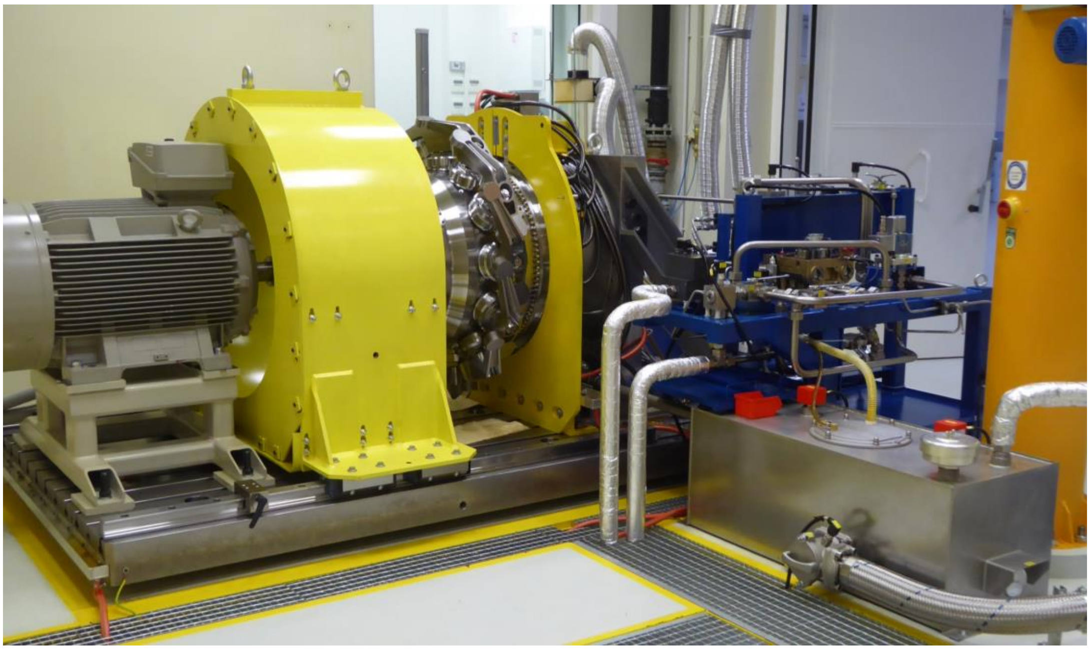


Figure 13: Fully assembled test bench in test facility

WP10 Test Bench Controls

The output of WP10 are two control systems installed in the Test Facility – shown as a block diagram in **Error! Reference source not found.**.

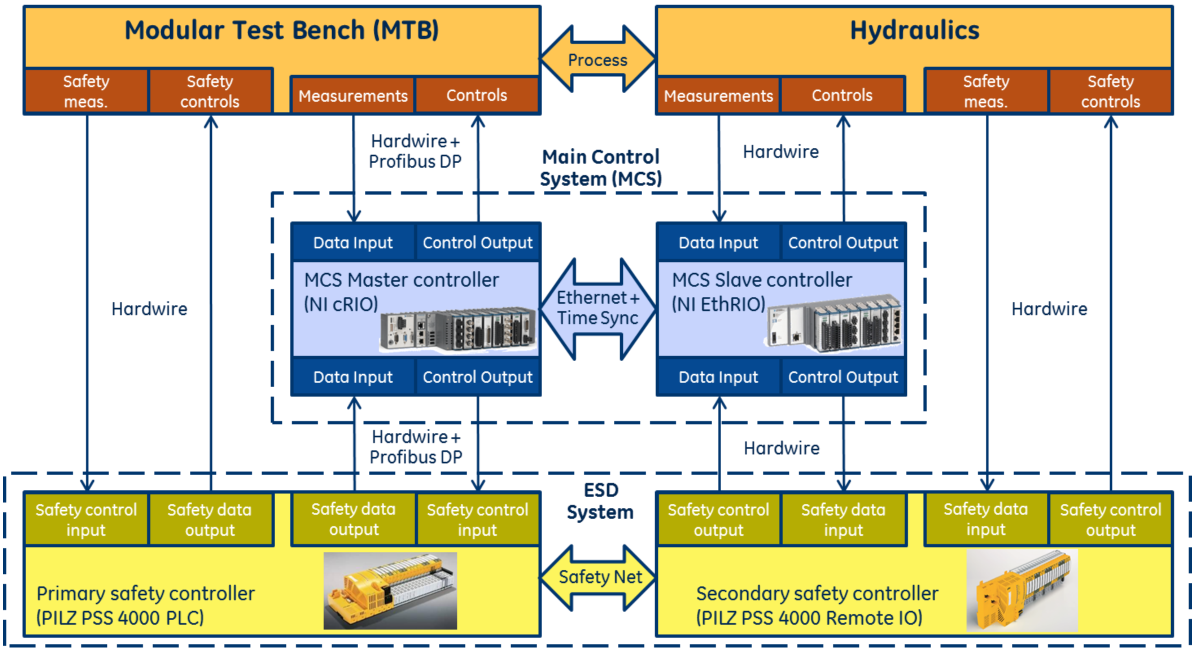


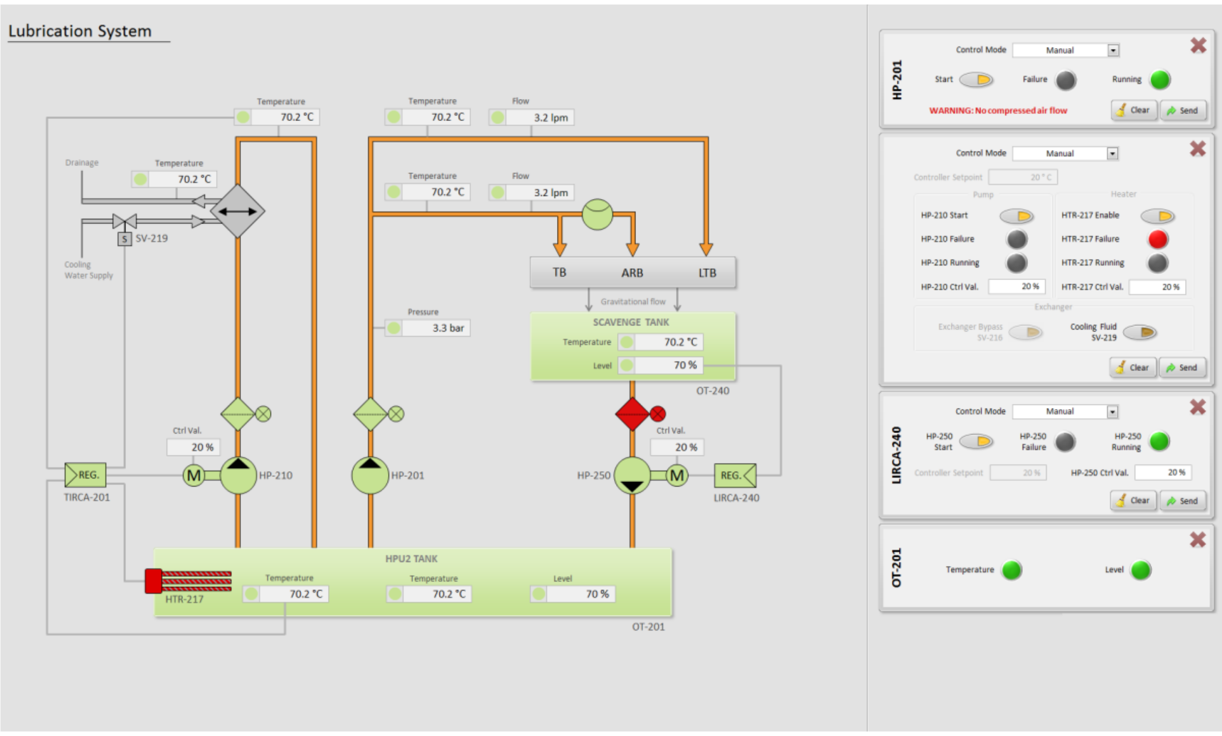
Figure 14: CS&DAQ – System Architecture

1. Main Control System (MCS), which is divided into two units:

- MCS Master - controller localized close to the Test Bench
- MCS Slave – controller localized in the Hydraulics Room

The principal functions of the MCS are as follows:

- Full MTB and lab infrastructure controls
- High frequency data acquisition
- Data streaming on servers
- Auto-diagnostics
- Communication with Human-Machine Interface (HMI) computer (Figure 15) located in the Control Room, which enables the operator to visualize data, configure and run automatic tests and control specific devices in manual mode.



Temperature 70.2 °C

Temperature 70.2 °C

Temperature 70.2 °C

Flow 3.2 lpm

Temperature 70.2 °C

Flow 3.2 lpm

Pressure 3.3 bar

Temperature 70.2 °C

Level 70 %

Ctrl Val. 20 %

Ctrl Val. 20 %

Temperature 70.2 °C

Temperature 70.2 °C

Level 70 %

Control Mode Manual

WARNING: No compressed air flow

Control Mode Manual

Controller Setpoint 20 ° C

HP-210 Ctrl Val. 20 %

HTR-217 Ctrl Val. 20 %

Control Mode Manual

Controller Setpoint 20 %

HP-250 Ctrl Val. 20 %

Figure 15: HMI screen which shows parameters of a chosen system (here lubrication system given as an example). Panels on the right give the possibility to control the devices by the operator in manual mode.

2. Emergency Shut Down System (ESD System), a superior system over MCS, divided into two units:

- ESD Primary – safety controller localized close to the test bench
- ESD Secondary - safety remote IO unit localized in the Hydraulics Room

The ESD System acquires critical safety measurements and is capable of controlling devices and to perform emergency shut down in case of failure/dangerous situation.

The principal functions of the ESD Systems are as follows:

- Rig safety monitoring (measurements and signalizations) and MCS health monitoring
- The ESD procedure execution by direct control of critical rig actuators and power supply
- Communication with ESD HMI Panel in the Control Room

The full system was implemented towards the end of 2015 with a working version available in mid-2015 which allowed for commissioning of the Test Facility and Test Bench.

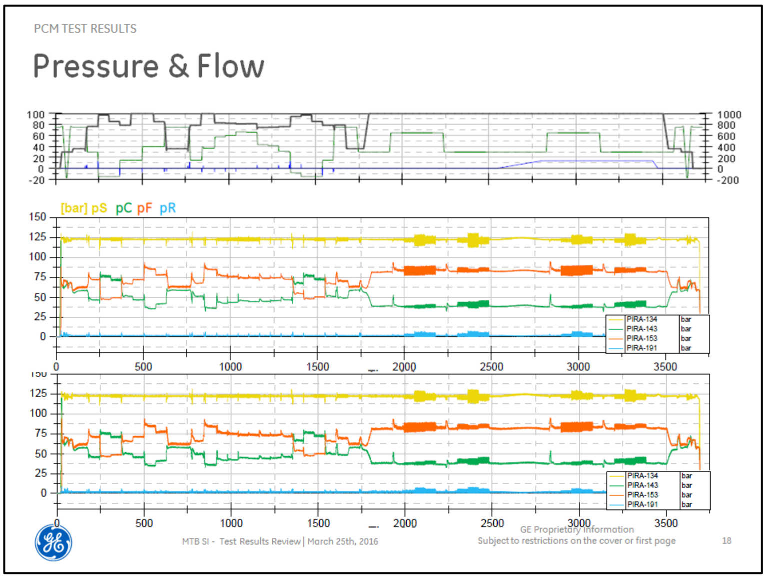
***WP11** Test Support*

Once all of the previous Work Packages were complete, the actual testing could be performed and thus the tasks that were part of the Test Support Work Package could be accomplished. The actual time required to finish this package was approximately 2 weeks longer than what was planned, as some of the required hardware was not available (Topic Leader) and the commissioning phase of the Test Bench delayed. Some of the additional work that was carried out during the testing phase included:

- Repair of the Test Bench ventilation system
- Installation of an additional filtration system for the ventilation system
- Technical inspections of the Test Bench

***WP12** Test Data Post Processing*

The final aspect of the testing phase was to post-process the data. This task was completed with the help of both in house tools and purchased software, National Instruments DIAdem. The goal of the post-processing task was to provide the engineering team with test data on an "online" basis. To allow for this, an automatic reporting system was created which streamlined the post processing phase. Thus the output was not only post-processed data but also tools that helped to automate this process. An example of post-processed data is shown below in Figure 16:



PCM TEST RESULTS

Pressure & Flow

MTB SI - Test Results Review | March 25th, 2016

GE Proprietary Information
Subject to restrictions on the cover or first page

18

Figure 16: Post processed data

WP13 *Dynamic and kinematic response analyses*

The objective of the last Work Package, one of the longest of the project, was to prepare a validated Matlab based model of the test article (FWD PCM). The work within this package included:

- update of model parameters based on actual measurements
- analysis of test data to select the optimum data for validation
- validation of the model based on test data by adjusting specific values

The Work Package was completed several weeks later than initially projected for several reasons:

- the test campaign running longer than expected
- instrumentation problems leading to challenges with using test data for validation

Ultimately the model was validated with a report being issued on the topic with some recommendations for possible future improvements.

WP14 *Support of engine demonstrator preliminary design - Complete*

The output from this Work Package was the following:

- Preliminary designs of the FWD and Aft PCM designs the SAGE2 Ground Test Demonstrator completed and reviewed
- Digital models prepared of FWD and AFT PCM designs sent to Snecma

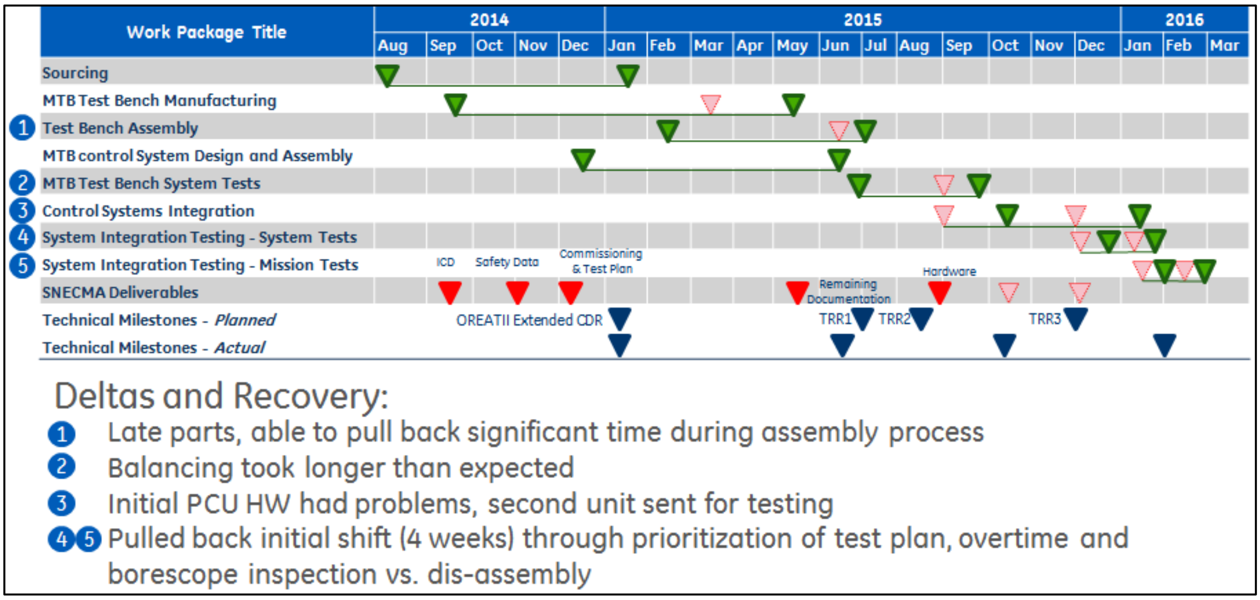
The following table (Table 3) summarizes the effort of each of the participants relative to the Work Packages:

Dowty P		01/12/2011 31/05/2013	01/06/2013 30/11/2014	01/12/2014 31/03/2016	
Average cost (in euro)=	15000	18	36	52	
	Contract (PM)	RP1 (PM)	RP2 (PM)	RP3 (PM)	Delta (Contract - RPs)
WP1	3.00	1.74	0.00	0.00	1.26
WP2	0.00	0.00	0.00	0.00	0.00
WP3	0.00	4.11	0.00	0.00	-4.11
WP4	0.00	0.00	0.00	0.00	0.00
WP5	0.00	0.00	0.00	0.00	0.00
WP6	0.00	0.00	0.00	0.00	0.00
WP7	0.00	0.00	0.00	0.00	0.00
WP8	0.00	0.00	0.00	0.00	0.00
WP9	0.00	0.00	0.00	0.00	0.00
WP10	0.00	0.00	0.00	0.00	0.00
WP11	0.00	0.00	0.00	0.00	0.00
WP12	0.00	0.00	0.00	0.00	0.00
WP13	0.00	0.00	0.00	0.00	0.00
WP14	0.00	0.00	0.00	0.00	0.00
Total	3.00	5.85	0.00	0.00	-2.85
WIA					
Average cost (in euro)=	4093.33				
	Contract (PM)	RP1 (PM)	RP2 (PM)	RP3 (PM)	Delta (Contract - RPs)
WP1	0.00	18.00	18.00	4.00	-40.00
WP2	9.00	0.00	11.60	2.00	-4.60
WP3	9.00	25.30	37.10	1.00	-54.40
WP4	7.00	3.10	8.30	4.30	-8.70
WP5	3.00	2.00	2.50	1.00	-2.50
WP6	4.00	0.00	4.70	1.30	-2.00
WP7	10.00	5.30	12.10	2.00	-9.40
WP8	4.50	0.00	0.30	1.50	2.70
WP9	13.00	0.00	0.00	7.20	5.80
WP10	8.00	1.60	0.90	1.40	4.10
WP11	29.00	0.00	0.00	12.00	17.00
WP12	6.00	0.00	0.00	0.00	6.00
WP13	10.50	8.30	6.80	0.50	-5.10
WP14	12.00	24.00	15.00	0.00	-27.00
Total	125.00	87.60	117.30	38.20	-118.10
GECP					
Average cost (in euro)=	4861.29				
	Contract (PM)	RP1 (PM)	RP2 (PM)	RP3 (PM)	Delta (Contract - RPs)
WP1	15.25	10.30	10.00	0.00	-5.05
WP2	2.00	0.00	8.00	0.00	-6.00
WP3	53.00	52.10	29.50	0.00	-28.60
WP4	5.00	2.00	2.00	0.00	1.00
WP5	1.00	0.90	0.90	0.00	-0.80
WP6	12.00	2.00	8.80	0.00	1.20
WP7	28.00	48.00	23.60	0.00	-43.60
WP8	10.50	1.60	17.40	0.00	-8.50
WP9	2.00	0.00	0.00	0.00	2.00
WP10	5.50	0.00	0.00	0.00	5.50
WP11	0.00	0.00	0.00	0.00	0.00
WP12	6.00	0.00	0.00	0.00	6.00
WP13	8.00	0.50	0.50	0.00	7.00
WP14	41.00	16.60	32.00	0.00	-7.60
Total	189.25	134.00	132.70	0.00	-77.45
Total forecast	317.25		Total real		515.65

Table 3: OREAT II - Project Effort by Work Package per Participant

5 Project Management

The main issues that were encountered during the project came about in the last phase and are shown below in Figure 17:



Deltas and Recovery:

① Late parts, able to pull back significant time during assembly process

② Balancing took longer than expected

③ Initial PCU HW had problems, second unit sent for testing

④⑤ Pulled back initial shift (4 weeks) through prioritization of test plan, overtime and borescope inspection vs. dis-assembly

Figure 17: Program schedule deltas and recovery

In support of the problems mentioned above, several project meetings with Snecma were held towards the end of project:

- Steering committee meeting – May 2015, Warsaw, Poland
    - Testing set at 300 hours
    - Snecma testing to cover all aspects of PCM testing needs
    - Snecma request for additional balancing information
- Steering committee meeting – December 2015, Warsaw, Poland
    - Additional status meetings requested (weekly)
    - Status of assembly discussed
- Steering committee meeting – January 2016, via teleconference
    - Actions identified for both sides to bring program schedule back on track due to testing delays
    - Two follow up meetings planned, January and February

- Steering committee meeting – February 2016, via teleconference
    - Steering committee meeting – February 2016, via teleconference Snecma presented a possible solution to decrease test time by focusing on high risk items.