Development of a Miniaturized Demonstrator for Foam Rheology Microgravity Experiments

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Challenge the future

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To my beloved father Luciano.
In the hope of being always your pride.

Abstract

The project under analysis is about the development and qualification of a demonstrator for a miniaturized foam rheology experiment performed in microgravity environment. The thesis is part of a larger feasibility study to evaluate the possibility of implementing such experiment on the International Space Station as an internal payload of the Fluid Science Laboratory in the Columbus module. The project was developed in the Fluid Physics and Payloads department at Airbus Defence & Space in Immenstaad, in accordance with European Space Agency expectations and under the supervision of the experts of foam science from the Pierre and Marie Curie University of Paris.

The study was dedicated to the development and validation of a miniaturized hardware, which will be integrated in the existent Soft Matter Dynamics Experiment Container available on the International Space Station. It was focused on the design and testing of the demonstrator hardware in a Verification Test Facility, which was as close as possible to the real target system intended for use in the future mission. The system qualification was done in close cooperation with the science team interested in the results of the space experiment.

The main findings of this research are related to the possibility of the studying foam in space. The microgravity conditions experienced in that environment are extremely useful to study specific fluid phenomena in gravity absence, to investigate foam proprieties and stability, and to obtain advance knowledge useful for foam practical applications on Earth. In particular, the understanding of rheology in wet foams has proven to be difficult on Earth and a dedicated space investigation could carry out interesting unknown properties, which could affect enormously the application of foams in industrial and commercial processes.

The work started with the study of the requirements and was focused on the evaluation of the design through the assembly, integration and testing of the miniaturized system. During the hardware evaluation the weaknesses of the proposed design were identified. Alternative solutions for the demonstrator were developed and recorded in order to improve the future system. Various tests were carried out to verify the design performances and functionality. Good results were obtained with the improvements applied after the first testing campaign.

Eventually, a series of verification tests were performed to complete the requirements compliance analysis. The majority of the results obtained was successful, however the full compliance of the current hardware was not reached and the validation campaign was not possible due to an open issue in the membrane application. At the present time, a solution for a multi-layer membrane is under development. Once it will be available, the demonstrator will be assembled and integrated, and a new series of verification tests will be performed. The final steps of the project will be the validation campaign and the presentation to European Space Agency about the system status and suggestions for future design improvements.

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List of Abbreviations

AC	Alternating Current
ADC	Analog to Digital Converter
AIT	Assembly, Integration and Testing
CAD	Computer Aided Design
CNC	Computer Numerical Control
DS	Defence and Space
DWS	Diffusing Wave Spectroscopy
EADS	European Aeronautic Defence and Space
eBB	Elegant Bread Board
EC	Experiment Container
ECs	Experiment Containers
ECCU	Experiment Container Control Unit
ECTS	European Credit Transfer and Accumulation System
EDR	European Drawer Rack
EGSE	Electronic Ground System Equipment
EGTE	Electrical Ground Test Equipment
EM	Engineering Model
EPM	European Physiology Module
ESA	European Space Agency
FGS	Foam Generation System
FM	Flight Model
FOAM-C	Foam Optics And Mechanism - Coarsening
FoV	Field of View
FSL	Fluid Scientific Laboratory
FWHM	Full Width at Half Maximum
GND	Ground
GTE	Ground Test Equipment
GTE	Ground Test Equipment
HCI	Human Computer Interface
ISPR	International Standard Payload Rack
ISS	International Space Station
IST	Integrated System Test
ISTs	Integrated System Tests
LC	Line Camera
LEDs	Light Emitting Diodes
LEO	Low Earth Orbit
LTU	LapTop Unit
MSc	Master of Science
MT	Moving Tray
NASA	National Aeronautics and Space Administration
NBR	Nitrile Butadiene Rubbers
PC	PolyCarbonate
PDR	Preliminary Design Review
POM	Polyoxymethylene
PLA	PolyLactic Acid
RoD	Review of Design
SC	Sample Cell
SCs	Sample Cells
SCU	Sample Cell Unit
SCUs	Sample Cell Units
SE	Systems Engineering
SFT	System Functional Test
SMD	Soft Matter Dynamics
SPC	StepsPerCount
STL	STereo Lithography
STMO	STepper MOtor
SVS	Speckle Visibility/Variance Spectroscopy
TBD	To Be Defined
TU	Technical University
UPMC	Pierre and Marie Curie University
VCM	Verification Compliance Matrix
VDM	Verification Design Matrix

VMU Video Management Unit
VP Verification Plan
VR Verification Requirements
VRM Verification Requirements Matrix
VTC Verification Test Campaign
VTF Verification Test Facility
WBS Work Breakdown Structure
WFM WaveForM
WP Work Package
WPs Work Packages

List of Symbols

ϵ_y	Critical Yield Strain
Δp	Pressures Differences
ϵ	Applied Strain
ϵ_0	Vacuum Permittivity
ϵ_e	Relative Permittivity
ω	Angular Frequency
ϕ	Liquid Volume Fraction
ϕ_c	Critical Liquid Volume Fraction
σ	Standard Deviation
θ_1	Angle of Incidence
θ_2	Angle of Refraction
A	Area
A_{tube}	Area Tube
C	Capacitance
D	Diameter
j	Imaginary Unit
L	Initial Gap Length
n_1	Refractive Index From the First Medium
n_2	Refractive Index From the Second Medium
p_{rate}	Rate Pressure
V_{gas}	Volume of Gas
V_{liquid}	Volume of Liquid
V_{SC}	Inner Sample Cell Volume
V_{syste}	System Volume
V_{tot}	Total Volume
X_c	Reactance
g	Earth Gravity Acceleration, equal to 9.81 m/s^2

1
Introduction

1.1. Context

Microgravity has proven to be an ideal environment for foam investigations, and researches in this field have been started since the 1980s [Minster, 1991]. Opportunities to perform experiments in microgravity conditions have progressively increased thanks to the development and installation of the European Columbus Laboratory on board the ISS. In this context, the Airbus Defence and Space (DS) (former European Aeronautic Defence and Space (EADS) ASTRIUM Space Transportation) has developed much of the hardware integrated in this module. In particular, the Fluid Scientific Laboratory (FSL) payload rack on Columbus has already performed fluid physics experiments so far, and others are currently being developed. The Soft Matter Dynamics (SMD) is an EC designed to be installed in the FSL for the study of foam phenomena, such as the foam coarsening within the FOAM-C Sample Cell Unit (SCU), which is being developed in phase C/D and its Engineering Model (EM) and Flight Model (FM) are under testing at the moment.

In this thesis, a particular attention is given to the rheology analysis on foams as extension of the scientific program for the Soft Matter Dynamics EC. The feasibility study for a SCU dedicated to rheology is now being developed under the name of REFOAM that stands for Rheology of Foam. The REFOAM study aims to explore the development of a specific hardware system (demonstrator stage only), to investigate foam rheology. The investigation of these soft matters (foams) in microgravity conditions represents an unique opportunity for the scientific community, as wet foams are not stable on Earth. The outcomes of such an experiment would lead to great improvements and breakthrough that could serve several branches of the industry.

1.2. Objective

The objective of the research project was to develop and qualify the REFOAM system dealing with rheology experiments on wet foams in microgravity conditions, by analysing the performance of a demonstrator, supported by a series of tests conducted in laboratory conditions. For this purpose, the study was focused on a demonstrator whose functionality was tested within a Verification Test Facility called Elegant Bread Board (eBB), which was already developed considering many aspects of the usability in space. To this end, REFOAM preliminary concepts and the best engineering solutions had to be compliant with the eBB specifications. The thesis project started from the analysis and compliance of project requirements, written in accordance with the customers expectations and with the expertise of scientists from the

Institut des NanoSciences de Paris (UPMC of Paris). It was followed by the assembly, integration and verification of the final Demonstrator for REFOAM in order to assess the experiment feasibility. To accomplish the mission, the implementation of project management tools helped at the beginning of the research. Organization and leading of several brainstorming sessions with competent collaborators also allowed to improve the design and to implement a detailed verification plan and tests schedule. A final evaluation of the results obtained at the end of the test session helped to identify possible causes of failure and to define the right improvements to assess the expected feasibility of the mission.

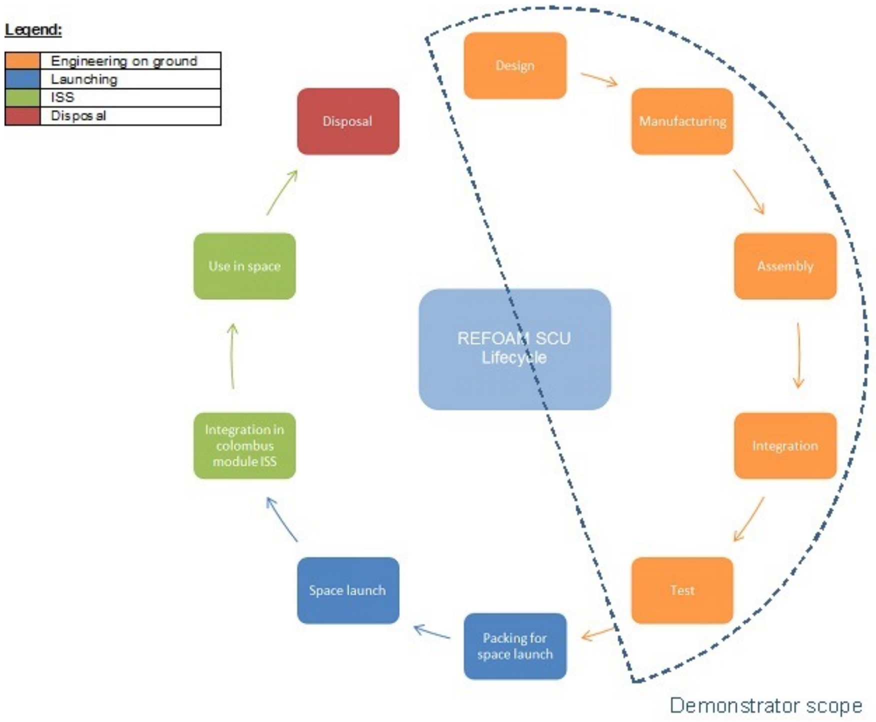


Figure 1.1: REFOAM Life Cycle.

The project life cycle, without the internal iterations, is shown in the Figure 1.1. The feasibility study takes into account the whole steps of the system´s life, however the demonstrator development is limited by the orange boxes representing the activities performed on ground. The rest of the steps will be achieved in the development of a potential EM and FM SCU.

1.3. RESEARCH QUESTION AND METHODOLOGY

The main research questions of the thesis was referred to the possibility to study the rheology of foam in a new SCU integrated in the Soft Matter Dynamics EC. The starting point of the thesis was the SCU manufacturing and integration. Then, a series of tests were performed, involving the scientific expertise on optical diagnostics calibration and experiment data evaluations. To this end, the research project was based on the following research question:

Would it be possible to study wet foams rheology behaviour under microgravity conditions within the existing Soft Matter Dynamics Experiment Container?

In order to provide a definitive answer to this question a series of sub-questions were formulated. These were referred to the phases of the project, which followed the design readiness review:

- Which tests are adequate to evaluate the validity of the proposed design?
- Which procedure and criteria are relevant for assessing the success of the performed tests?

Once the tests were completed, the evaluation of the results was carried out and the feasibility of the investigated concepts was evaluated by Airbus DS together with the scientific expert Professor Höhler (from UPMC), and the following sub-questions found an answer:

- Is the design compliant with the requirements?
- How the system can be improved or adapted to be successful?

These sub-questions provided the steps needed to be elaborated in order to get the final answer to the main research question and to accomplish the project goals. Each subquestion was related to a task of the project and they helped to obtain the adequate knowledge and research contents to succeed in the aim proposed. In particular, the final result was the functional evaluation of the system implementation with the relative limitations and possible improvements. The potential success of this project represents an unique opportunity for the scientific community in the investigation on wet foams, reducing cost and risk in the development of a FM which will be operated on the ISS.

The answers to the research questions was developed through the practical application of the theory of Systems Engineering (SE) tools and methodologies. These activities were fundamental for the overall project cycle validation and verification phases. In particular, it was chosen to describe the whole SE process through the so called "V" Model, which shows the relationship between the definition/decomposition/validation process placed on the left side of the "V", and the corresponding integration/verification process on the right side. "*A proper development process will have direct correspondence between the definition/ decomposition/ validation activities and the integration/verification activities*" [Haskins et al., 2006].

The first step to achieve the goals expected was an accurate evaluation of the project requirements. In particular, a Verification Design Matrix (VDM) was needed to determine the method of verifying each system requirement, and the specific procedure according to which the verification would be accomplished [Engel, 2010]. Then, all the requirements that needed to be evaluated through a testing procedure were collocated in the Verification Plan (VP), where details about the verification strategy and the testing phase were given.

In parallel with writing the Verification Requirements (VR), the integration set-up and integration schedule were defined. The integration involved the physical and functional components combination and it aimed to the identification of possible unforeseen problems, in order to predict, analyse, and solve them as early as possible [Larson, 2009]. To this end, a bottom-up strategy was the best solution in order to test each components during the whole process and to allow to preventively cope with possible unexpected problems. A detailed integration schedule was developed in strict relation with the design and forces to analyse the design from an integration perspective, helping to discover many unresolved implicit assumptions [Larson, 2009]. The Systems Integration Review defined the end of the final design and fabrication phase and its successful completion indicated the readiness to proceed to the verification tests [NASA, 2007].

These tests were performed within the Verification Test Facility (VTF) under laboratory conditions, based on establishing the Test and Evaluation Master Plan, which provided the philosophical and practical guidance during the test development [Larson, 2009]. The final aim was the compliment of the design defined against the pass/fail criteria, which identify the critical operational conditions and experiment limits. The relevance of criteria and achieved test results were assessed together with the scientific experts. The end project results will be documented in the final Test Report. The final output was a series of documents, which control the definition of the project from inception to conclusion and contain clear statements about the strategy utilized [Lévárdy et al., 2004]. Then, thanks to a deep evaluation of these documents, the system critical areas were identified. In case of test failure, new design solutions needed to be investigated to improve the system and overcome the critical aspects.

If the feasibility is assessed, the EM and FM will be developed. Finally, all the results and the final considerations, conclusions, recommendations, and steps toward the FM implementation will be collected in the Final Project Report, which will be presented together with the final hardware to the European Space Agency (ESA) team, approximately by the end of September 2017.

1.4. THESIS CONTRIBUTIONS

The present thesis aims at the development of the REFOAM hardware in the framework of the feasibility study. The study stared from a defined and approved theoretical design, and was focused on its testing and qualification. However, during the first review critical issues were identified and multiple iterations were required to achieve the expected goal. In particular, a series of improvements and innovations were brought to the current state of art in terms of design solutions and methodology.

During the feasibility study different design options were investigated in order to obtain the best achievable performances within the budget constrains. The introduction of 3D printed miniaturized elements, in the demonstrator development, was the greatest innovation brought by this thesis. The application of this technology was not taken into consideration during the first design review, since it is not compatible with the FM requirements. However, the 3D printing was incredibly useful in the course of the testing phase as an alternative solution during the procurement of the final elements. Thanks to the fast prototyping, it allowed to carry out the required development tests in short time without any additional costs in the manufacturing.

In addition, the thesis study contributed in the testing phase with the definition and development of systematic test procedures and customized set-up. For each performed test, after a detailed analysis of the test specifications and conditions a specific set-up was built. Over the test planning and the results evaluation, the SE methodologies were used. The application of these tools, such as the VDM, Gantt Chart and VP, was crucial and helped in the system verification analysis and in the final project documentations.

1.5. PROJECT PLAN

The thesis project was organized through a Work Breakdown Structure (WBS), where the different work packages, which were relative to the tasks that was developed during the research period, are clearly identified. The WBS is presented in Figure 1.2. The time frame necessary to develop the tasks identified in the WBS was defined in accordance to the TU Delft thesis requirements [1]. The Master of Science (MSc) thesis corresponds to 42 European Credit Transfer and Accumulation System (ECTS) that are equivalent to a period of approximately 30 weeks, form the project beginning to the final defence.

The WBS presented five main Work Packages (WPs) that were numbered to make an easy identification and derivation of the sub-packages relative to each task. Each Work Package (WP) identified a specific phase of the project. It started from the studies of the requirements and the system design, passing through the manufacturing, assembly and integration and it concluded with the system verification and validation. In addition, the last WP was dedicated to the whole management of the project and thesis development. This subdivision made clear the steps to follow during the research period and defined the fundamental milestones, which helped to manage successfully the time at disposal.

A brief description of the main WPs follows.

> WP1000: REQUIREMENTS AND DESIGN STUDIES. Since the MSc thesis was focused on an on-going project, an accurate analysis of the requirements and a deep knowledge of the completed design was the starting point of the research. This phase involved also the studies of the operations of the VTF, which was utilized to perform the verification tests in the Verification and Validation phase. Once a good level of confidence had been acquired the requirements compliance analysis was carried out as a conclusion for the design phase.

> WP2000: MANUFACTURING AND ASSEMBLY. This package was dedicated to the manufacturing and ordering of the system parts according to the design, and the assembly phases. In particular, it was aimed to the preparation of the assembly procedure, where the steps to follow and the necessary tests that needed to be performed for a successful assembly were defined. This phase concluded with the final assembly of the system.

> WP3000: INTEGRATION. Once the system was assembled, an integration plan was defined. It included the procedure to follow to integrate the system in the VTF and the tests that to be performed. The final result was the integration of the system in the VTF.

> WP4000: VERIFICATION AND VALIDATION. This work package was the heart of the project and for this reason it needed more time to be accomplished. It included the preparation of a verification plan, where the tests, which were necessary to close the requirements compliance, were listed and scheduled. Then, the main task was related to the test set-up and performances evaluation in order to asses the experiment feasibility in microgravity.

[1] TU Delft Thesis: http://studenten.tudelft.nl/index.php?id=104253

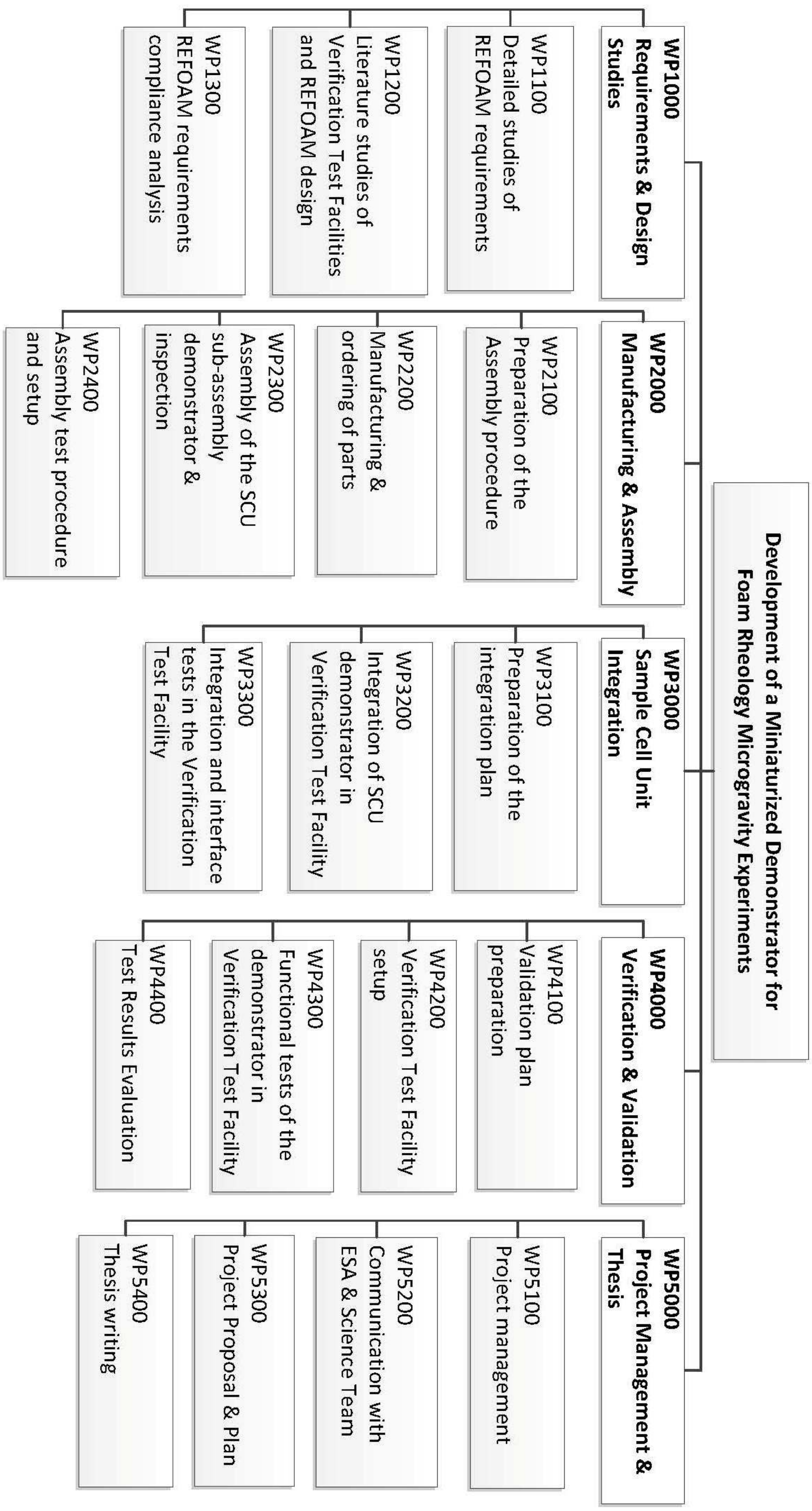


Figure 1.2: Master's Thesis Work Breakdown Structure.

WP5000: Project and Thesis Management. This was an activity, which was performed simultaneously with others. It concerned the REFOAM project management itself, which included weekly meetings and communications with the other project parties. As well as, the thesis planning and writing were parts of this packages with the relative milestones and meetings with the university supervisor.

Each work package required a different amount of time to be accomplished, to this end the Gantt Chart (Appendix A), helped to shows the WPs durations and correlations. The success of a task was dependent on the success of the previous one, and a delay in one work package could influence the whole work. In order to avoid delays in the thesis submission and to take into consideration possible unforeseen, the time needed per task was overestimated.

The key relevant project and thesis milestones are also indicated in Chart, such as the Kick-off meeting, Mid-term meeting, Draft Hand-in, Green light review, final Hand-in and the final Defence. Of course, also a preparation time was considered to succeed in the tasks mentioned. Finally, green bars were added to take in consideration the Holidays periods.

1.6. Report Structure

The report is divided into three parts. The Part I, "REFOAM Experiment", gives a further introduction into the experiment aims and theoretical system design. In particular, in Chapter 2 an introduction to the key aspects of foams physics and rheology is given together with a brief description of the microgravity environment and facilities available on the ISS. In Chapter 3 the attention is focussed on the REFOAM project. There, the aim of the experiment, the system preliminary design and its operational scenario are presented.

The Part II, "REFOAM Demonstrator Phase", deals with the tasks developed during the research period. In Chapter 4 the VTF and its qualification according to the experiments needs are described. The Chapter 5 presents some of the improvements introduced with respect to the previous design version. Then, in Chapter 6 the assembly and integration of the hardware are described with the related development tests. The second part is concluded with the Chapter 7, dedicated to the verification and validation phase.

The Part III, "Conclusions and Future Prospects", deals with the conclusions of the research. In Chapter 8 is dedicated to the results obtained, which are summarized in the final compliance analysis. Finally, the Chapter 9 presents the final considerations of the study, and the possible future improvements and recommendations.

I

REFOAM Experiment

2
Mission Overview

The microgravity space research started more than 35 years ago, with European national programs. In January 1982, the ESA initiated a European funded programme in which governments could contribute according to their interest and budget [ESA, 2015] in the development of low gravity experiments. Since then, ESA has sponsored more than 2000 experiments, payloads and facilities, which have been integrated and operated on various types of low gravity platforms [ESA, 2015].

Nowadays, various facilities for microgravity investigations [Lorenzen and Schweizer, 2008] are available, which include drop towers, air-crafts for parabolic flights, sounding rockets and the ISS. The right platform has to be chosen with respect to the mission needs, considering the average ranges of low gravity (with respect to Earth's gravity) experienced and the average range of time to which experiments are exposed to these values [ESA, 2015]. Among all, the experiments on the ISS, which is a long term space based environment, play a leading in the investigation on microgravity phenomena. On the other hand, the various facilities on Earth provide a realistic scenario for a function test of the experiment systems, in order to reduce the engineering risk for the FM [Schütte and Grothe, 2005].

Thank to these facilities, it is possible to carry out investigations on fundamental states of matter and fluids, and on the forces that affect them in a microgravity environment, studying their interactions in order to expand the frontiers of science [Rogers et al., 1997], and to develop new technologies and products in a way that is not possible on Earth [JAXA]. In particular, microgravity conditions experienced in space are extremely useful to study specific fluid phenomena, such as the investigation of foam proprieties and stability, and to obtain advanced knowledge useful for foam practical applications on Earth.

In this chapter the foam physics fundamental and the associated phenomena are described in Section 2.1. Then, in Section 2.2 a technical description of the ISS and *Columbus* European module is given with a particular attention to the FSL. Finally, in Section 2.3 an insight into the Soft Matter Dynamics EC and its functions is presented.

2.1. Foam Fundamentals

Foam can be defined as a mixture of a gas and a liquid. It exists in different forms as food foams (whipped cream, beer and soft drinks), detergent foams (soap, showering foam, bubble bath), fire-extinguishing and metal foams (light-weight and very sturdy, used as building materials, shock absorbers and sound dampeners).

Despite foam abundance in industrial and commercial applications, many questions about their properties are still unsolved and their stability remains mysterious. Nowadays numerical computations are more and more used in the fluid physics analysis, but empirical tests are still essential to estimate the operational window and design for foam handling [Caps et al., 2014a], especially when there is no theoretical model available.

2.1.1. FOAM PHYSICS

Liquid foams are defined as a mixture of gas bubbles of many size dispersed in a liquid and stabilised by surface-active species, such as surfactants or polymers [Caps et al., 2014b]. They can be created mixing gas and liquid together and the use of surfactants to the liquid helps to obtain a more stable structure. In particular they reduce the surface tension of pure water, when the foam is created it immediately starts to evolve and change its aspect. In these phenomena the main role is played by the surface tension, which minimises the surface of the liquid that keeps the molecules together.

The composition, surfactant concentration and other boundary conditions influence structural and geometrical parameters of the foam: the most relevant are bubble size, non-uniformity (polydispersity) and liquid fraction [Dollet and Raufaste, 2014]. Foams are classified as dry or wet according to liquid content, which may be represented by liquid volume fraction ϕ, defined as:

$$\phi = \frac{V_{liquid}}{V_{liquid} + V_{gas}} = \frac{V_{liquid}}{V_{foam}} \tag{2.1}$$

The liquid volume fraction, ϕ, may vary from less than 1% (dry foam) to around 35% (wet foam) [Langevin and Vignes-Adler, 2014], as showed in Table 2.1.

Table 2.1: Foam Nomenclature in Function of the Liquid Fraction [Stevenson, 2012].

Liquid Fraction [%]	**Classification**
$0 < \phi < 20$	Dry Foam
$20 < \phi < \phi_c$	Wet Foam
$\phi > \phi_c$	Bubble Dispersion

At low volume fractions, the bubbles are deformed into polyhedra with both flat faces (bordering films) and curved faces (at the edges), while for higher volume fractions the bubbles show a circular shape as presented in Figure 2.1.

The dimension of the foam bubbles depends on the foam generation process. In nature, they are generated through vortex by recirculating flows. In industrial and scientific applications high energy mixers are employed. In the generation process some foams reveal to be stable, while others prove to be very difficult to generate and present an unstable behaviour. Stability is directly related to foam-ability: a foam that can be generated easily will prove to be stable [Caps et al., 2014b]. In the first instants of formation bubbles have spherical shape, with a small average diameter, and are closely arranged to each other [Langevin and Vignes-Adler, 2014]. The main difficulty of foam studies arises because they are short-lived in general. Foams are metastable systems and energy is required in their formation in order to create new interfaces between liquid and gas phases [Langevin et al., 2005]. The foam evolution is related to the decrease of the surface energy via two independent processes: coalescence, which is the rupture of films between bubbles, and coarsening, which is gas

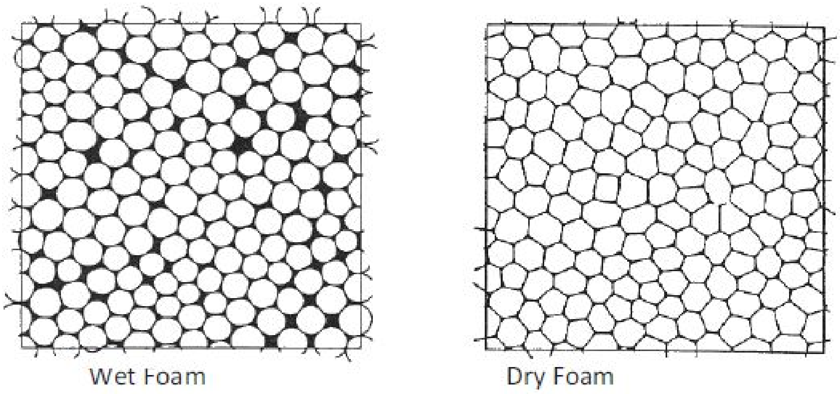


Figure 2.1: Schemes for Foams with Different Liquid Volume Fractions [Langevin and Vignes-Adler, 2014].

transfer between the bubbles due to their different internal pressures [Caps et al., 2014a]. Both processes provoke an increase of the bubble radius with time, but they are not easy to distinguish. A third ageing mechanism is the gravity-driven drainage of liquid between the bubbles, which removes liquid from the foam and influences both coarsening and coalescence [Caps et al., 2014a].

Because of their multi-scale structure, liquid foams display a complex mechanical behaviour: they have elastic, plastic and viscous properties. For example, wet foams show a particularly interesting transition when the bubbles are closely packed, but still spherical. For disordered foams this phase is called "jamming transition", and it usually occurs at a liquid fraction $\phi_c \sim 36\%$ (Figure 2.2) [Caps et al., 2014a]. At lower liquid fraction, when the bubbles are distorted into polyhedra the foam behaves like a soft solid. By contrast, at larger ϕ, when the bubbles are separated by enough liquid to move independently, the foam behaves like a viscous liquid [Caps et al., 2014a]. These complex mechanical behaviours qualify foams as complex fluids, like colloidal and granular suspensions, polymers, pastes, slurries and emulsions and the measurement and understanding of their complex mechanical response belongs to the field of rheology (Subsection 2.1.2) [Dollet and Raufaste, 2014].

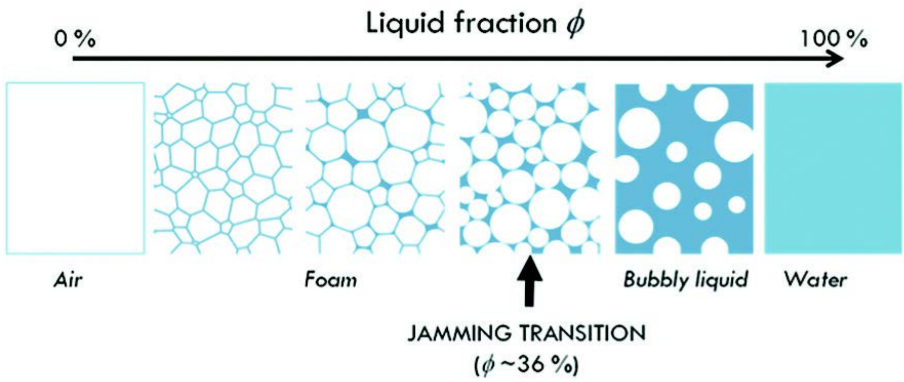


Figure 2.2: Scheme of Foam Evolution upon Increasing Liquid Fraction[Caps et al., 2014a].

2.1.2. FOAM RHEOLOGY

Rheology is the scientific domain dedicated to the study of flows and their deformations experienced by strained materials. These materials are characterized by a behaviour sometimes elastic, sometimes plastic, or viscous. In this domain foams, which are formed by the complex network of gas/liquid interfaces, present extremely interesting physical and rheological properties [Caps et al., 2014a] and peculiar behaviour under stress. Although foams consist mainly of gas and a small amount of liquid, they can support shear elastically, like a solid, through the distortion of tightly packed bubbles away from area-minimizing shapes. However, when the applied stress is sufficiently great, the bubbles can move around, allowing the foam to flow and deform indefinitely acting as liquid [Durian and Gopal, 1994].

The combination of elastic/solid-like and viscous/liquid-like behaviour in foams is further surprising [Durian and Gopal, 1994]. Foam rheology can prove that this changing in foam behaviour occurs at ϕ_c, close to 36%, where the foam changes from solid-like to liquid-like, as shown in the Figure 2.3 [Langevin and Vignes-Adler, 2014]. For $\phi > \phi_c$ liquid-like behaviour can be obtained by applying a strain larger than a critical value called critical yield strain, ϵ_y [ESA, 2015]. This transition prevents the foam from resisting to a static stress. The change in the behaviour happens at the so called jamming transition [Langevin and Vignes-Adler, 2014]. The understanding of this feature has proven to be difficult on Earth, but the application of this rheological properties has such an appeal that ESA and other organizations keep investing resources for research in this field. Thus, microgravity conditions are of fundamental importance for the investigation of the jamming transition [ESA, 2015].

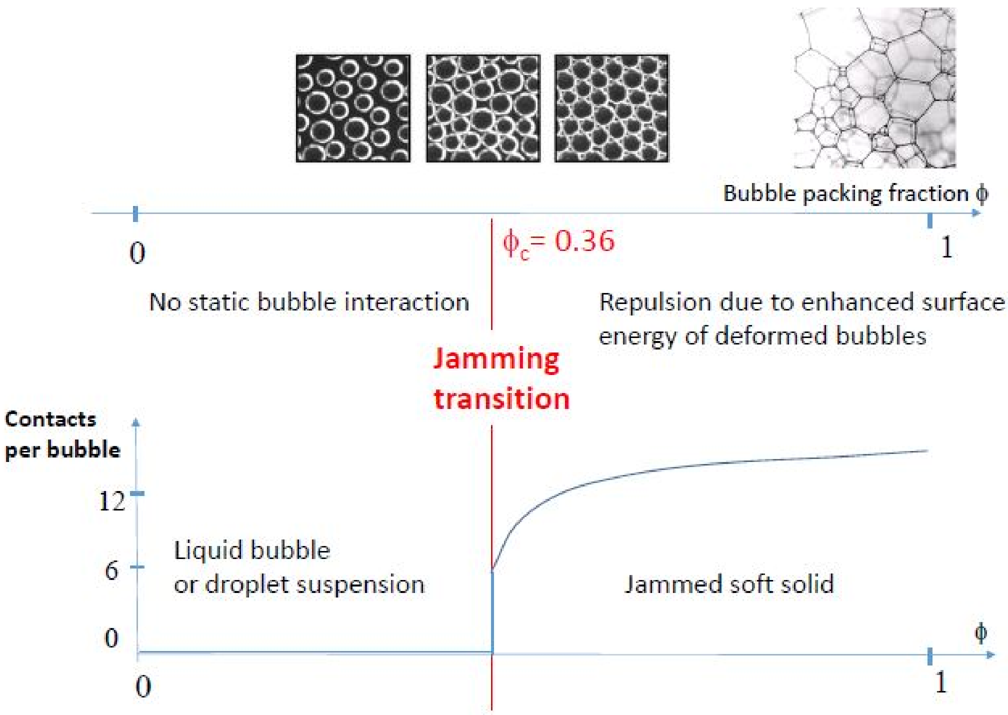


Figure 2.3: Jamming Transition of Wet Foam with Respect to the Volume Fraction Value.

2.2. EXPERIMENT FACILITY

On Earth, it is not possible to experimentally study the dependence of foam structure, rheology, and stability with respect to its liquid content without interference from gravity. In particular, the volume fraction of liquid accessible on Earth is restricted to a very narrow range, below about 10%, where the foam is still relatively dry with nearly polyhedral bubbles. Therefore the dramatic changes in foam structure, bubble dynamics and rheology that are expected on approach to the jamming transition cannot be studied by ground based experiments. To this end, microgravity conditions are needed in order to eliminate the increasingly rapid gravitational drainage between gas bubbles [Durian and Zimmerli, 2002]. In addition, in microgravity environment it is possible to systematically measure a sequence of foams with increasing liquid content, especially for wet foams and near the rigidity loss transition [Durian and Gopal, 1994].

Nowadays, various foam experiments are in preparation for the FSL on-board the ISS, supported by the ESA and developed by Airbus DS. In fact, this facility is the only one that provides the microgravity level and the highest time margin possible for the operations required by foam experiments with respect to the other ground based facilities.

2.2.1. INTERNATIONAL SPACE STATION

The International Space Station Programme is the most complex space project ever undertaken, with 15 countries involved. The project came from the National Aeronautics and Space Administration (NASA) establishment of the 'Space Station Task Force' in May 1982, dedicated to study user requirements and to propose a conceptual design of a Space Station [ESA, 2015]. Then, it was turned into an international cooperative programme where Canada, Europe (represented by ESA) and Japan took part. In 1993, with the end of Cold War conflict, the Russian Federation was invited to join the program and an agreement was signed with the Russians, giving birth to the ISS [ESA, 2015].

The ISS offers a wide range of research facilities and laboratories in a unique environment. It has a nearly circular orbit inclined at 51.63° to the equator with an average altitude that has ranged between 330 and 400 km, a velocity of almost 28000 km/hr, orbiting Earth every 90 – 93 minutes. The Earth's gravitational field at the altitude of the ISS has 88.8% of its strength compared to the Earth's surface value. The microgravity environment measures about 10^{-4} g [ESA, 2015].

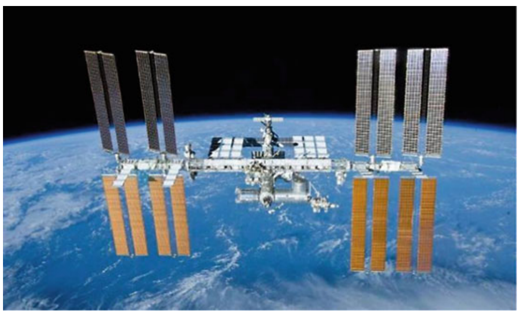


Figure 2.4: The International Space Station [Beysens et al., 2011].

Figure 2.5: Picture of the Columbus Module on the ISS [NASA, 2015].

Europe carried out almost 200 experiments on the ISS from 2001 until the launch of

Columbus in February 2008, mainly associated with short-duration missions involving European astronauts [Beysens et al., 2011]. The Columbus module consists of a cylinder (Figure 2.5) with an inner diameter of 4216 mm and an overall length of 6137.2 mm, closed by a truncated end cone at each end. As part of the ISS, ESA's Columbus module represents an element of a multi–functional, orbital infrastructure that generates and distributes the resources required for scientific and technological research in Low Earth Orbit (LEO) [ESA, 2015]. Columbus is ESA and Europe's biggest single contribution to the ISS and its arrival greatly increased Europe's research potential. Among the multiple disciplines being investigated in Columbus, four major research areas are identified: human physiology, biology, physics and Earth science [ESA, 2015].

For each of these, an International Standard Payload Rack (ISPR) is dedicated, which provides Experiment Containers (ECs) with power, cooling, video and data lines. In particular, Columbus hosts ten standard-sized research racks [Beysens et al., 2011], the most important are the BioLab, the European Physiology Module (EPM), the FSL, the European Drawer Rack (EDR), and four external payload locations.

2.2.2. FLUID SCIENCE LABORATORY

Among these racks, the FSL, in Figure 2.6, stands out for its role in the investigation of fluid physics in microgravity conditions. In this platform, experiments that looks into fluid flow, heat transfer and foam stability/instability mechanisms in weightlessness are developed [Lorenzen and Schweizer, 2008].

Figure 2.6: Fluid Science Laboratory Rack [ESA, 2017].

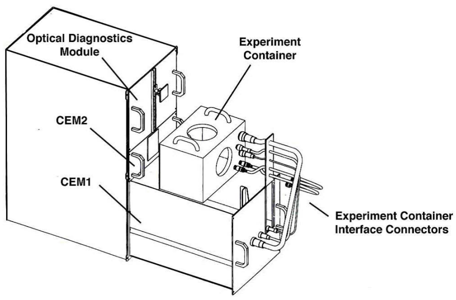


Figure 2.7: Experiment Container in the Central Experiment Module [ESA, 2017].

This facility can be operated in fully automatic or semi-automatic mode on station by flight crew, or remotely by ground engineers in telescience mode. Interacting with the FSL in quasi-real time from the ground allows the scientists to follow the evolution of their experiments and to provide feedback on the data they receive [Feustel-Buechl, 2003]. The FSL telemetry data can be monitored by the crew through the LapTop Unit (LTU), which can be also used to issue commands to the FSL facility when required. A specific Human Computer Interface (HCI) software allows a user-friendly representation of recorded data and of command preparation to the experiment, if it is necessary that then crew intervene.

The FSL is characterized by a modular design based on the use of drawer elements, which facilitates the exchange and transport of its components, both to upgrade their functions or to repair in case of defects. The drawer elements contain the ECs where the experiment hardware are integrated. An EC has a typical mass of $30-35\,\mathrm{kg}$ and standard dimension of $400 \times 270 \times 280\,\mathrm{mm}^3$ and are tested and integrated on ground (see Figure 2.7).

2.3. SOFT MATTER DYNAMICS MISSION

The Soft Matter Dynamics EC is one of the FSL ECs currently developed by the department of Fluid Physics and Payloads at Airbus DS in Friederichshafen. It is equipped with optical diagnostic subsystem, actuators, avionics and it can be used in the analysis of physics phenomena acting on soft matters under microgravity conditions. In Figure 2.8 an overview of the subsystems available on the Soft Matter Dynamics EC is presented in a Computer Aided Design (CAD) model, which represents the exact FM system.

On board the ISS the experiments are carried out through dedicated SCU. These contain the Sample Cells (SCs) that are small containers where the experiment solutions or solid material are stored. Each SCU presents particular features and different numbers of SC according to the aim of the experiment. The SCU works as a cartridge that is inserted into the EC and it is easily accessible by the astronauts through an access port. Moreover, the Sample Cell Units (SCUs) are exchangeable and can be inserted and removed in the EC without any specific tool, simply plugged into the dedicated spot. The Soft Matter Dynamics EC can host up to five SCUs directly plugged into the Moving Tray (MT) that works as a carousel and put the SCU in the operational position for the experiment. The MT is characterized by a rotational movement generated by a belt and a stepper motor actuation coupled with a bar-code reader to identify the cells. Only one SCU at time can be under experimentation [Kirkorian, 2016]. The main feature of the Soft Matter Dynamics EC is versatility and ability to reuse all the subsystems and diagnostic elements to implement different SCUs with different scientific outputs.

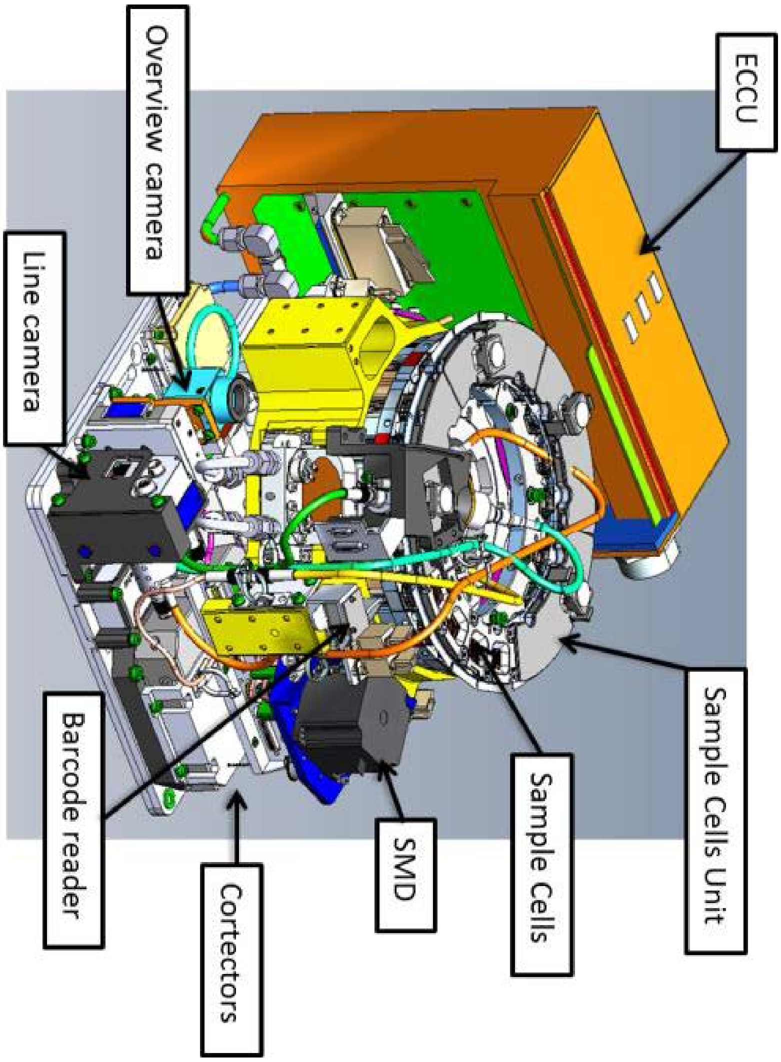


Figure 2.8: Overview of the Soft Matter Dynamics EC [Kirkorian, 2016].

3
REFOAM

The REFOAM project is dedicated to the feasibility study of the implementation of rheology investigation on wet foams reusing the Soft Matter Dynamics EC. The idea is to dedicate a SCU to perform experiments on foam rheology. This is possible thanks to its exchangeability, which allows variation of the liquid fraction content, and thanks to the suitability of the optical diagnostics for this type of investigations. Airbus DS is working in collaboration with ESA in order to design and verify this concept through the development of a prototype hardware with appropriate strain stimulation capabilities, compatible to the optical diagnostics and able to provide valuable results form a scientific point of view. To this aim, the scientific experiment is supported by the Professor Höhler from the Institut des NanoSciences in Paris. During this cooperation, technical concepts, test concepts and test results will be shared in order to achieve a common understanding on the feasibility of the final experiment concept in space.

In this chapter the REFOAM project is presented based on the Airbu DS internal document: *"REFOAM Design Report and Validation Plan"* [Calabrese, 2017]. In Section 3.1 the aim of the project. Then, in the Section 3.2 an evaluation of the project requirements is given. In Section 3.3 the final version of the REFOAM system design is shown, and in Section 3.4 the experiment operational scenario is finally analysed.

3.1. Experiment Objective and Schedule

The objective of the REFOAM technology study is the evaluation, design, manufacturing and testing of a prototype that allows the mechanical deformation of foams in a microgravity environment, integrated in the Soft Matter Dynamics EC developed in collaboration with the scientific team and the SMD instrument provider.

In the development of the SC the structural integrity, safety, fracture, off-gassing and reliability standards stated in ESA and NASA safety requirement documents shall be matched. Material compatibility is an important issue also in the choice of components for the subsystems, as chemical reactions with the fluid sample must be avoided. Furthermore, the performance of the product and the hardware itself should not be affected by the environment of operation and scientific liquid compositions must not be altered. However, in a feasibility study the costs and quality checks can be lowered by testing the demonstrator with liquids and components not qualified for transport and use on board the ISS. Despite the considerations that influence the development of a space flight-worthy product, the REFOAM demonstrator will not be strongly influenced by these. In fact, a demonstrator's project has usually a moderate budget with respect to a FM. As a consequence, the amount of tests that can be performed for qualification is reduced to the minimum extent necessary. Furthermore, budget constraints also contribute to lessens some quality standards, in particular those which will not compromise the functionality of the system (e.g. grounding of equipment).

The final target of REFOAM is the development and production of a demonstrator that will be operated in laboratory conditions. For this purpose, the outcome of the study shall be a demonstrator whose functionality shall be tested within the SMD eBB as VTF. The eBB is representative of the Preliminary Design Review (PDR) of the design of the Soft Matter Dynamics EC, with the main exception that it does not have an Avionics Unit and cannot be operated with the official FSL Electronic Ground System Equipment (EGSE). Otherwise it is form fit and function equivalent (but not identical) to the FSL EC EM/FM currently in development. The intention is to get the most realistic test environment possible and gain study results that are actually relevant to a future development of a potential REFOAM FM.

3.2. Scientific Requirements

The REFOAM SCU was designed in accordance with a series of requirements defined by Airbus DS team in collaboration with scientists of the Institut des NanoSciences de Paris and ESA, in order to guarantee the relevance of the scientific outputs, and to agree on the operational/performance demands for a rheology experiment. During this cooperation, technical and test results were shared between the three organizations in order to achieve a common understanding on the feasibility of the final experiment concept in space.

The definition of requirements constitute the first phase of the feasibility study. They are grouped in topical sections, within each section the requirements are categorized as Minimum (M), Optimum (O), Nice to have (NH). The Minimum stands for an absolutely critical requirement, the Optimum one expands the science scope, and the Nice to Have enhances the fidelity of the experiment. Verification strategy provides proof of the compliance of the product with the user requirements. In general, verification concept is developed considering the system level (e.g., component or subsystem) and the applicability, through a set of verification methods [Larson, 2009]. Each Verification strategy occurs at different stage of the system development. The main strategies used and proposed to validate the REFOAM requirements are hereafter explained.

- **Analysis**. It is generally run during design phase with specific software. The studies of the magnetic field around a magnet or of the deformation of a part are typically examples of analysis.
- **Review of Design (RoD)**. It means that the choice of concept and the design are enough to foreseen if the system will be compliant to the requirement. There is no immediate need of a further test or investigation to validate the statement.
- **Similarity**. It means that other projects or system have already complied with this requirement. Consequently it is not necessary to repeat the test, when both requirements and situations are similar. It is not mandatory to re-do the verification and validation.

- **Development Test**. Tests performed during design phase, which allow to validate a first concept or idea in the development phase. The main advantage is to avoid a waste of time by using concepts that will not be mastered once the system is built.
- **Demonstrator Test**. It stands for a test that will be achieved on the demonstrator system to verify if the demonstrator is able or not to achieve the requirements.
- **Depends on Concept**. It means that the Verification Strategy should be adapted to the concept chosen. For instance, one concept could imply just an Analysis, whereas another concept directly needs a validation test.
- **Validation Test**. It is conducted at the end of the product development to validate if the system is compliant on this specification by conducting a well-defined test.

The complete table with the requirements identification number and description is provided in Appendix B. Once the SCU design was accepted by the third parties a first iteration of the Verification Compliance Matrix (VCM) and the Verification and Validation Plan were defined (see Chapter 7).

3.3. First Design Concept

The REFOAM demonstrator design is made in order to test on ground the capability of a possible new SCU for rheology experiment within the VTF of SMD. In order to enhance the development and have a system compatible with the existent Soft Matter Dynamics EC, the design of the REFOAM demonstrator SCU was developed adopting the main following drivers:

- The reuse of as many components as possible of the Soft Matter Dynamics EC;
- The design of a compatible SCU with the available interfaces of the VTF forSMD: ie. Electrical interface / Optical interface / Mechanical interface / Available envelope.

In Figure 3.1 and Figure 3.2 a brief overview of the first design concept with the main components is given. As presented the SCU is mainly composed by a main frame that contains the subsystem involved in the foam experiment. The foam is generated inside a SC thanks to the movement of an internal piston (Figure 3.2), an actuation system, which is composed by a piezo motor and an encoder, which provides the strain required for the rheology tests, and a couple of mirrors that redirect the laser beam to the SC observation window to observe the disposition of the bubbles before and after the perturbation.

3.3.1. Sample Cell Unit: Main Structure

The main function of the SCU is to hold the components and to be inserted in the EC. Mechanical, electrical interfaces and the designed volume of the REFOAM SCU should fit in the Verification test facility. The SCU is composed of three main parts: the upper part (light gray colour), the lower part (brown colour) and the top cover (dark gray colour); as shown in shown in Figures 3.3, 3.4, and 3.5.

The SCU is made of standard aluminium material. One millimetre minimal thickness was used everywhere on the SCU design to prevent any damage due to internal stress during the experiments. As the system will not meet high loads or torques during its utilization, it was not necessary to run stress analysis during the design phase. For a potential EM and FM,

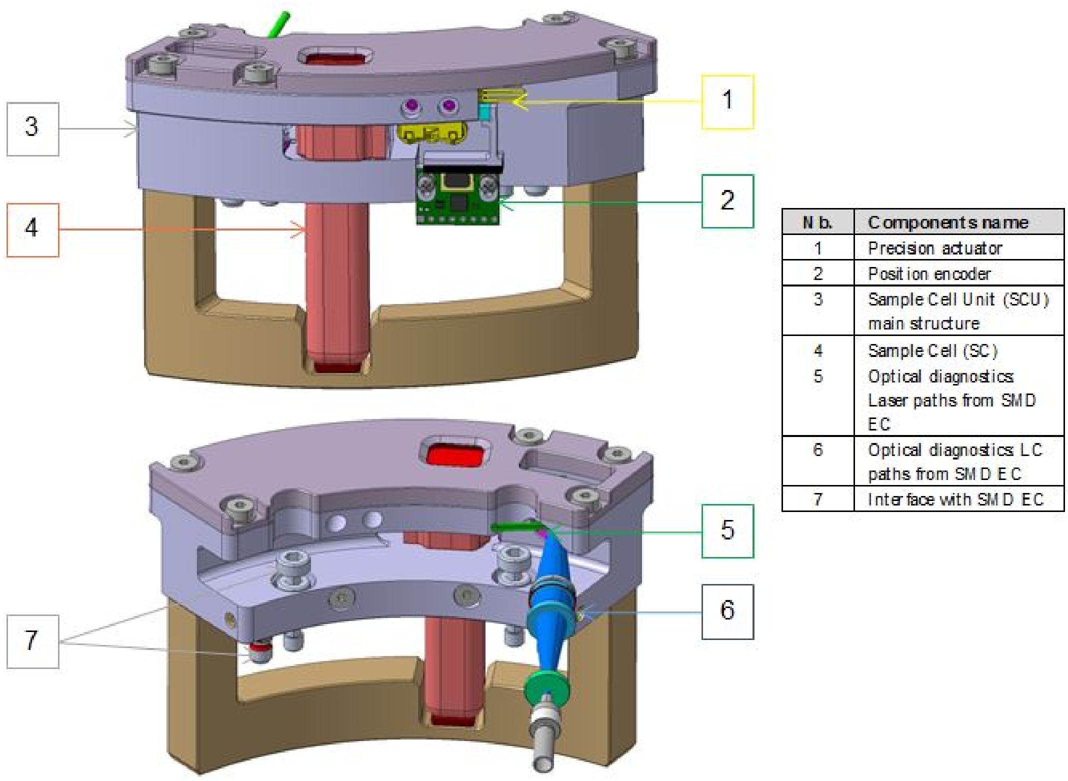


Figure 3.1: Demonstrator Overview [Calabrese, 2017].

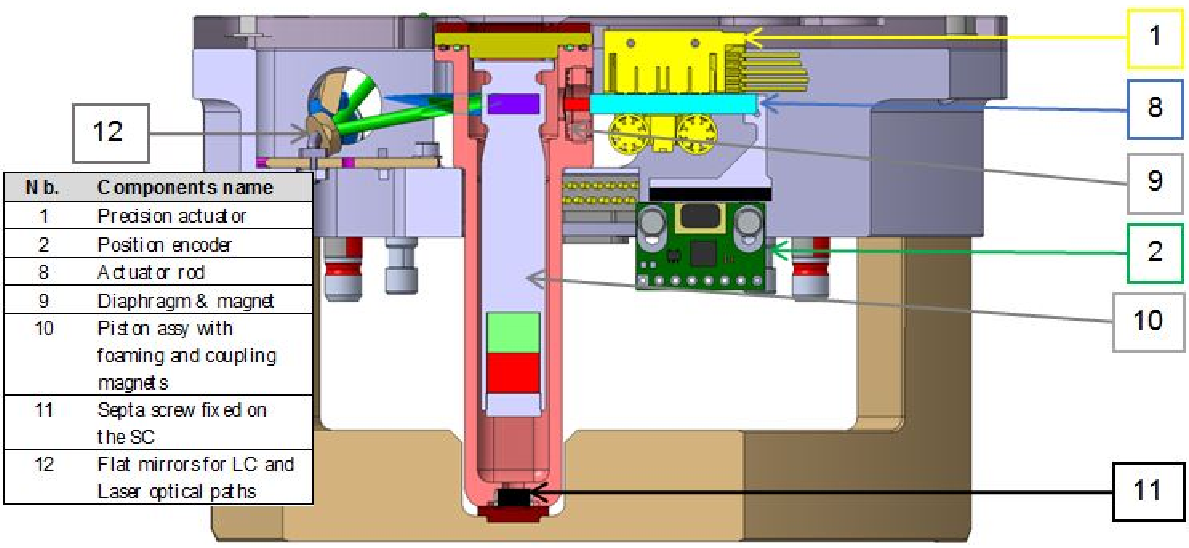


Figure 3.2: Demonstrator Overview - Section View [Calabrese, 2017].

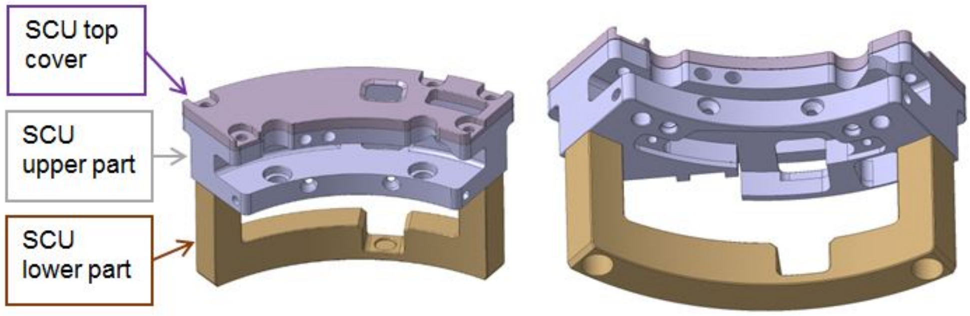


Figure 3.3: Sample Cell Unit Front and Bottom Isometric Views [Calabrese, 2017].

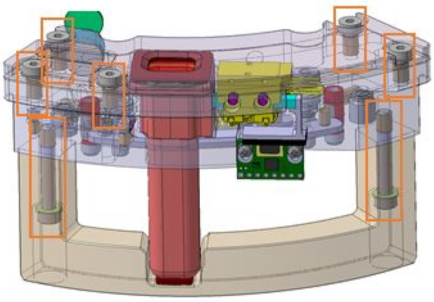


Figure 3.4: Closing of the Sample Cell Unit [Calabrese, 2017].

Figure 3.5: Sample Cell Unit Top Cover Bottom View [Calabrese, 2017].

thermal and stress analysis would be run on such component to validate the design. For the potential intended FM, a back cover in aluminium sheet should be added to the SCU frame structure in order to hermetically close the system.

3.3.2. SAMPLE CELL ASSEMBLY

The SC contains the liquid solution that will generate the foam to be investigated for rheology experiment. The cell is made of three main components: the main body, the top cover, the septa screw and the membrane, as shown in Figure 3.6.

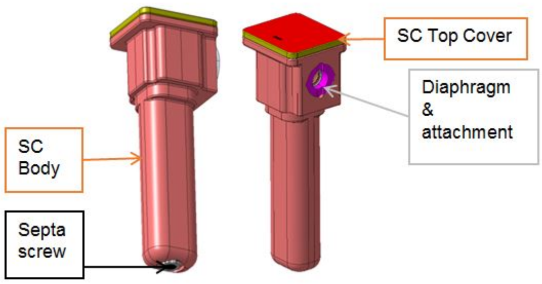


Figure 3.6: Sample Cell Isometric Front View [Calabrese, 2017].

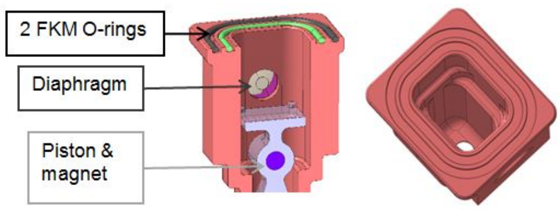


Figure 3.7: Sample Cell Isometric Section View [Calabrese, 2017].

The cell is made of plastic-like material polycarbonate or stereo lithography material). The main reason for using a non-metallic material is to permit the outside located coils of the Soft Matter Dynamics EC to check the piston during the foaming phase. The SC is closed by a top cover, 2 O-ring seal. A piece of rubber-like material called Shim (with predefined thickness) compensates integration and manufacturing tolerances located between the top cover of the SCU and the top cover of the SC and compresses the O-rings of the SC (see Figure 3.7). Another shim is used at the bottom of the cell for the same reason and also to work as second backup sealing after the septa screw. Both nominal shim thickness were designed by the study of tolerance chains for the involved components.

3.3.3. Piston assembly

The piston is characterized by two main functions. It is firstly used to generate the foam by shaking vertically, and then reused for the rheology experiment. The neck is modified to implement a cylindrical volume to create the so called deformation/rheology plate used for the rheology experiments (see Figure 3.8). The other side of the cylinder is designed to be a specific coupling plate that will be in contact with the membrane end tip. To manufacture the piston body additive manufacturing method is considered to be able to insert a magnet inside during printing process and to guarantee a full tightness.

The magnet is centred inside the piston neck to prevent the piston from tilting during the shaking phase for foaming (moment of inertia stays constant). In order to keep the good foaming performances of the piston, the rest of the piston: foaming/shear plate, foaming magnet, bottom piston cork are identical to former piston design already tested and qualified (as for FOAM-C). The shear plate of the piston has 4 small pillars especially designed to limit the chock of the shear plate to the inner wall of the SC top cover. In case of damage of these pillars due to these repeated chocks, the performance of the foaming shear plate will not be affected. The piston cork has two functions: acting as a damper when the piston is hurting the inside surface of the cell (during checking), so that no damages are made to the SC inner body or the piston body, and sealing of the pocket where the foaming magnet is inserted. Indeed the relaxed piston cork is slightly larger ($\sim 15\%$) than the pocket size. This compression of the Viton material during the assembly avoids the solution to enter inside the pocket during piston life inside the cell.

3.3.4. Magnets and Diaphragm Membrane

The magnets used to couple piston and actuator rod have a cylindrical shape. The first magnet (purple colour) is inserted and enclosed inside the piston neck. The second magnet (red colour) is glued and fixed in the centre of the square rod of the actuator (refer to Figure 3.9). The magnet pull force needs to be strong enough to couple the rod with the piston plate and to allow the rod to push or pull the whole piston assembly (mass $\sim 6\,\text{g}$) for the rheology experiment. The magnet attraction force should not be too strong ($< 3\,\text{N}$) so that the piezo motor can decouple the actuation part from the piston when the experiment is finished and when the rod is moving back to the stored position.

The diaphragm is a custom part especially made for REFOAM demonstrator. The main advantage of the membrane is to avoid a sealing with for instance O-rings that could create large friction forces and stick slip behaviour as well as sealing performance during the strain cycle is unknown. The attachment of the membrane to the SC is made with a ring and a pressure screw (see Figure 3.9). The functioning of the membrane attachment is simple: the screw presses the ring against the membrane which is then clamped to the inside wall of

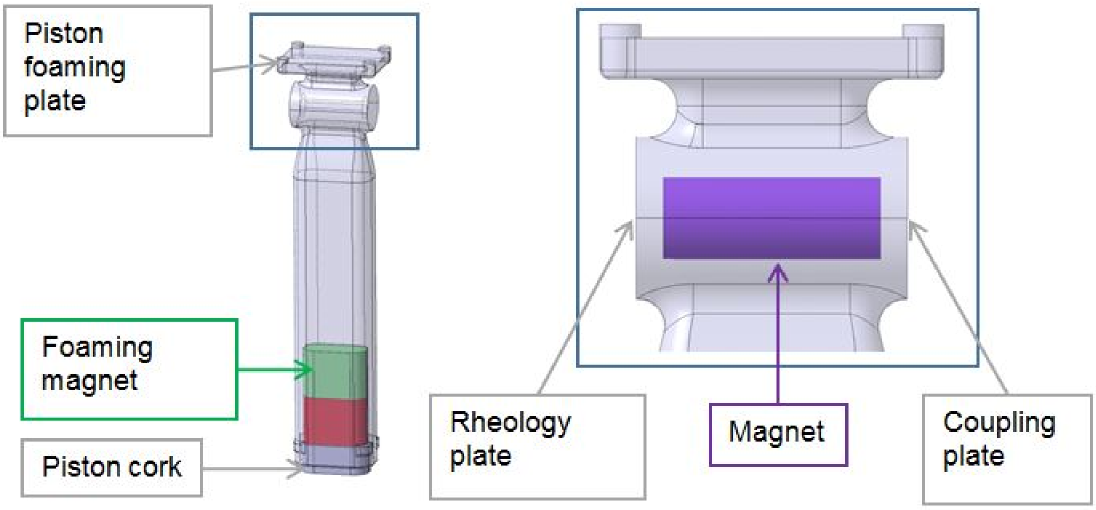


Figure 3.8: Isometric Front and Zoom View of the Sample Cell Piston Assembly [Calabrese, 2017].

the SC hole. This support washer was built to count two circular walls for a double level of containment between the cell and the membrane. The ring has also four rounds protuberances that fit the four grooves of the SC. These shapes prevent the ring from turning when the screw is in contact with the ring. Without these protuberances, the ring walls would have probably torn the membrane during the clamping.

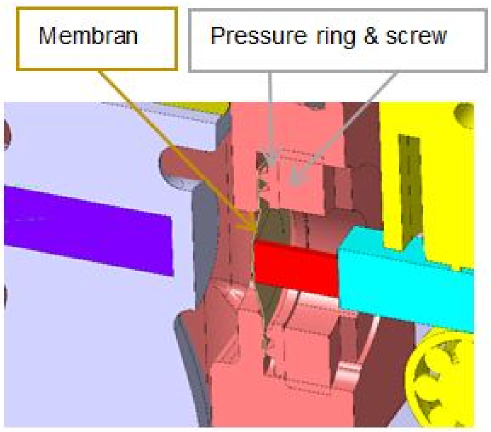


Figure 3.9: Isometric Section View of the Membrane Environment [Calabrese, 2017].

3.3.5. ACTUATION SYSTEM

The actuation part shall perform a stroke of 3.0 mm: ~ 1.9 mm represents the distance between the retracted membrane and the piston in the initial position (with gap L to opposite inner wall of SC) for rheology test. For the strain cycle, 0.20 mm stroke is needed with 100% margin against requirements plus 0.800 mm contingency for integration and manufacturing tolerances. The actuation is performed by a piezo actuator from *PiezoMotor*, model: Piezo LEGS Linear 6N LL1011D non-magnetic and vacuum proof version, as presented in Figure

3.10. The use of the non-magnetic version is recommended to prevent the magnet glued on the rod to disturb the well-functioning or performances of the piezo motor.

Figure 3.10: Piezo LEGS Linear 6N LL10 [PiezoMotor, 2016].

The piezo rod for REFOAM demonstrator should be customized with shorter length: 26 mm (instead of 30 mm for standard version) and no mechanical adapter needed. Piezo LEGS LL10 displays predictable sub-micron, direct-drive motion free from backlash. Resolution extends to single nanometer level or below when required. Gear-heads and linear screws are not needed, which reduces overall size. It is able to fit in spaces that other motors find difficult and it delivers up to 6.5 N force. Its friction drive ensures full-force, power-off locking, and its Piezo LEGS® technology is ideal for any 'move-and hold' application able to benefit from high precision, instant response and low power consumption [PiezoMotor, 2016].

The piezo actuator is adjusted in the desired position during integration and fixed to the SCU upper part with 4 pressure screws (purple colour in Figure 3.11) that clamp the motor chassis.

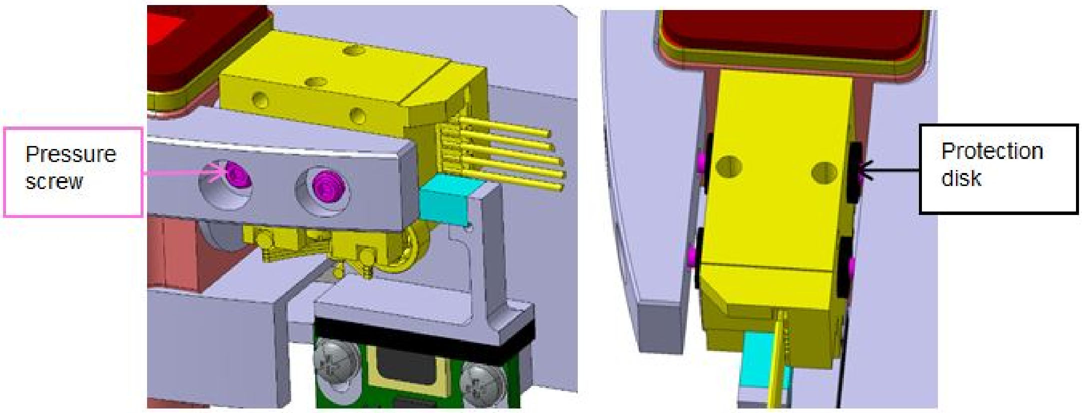


Figure 3.11: Motor Adjustment and Attachment [Calabrese, 2017].

To prevent any damage during the clamping of the actuator, disks of different diameters (4 – 7 mm) (black colour in Figure 3.11) could be added to the pressure screw endings to spread the push forces. These disks made of Polyoxymethylene (POM) material could also help to have a better adherence and a well-defined thickness between the screws and the actuator.

The piezo actuator is controlled by the microstepping Driver 101 PMD101 (see Figure 3.12). The PMD101 is a 1-axis microstepping driver especially developed for Piezo LEGS®

motors and by PiezoMotor company. One of the more advanced drivers in their range, it gives motors resolution down to the nanometer/microradian range. Driving in closed-loop mode is possible when reading back position from a position sensor. The PMD101 supports quadrature and analog encoders. By issuing a single command, it guides the motor to the exact encoder count, taking into account parameter settings for ramping behaviour. This driver delivers up to 2048 micro-steps per waveform cycle, giving approximately 2 nm (0.002 μm) movement per micro-step for a Piezo LEGS® linear motor. Waveforms optimized for speed, resolution or force are available. The unit communicates with the host through serial USB. Several I/O pins are available [PiezoMotor, 2016].

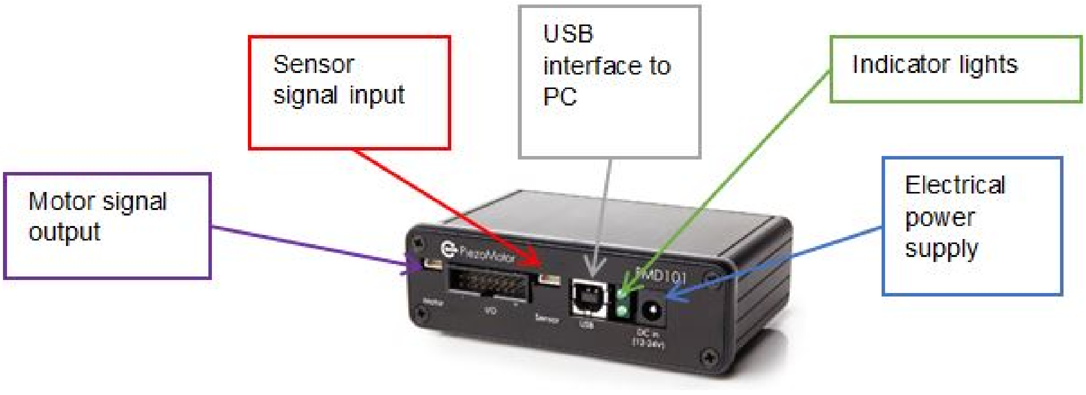


Figure 3.12: Microstepping Driver 101 PMD101 [PiezoMotor, 2016].

For easy manual adjustment during integration and commissioning of the demonstrator, the Piezo LEGS LL10 can be driven in a close loops mode directly from the graphical interface of the PiezoMotor's software.

The position feedback of the Piezomotor LL10's rod is given by the encoder RLC2IC. To maximise the accuracy of the reading of the position by the encoder, its position (along the vertical axis) can be adapted as the encoder fixation holes have an elongated shape (2,8 mm stroke of vertical positioning adjustment). The piezo actuator and the encoder are linked by the encoder foot (grey part in Figure 3.13) where a 19 mm-long-magnetic tape is stuck on. The encoder foot is glued to the rod of the actuator with a specific glue which is compatible with the rod material (aluminium oxide commonly called alumina) and the encoder foot material. The encoder foot stays perpendicular to the piezo rod thanks to the two walls and glue attachment, as shown in Figure 3.13. Installation guidelines and tolerances of the position encoder are given in the encoder data sheet of the manufacturer [RLS Product, 2016].

The encoder quadrature signal is directly routed to the micro-stepping Driver 101 PMD101 that will reuse the position information feedback to drive the piezo in a closed loop mode.

3.3.6. DETECTION AND ILLUMINATION

A direct reuse of the laser and Line Camera (LC) optical rays provided from the Optical subsystem of Soft Matter Dynamics EC were considered. To illuminate and observe the foam investigation window, both optical beams (laser and LC) need to be redirected to the side of the SC. In particular, the observation/illumination should occur in the alignment of the direction of displacement of the deformation piston. The optical paths of the LC were reverse

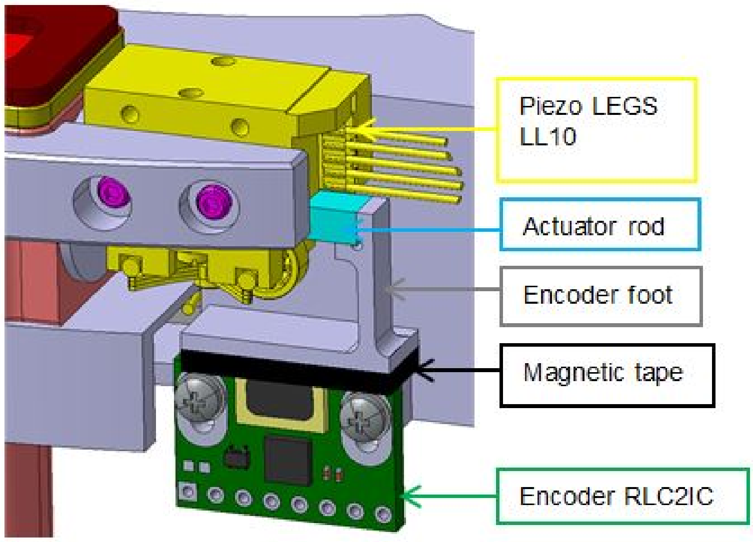


Figure 3.13: Feedback Loop: Piezo Motor LL10 and Encoder RLC2IC [Calabrese, 2017].

engineered from the design report of Soft Matter Dynamics EC and the CAD model made for the optical subsystem.

Mirrors position and adjustment

For REFOAM demonstrator, flat mirrors are redirecting the rays so that they cross the PolyCarbonate (PC) window in the centre of the inner wall. The mirrors have a simple cylindrical shape: diameter 7 mm and thickness 2 mm and a silver coating.

Refraction

Optical refraction of rays (laser and LC) through material (polycarbonate mainly) is calculated via the parameter and formula tools of Catia CAD software. Following parameters are created :

- Refractive index of the PC Sample Cell = 1.5853
- Refractive index of the water-like-solution inside the cell = 1.33
- Refractive index of ambient air = 1.00272

The parameters are then used in the formula editor to calculate the refracted angle in function of the incident angle with the Snell-Descartes formula:

$$n_2 sin(\theta_1) = n_2 sin(\theta_2) \tag{3.1}$$

$$\theta_2 = sin^{-1}[\frac{n_1}{n_2} sin(\theta_1)] \tag{3.2}$$

with n_1 refractive index from the first medium and n_2 refractive index from the second medium and θ_1 angle of incidence and θ_2 angle of refraction.

The surface, which splits the two media, is called the interface. As a first design concept, the two mirrors are inserted in a putty material during integration. This material is flexible at room temperature and gets solid after a 30-minutes-backing at 110° C in an oven. The adjustment of the mirrors would be made in the VTF, during integration.

The current design of the optical elements allows the laser and the LC to be centred to the observation volume, i.e. to the projection of the rheology plate to the inner wall of the SC. The Field of View (FoV) of the LC has a rough size of diameter 3.30 mm (in the nominal case) From the sequence of LC images, the synchronisation of the strain cycle can be determined. For REFOAM potential FM, the mirrors need to be made of a full metallic material, as glass material represents a NO-GO for human space flight. In order to guarantee a perfect adjustment of mirrors, a fully integrated optical box in just one block of metallic material (with high manufacturing tolerances and a perfect roughness) represents the optimal solution.

3.4. OPERATIONAL SCENARIO

The operational capacities of the new SCU for REFOAM are characterized by six operations, through which the demonstrator is able to perform its main functions of foaming and rheology study. The SCU is designed to allow two ways of filling the SC. Once the SC is assembled with the membrane and the piston inserted inside, the ready made reference foam can be filled from the top. Then the two O-rings, the SC and SCU top covers are sealing the SC.

The second way of filing the SC is represented in Figure 3.14 by using the Septa screw located and fixed to the bottom of the SC. A syringe is inserted through the septa screw and the ambient air inside the SC is evacuated. Then a well-defined amount of gas (70% of air and 30% of C6F14) and liquids (water and 5 g/l of TTAB) – according to desired rheology experiments – are injected directly from the bottom of the SC. During this phase, the SC is closed at the top with the top cover and the SCU lower part is removed to guaranty an easy access to the septa screw.

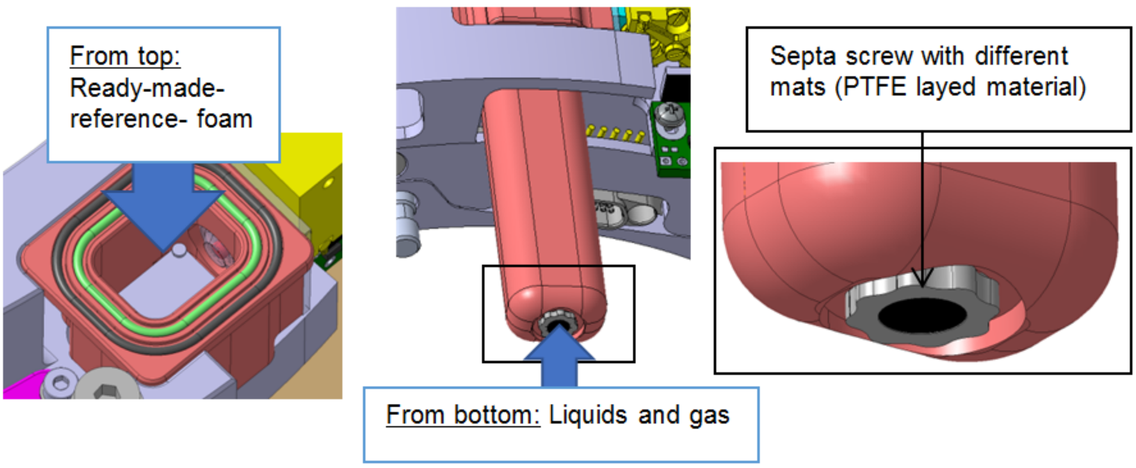


Figure 3.14: Two different Ways of Filling the SC for REFOAM [Calabrese, 2017].

3.4.1. POSITIONING OF THE SCU

Once the SCU is inserted in the EC through the crew access port, the SCU needs to rotate via the MT rotation to the position for SCU under investigation. The REFOAM SCU is inserted within the VTF in the slot 2. Two positions are now used for REFOAM SCU: the foaming position and the rheology position, both accessible by the rotation of the MT (see Figure 3.15). When the SCU is in the rheology position, the LC and laser rays are targeting the two mirrors of the REFOAM SCU.

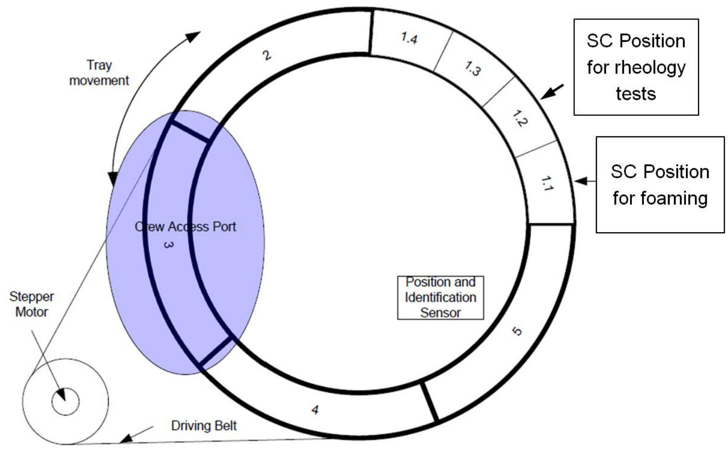


Figure 3.15: Positioning of the Moving Tray of Soft Matter Dynamics EC [Calabrese, 2017].

3.4.2. Foam Generation

The foam is generated by the Foam Generation System (FGS) when the REFOAM SCU is located at the foaming position. The two coils of the FGS are agitating the foaming piston from bottom to top. As shown in the Figure 3.16, the rod of the actuator (blue colour), the magnet (red colour) and the membrane (light brown colour) stay in the stored position so that any collision, between the membrane and the piston that will shake, is prevented.

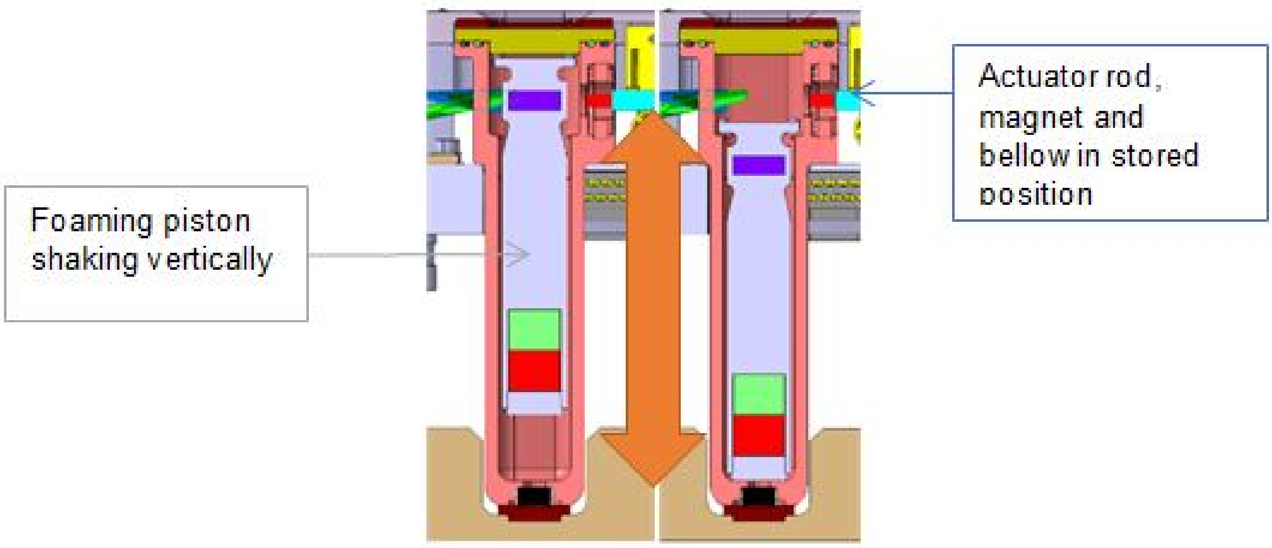


Figure 3.16: Piston Shaking Up and Down – Actuation in Stored Position [Calabrese, 2017].

During the foaming phase, it is possible to observe the foam with the overview camera from the REFOAM SC top cover window.

3.4.3. COUPLING OF MAGNET WITH PISTON PLATE

The REFOAM piston serves two main functions: foaming and applying the strain during the rheology experiments. For the second purpose the REFOAM piston will be located in the upward position after foaming and is magnetically coupled to the high precision actuator.

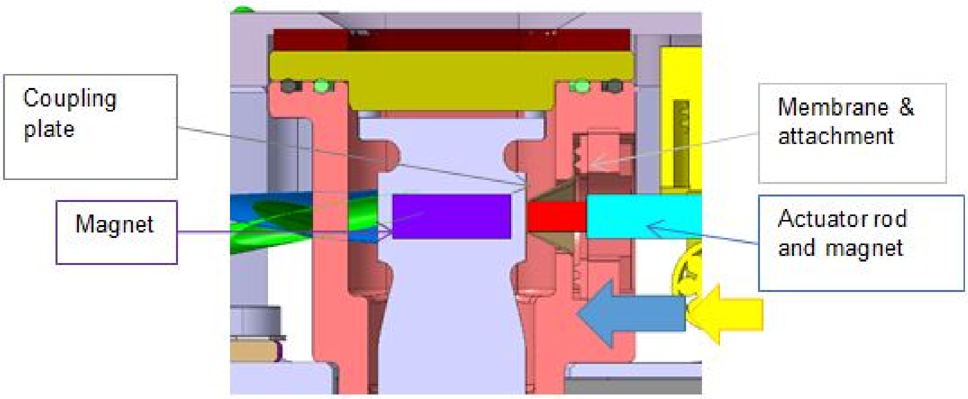


Figure 3.17: Coupling Plate and Actuator-rod Coupled by Magnets [Calabrese, 2017].

Whereas the piezo rod is pushing the magnet and the membrane from the stored position to the coupled position: stroke around 1.9 mm, the magnet inside the membrane and the magnet inside the piston are doing the coupling between the piston and the rod of the actuator like shown in Figure 3.17. The piston is now coupled and aligned, ready to conduct rheology tests.

3.4.4. RHEOLOGY TEST

The actuator moves the piston rheology plate to the initial reference position, with an initial gap of L (= 2 mm) with the opposite inner wall of the SC. After a To Be Defined (TBD) relaxation time of the foam the piston performs the strain cycles to the foam inside the deformation volume. Thanks to the accurate coupling actuator rod-piston, both compression and extension of the foam are possible from the reference position. During rheology tests, the foam is illuminated by the laser and observed by the LC.

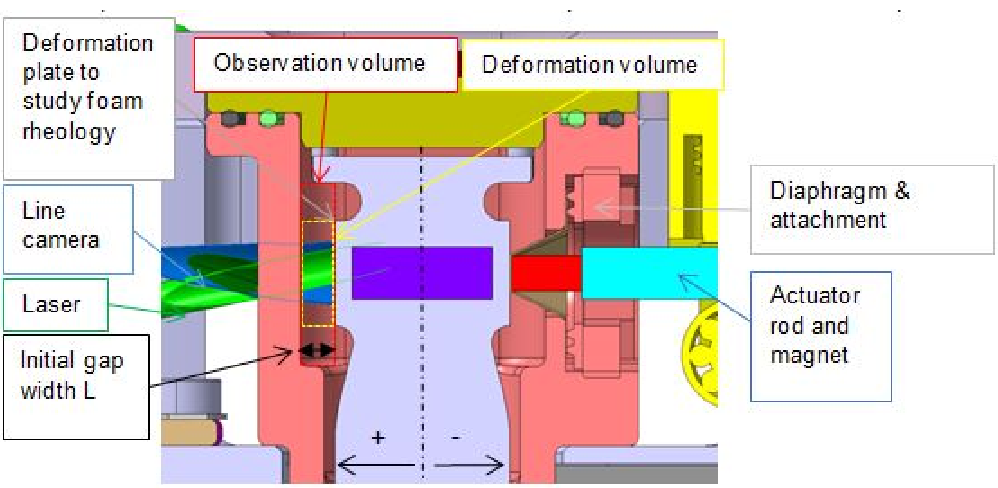


Figure 3.18: On-going Rheology Test – Compression or Extension of the Foam [Calabrese, 2017].

The observation volume represented by the red box on the Figure 3.18 is centred with the left inner wall of the SC. The observation volume is $10 \times 6 \times 2$ mm big. The deformation volume is centred on the observation volume and has an initial gap L of 2 mm and an area of diameter 6 mm ($= 3L$). Around the rheology plate of the piston, sufficient free space 2 mm at least to the bounding walls is left to allow an undisturbed flow of foam around the rheology plate during the strain cycle. The strain applied by the rheology plate to the foam is a uni-axial deformation. During the deformation stroke ($= 100\,\mu$m), the volume change due to the expansion of the membrane stays negligible: $\sim 5 \cdot 10^{-3}$ ml.

3.4.5. UNCOUPLING OF THE ACTUATOR AND THE PISTON

The actuator has to drive in the negative direction until the piston gets blocked against the SC body wall. Then to uncouple the piston from the actuator rod, the actuator has to overcome the magnetic coupling force (< 1N). Finally, the actuator is retracted further until the membrane is not stressed. The REFOAM SCU rotates to its initial position (N.2) and the foaming phase can start again.

II

REFOAM Demonstrator Phase

4

Verification Test Facility

The Verification Test Facility (VTF) or Elegant Bread Board (eBB) was built and involved in the SMD parabolic campaign in 2012. It is an experimental prototype developed considering many aspects of the usability in space. Nowadays, it is utilized in the tasks related to breadboard testing, life time testing, components test and so on, for the feasibility study and evaluation of possible SCU to be integrated in the Soft Matter Dynamics EC FM.

In this chapter a short introduction to the hardware system and subsystems, interfaces and their utilization is given in Section 4.1. The functional tests carried out to evaluate the system performances are analysed in Section 4.2. Finally, in Section 4.3 the REFOAM interface in the VTF is described.

4.1. State of the Art

The Elegant Bread Board is a reproduction of an experiment container, equipped with the SMD essential sensors and measuring tools. The dimensions are 270 × 280 × 400 mm and the weight of about 30 kg. The eBB is provided with an opening cap to access to the MT for the SCU insertion. The container has five fittings for the SCUs each with one connector and the housings for the pins and screws that fix them together. To position the MT in the right position, a Locking Pin needs to be lifted and the tray can be rotated by hand to the desired position. Once the desired position is reached, the the pin is locked again. Before powering up the system, the cap has to be correctly closed in order to activate the laser and unlock the pin, letting the MT free to be rotated via the STepper MOtor (STMO) software.

The eBB is powered by the Electrical Ground Test Equipment (EGTE), which also controls the FGS and the Optic Diagnostics system (see Figure 4.1). The foaming technique does not require moveable parts, but a magnetic coupled transmission is utilized. The solution involves two coils coupled in series with a stepper motor driver. Once the SCU is moved to the FGS position, the SC under investigation is at an equidistant point between the two coils. In that configuration, the magnet integrated in the SC piston is subject to two magnetic fields of the same intensity and polarity. When the coils are powered with alternate current, a magnetic field with a switching polarity is induced between the coils, thus implying alternating repulsion and attraction forces on the permanent magnet. As a result, the piston moves inside the SC body volume, hitting both the bottom of the SC body and the inner surface of the top cover. The best foaming results achieved during ground tests were obtained with the piston shaking at 10 Hz. Foam is generated thanks to the shear forces originated by the movement of the piston. These forces are strongly dependent on the speed of the piston and on the gap between the shear plate and the SC inner body walls. The speed of the piston depends on the current feeding the coils. In order to have a proper illumination for image capturing of the foam, six LEDs are used pointing to the SC at 120° far from each other. The LEDs are switched on by the 12 V power panel of the EGTE, and controlled through a LabView program. Through the EGTE the Laser Autostart Adapter is activated, only after the insertion of the Laser key, a safety device, necessary to unlock the power up of the laser inside the EC (see Figure 4.1). The laser light causes a speckle pattern recorded by the LC sensor. The final output of this devise is a grey spectrum band representing the speckle patters. The LEDs light and laser light are chosen considering the features to analyse, the measurement equipment and its proper illumination and they are operated for the required time frame.

Finally, an overview camera is installed on top of the eBB with the aim to inspect foam homogeneity after production and to determine the average bubble diameter. It has optical access to the SC top window thanks to a series of optics mounted on two flanges and fixed to the MT. The camera is characterized with a high resolution, which makes possible to determine bubble size accurately, defined as the diameter of the cross sectional area of the bubbles in contact with the SC top window.

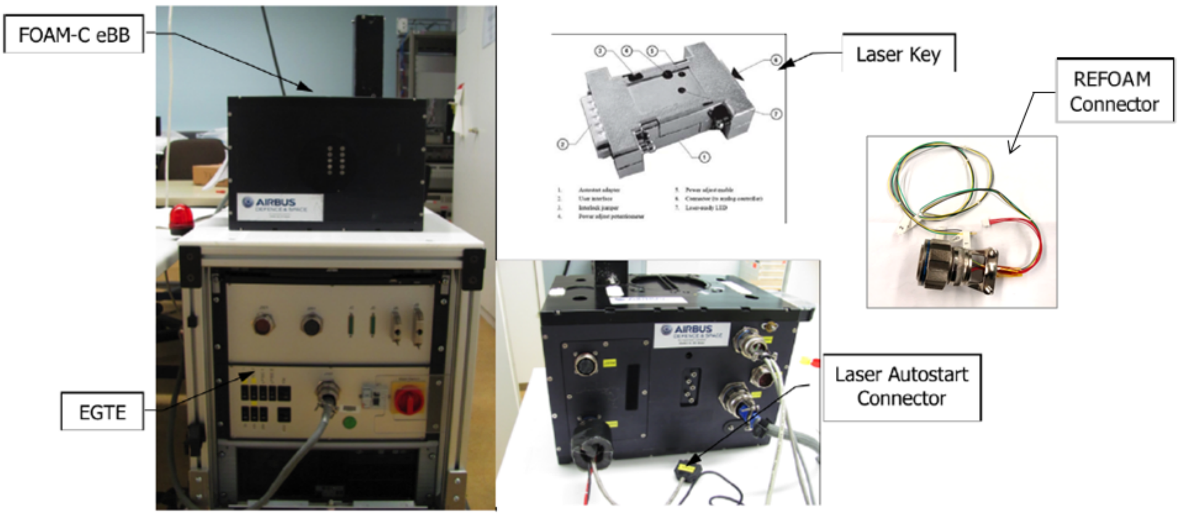


Figure 4.1: Elegant Bread Board Overview.

The eBB is connected to the EGTE and to the laser system via two 66-pins Amphenol circular connectors. The cameras are controlled via a dedicated laptop, equipped with the required software and connected via Ethernet cables and a 66-pins connector. The two cameras cannot be utilized at the same time due to interference problems. An additional connector is used to provide the interface with the actuation system and its microstepping Driver 101 PMD101. The driver is then connected to the laptop via USB direct interface.

4.2. FUNCTIONAL TESTS

A series of tests were performed in order to assess the reliability and functionality of the VTF. The first check concerned the EGTE, all the power sources were evaluated and the test was considered successful if the signals arrived to all the subsystems. Then, the eBB was tested in its mechanical and electronics components. The wires connections between the inner and outer connectors were evaluated, the MT was activated together with the STMO utilized to test the MT functionality, and the LabView was utilized to switch the LEDs on and regulate their intensity.

An assembled FOAM-C SCU was insert in the eBB in order to check the FGS, the cameras and the laser. The SCU was provided with four filled SCs, each of which had a piston inside to generate the foam (see Figure 4.2). Thanks to that SCU the FGS was tested and the foam generated and the speckle pattern were recorded respectively by the overview and by the LC.

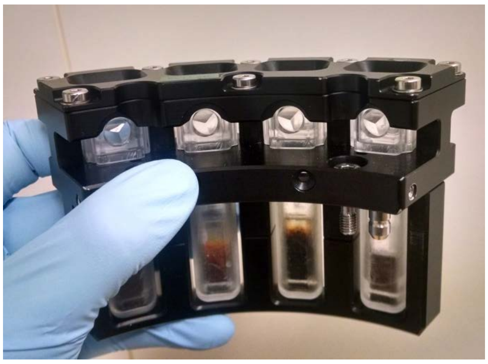


Figure 4.2: FOAM-C Sample Cell Unit Insert for the eBB.

In the Table 4.1, the analysed subsystems, the status of the test, and the results are presented. This evaluation was essential to ensure a successful integration of the REFOAM SCU in the VTF. The good functionality of the container reinforced the reliability of the system. Moreover, it guaranteed that unforeseen problems would have not arisen during the SCU integration tests due to a malfunctioning of the facility itself. However, a preliminary check of all the electrical interfaces was always carried out, together with a visual inspection of the wire connections and mechanical parts.

Table 4.1: Elegant Breadboard Status.

Subsystem:	**Status:**	**Result:**
Electrical Ground Test Equipment (EGTE)	Tested	Working
Moving Tray (MT)	Tested	Working
Foam Generation System (FGS)	Tested	Working
LED´s	Tested	Working
Overview Camera	Tested	Working
Line Camera (LC)	Tested	Working
Laser	Tested	Working

4.3. REFOAM INTERFACE WITH VERIFICATION TEST FACILITY

The REFOAM SCU can be integrated in the VTF in the insert slot 2 of the eBB MT. With respect to the FOAM-C, the REFOAM SCU is characterized by an embedded actuation system that is powered and controlled through the VTF itself. Five wires connections (four for the four legs and one for the Ground (GND)) to drive the motors and five wires of the encoder are directly rooted in the SCU thought the 15 pins connector Glenair (see Figure 4.3). Each wire has an individual connector to facilitate an eventual disassembly of these components inside the SCU. The Glenair male of the SCU is then plugged to one of the EC MT female connectors, depending on the position where the SCU will be located in the MT. The external connector for REFOAM is then plugged to the external sockets of the VTF. These ten wires are then plugged into the external micro stepping driver PMD101 (located outside the EC) which communicates with the laptop.

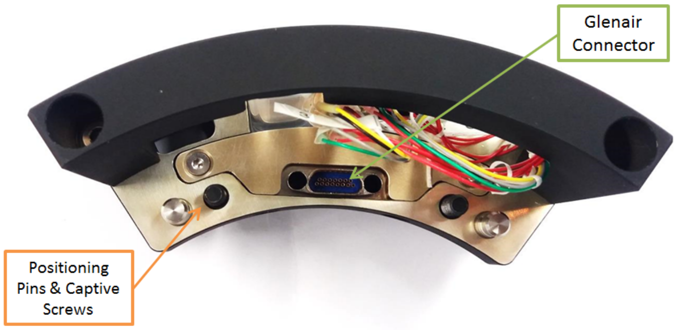


Figure 4.3: Sample Cell Unit Interface with Verification Test Facility.

In addition, the SCU is provided with mechanical interfaces (positioning pin and screws) fully compatible with those required by the eBB design (see Figure 4.3). An essential issue in the integration is the envelope volume. It defines the space occupied by the SCU subsystems, ensuring that everything fits in the VTF, and none of the components (fix or moving parts) collides with the available envelope. Finally, in Figure 4.4 the eBB with connectors and external systems is shown. It is the actual representation of the SCU integration and represents the set-up utilized during the functional and verification test campaigns.

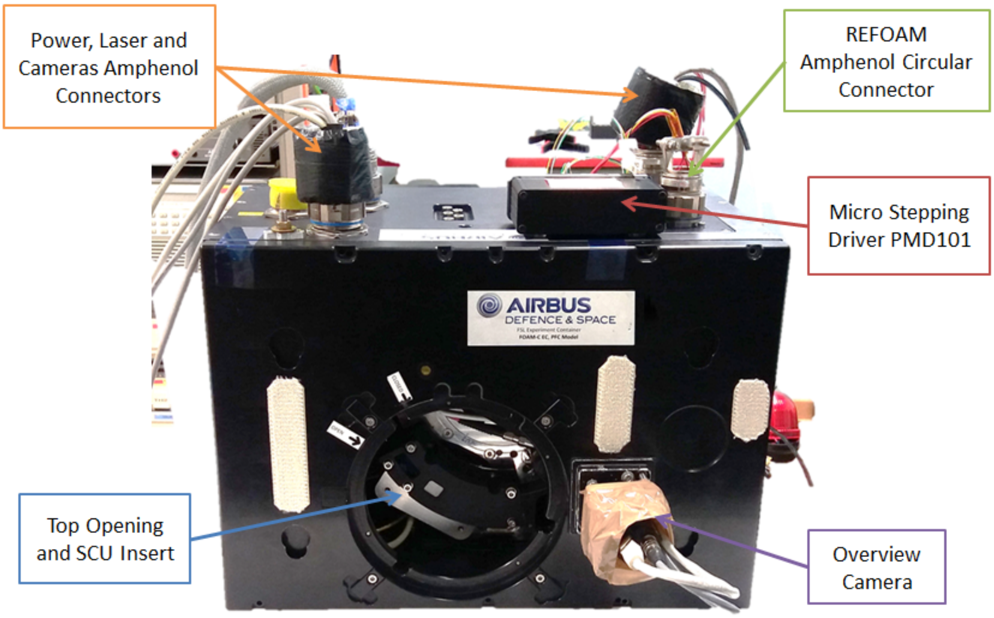


Figure 4.4: Verification Test Facility Subsystems Set-up.

5

Design Improvements

The REFOAM design concept was based on the reuse of the Soft Matter Dynamics EC and on the compatibility of the SCU with the VTF interfaces and diagnostic systems. To this end, a SCU design was proposed in order to carry out foam rheology experiments. The first design concept was described in Chapter 3, where the SCU and the SC systems with the related subsystems were illustrated. The whole system can be divided in the following subsystem:

- **Optical System.** The SCU optical system consists in a couple of mirrors positioned at a defined orientation to redirect the laser beam and to allow the detection of the speckle pattern.
- **Sample Cell.** The SC is the container of the liquid and gas solution utilized to generate the foam. It consists of a top cap, a bottom septa screw and a lateral sealing membrane.
- **Actuation System.** The actuation system is the key element of the rheology experiment. It provides the strain to be applied to the foam. It shall be able to work in open and closed loop with a specific repeatability and accuracy in the movements.

However, during the design analysis some unsolved issues arose. In the proposed concept, some of the design elements were not fully compliant with the requirements of the system, as proved by preliminary development tests (see Section 6.2). In particular, the main problems concerned the mirror holder of the optical system, the SC membrane and the proposed actuation system. In this chapter the design changes are described and justified, supported with trade-off analysis when more the two options were evaluated. In particular, in Section 5.1 the improvements made to the optics system are described; in Section 5.2 a new solution for the rheology membrane is provided. Finally, in Section 5.3 the changes in the actuation system are presented.

5.1. Sample Cell Units Optics Holders

The illumination and detection systems for the REFOAM experiment are based on the utilization of the laser source and LC provided by the VTF. To this end, the SCU needs two circular mirrors, with 7 mm diameter and 2 mm thickness, to redirect the beams. Their orientation was computed with the Catia tool software and it is was implemented in the CAD model considering flexible tubes, where the mirrors directly connected to the extremities, as a preliminary design solution (see Figure 5.1). This solution includes a metallic plate to be installed in the SCU, on top of which the tubes are fixed. This arrangement has the advantage of be modified during the assembly and the integration. Small changes in the mirrors angles can be made during the operation in order to optimize the detection and illumination performances. However, the manufacturing of this solution in the available budget and project time frame was not possible and alternative solutions were considered.

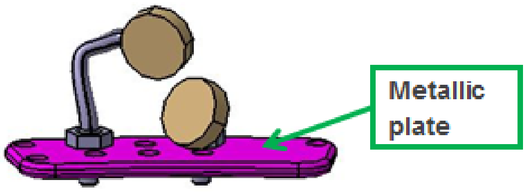


Figure 5.1: Mirrors CAD Model.

5.1.1. FIRST DESIGN SOLUTION: PUTTY MATERIAL HOLDER

The first concept involved the insertion of the two mirrors in a putty material support. This material is flexible at room temperature and it can be easily modelled to obtain the shape required. Once the modelling is completed, the part gets solid baking it in oven for 30 minutes at 110° C. The main advantages concern the low development and manufacturing costs and simple use of the material. On the other hand, shaping it to get right mirrors orientation was really hard considering the small dimensions of the system, and its attachment to the metallic plate was not enough reliable with respect to the system requirements. In the light of that, the solution was never developed, and consequently not tested during the assembly and integration.

5.1.2. 3D PRINTED SOLUTION

A second concept was the development of a 3D printer holder in PolyLactic Acid (PLA) material. The idea came up considering the small dimensions of the part, which implied short printing time. The holder was developed with the 3D printer "MakerBot Replicator x2" available at Airbus DS.

The first step was to design a new CAD model for the holder based on the calculation available. The holder was design to be installed on top the metallic plate via three screws in order to provide a good and reliable attachment and to avoid warping of the plastic support. Then, two rectangular structures with different heights were developed as mirrors holders. At the top of both of them, a planar surface with a circular profile was designed at the required orientation. The design requires that the mirrors are glued on the surface in contact with the circular profiles. The final CAD model is presented in Figure 5.2, while in Figure 5.3 is shown the 3D printed mock up with the mirrors installed on it.

The CAD model was converted into a STereo Lithography (STL) model and then sliced using MakerBot Print, the setting utilized are reported in the Table 5.1. The G-code obtained was loaded into the machine and the print started, with only one of the two available nozzles. The material was PLA with a diameter of 1.75 mm. The total printing time was about 40 minutes.

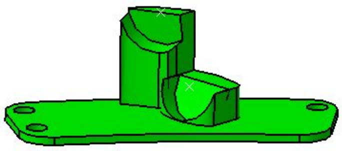


Figure 5.2: CAD Design for a 3D Printed Holder.

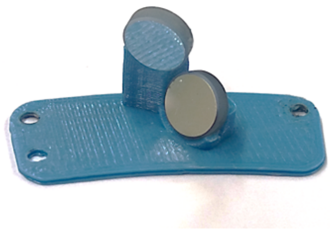


Figure 5.3: 3D Printed Holder.

Table 5.1: 3D Printer Settings.

Parameters:	**Values:**
Nozzle Diameter	0.4 mm
Layer Height	0.1 mm
Perimeter Shells	2
Infill	100% (grid pattern)
Extruder Temp	190° C
Heated Bed Temp	50° C

The great advantages of this concept were the rapid prototyping and developing. In addition, it was a cost zero design and it fitted perfectly in the project manufacturing time line. However, it can be used only in a demonstrator stage since the PLA melting point temperature is between 150° C and 160° C, consequently it is not compliant with the temperature range required by a FM design. The 3D printed holder was assembled and verified in the SCU. The results are discussed in the following chapters.

5.1.3. METALLIC SOLUTION

A third concept was the development of an aluminium holder, produced via Computer Numerical Control (CNC) manufacturing by the Mechanical department at Airbus DS. The idea is close to the optimal solution for a FM implementation, which requires a dedicated optical box with just one metallic block, where the mirrors are installed. The glued mirrors are the only difference from the FM design, which is not compliant with the space requirements.

The holder was manufactured from the CAD model presented in Figure 5.4. It is a modified version of the one developed for the 3D printed holder. It is designed as a unique part, without any external metallic support and it can be assembled as a stand-alone part in the SCU. It is provided with a single support for both the mirrors and the two surfaces are cut at the required angles. Two circular grooves are manufactured as profiles where to glue the mirrors. The final outcome is presented in Figure 5.5. For future improvements it is highly recommended to black paint the surface to avoid reflection problems.

The total cost of the part was about 600€ and it took approximately two weeks to be procured and manufactured (the CNC phase was in total 4 working hours). The advantages of this concept are related to the high manufacturing tolerances provided by the CNC machine and the quick and simple assembly. The holder was installed in the SCU and tested during the verification tests campaign to asses its compliance with the requirements.

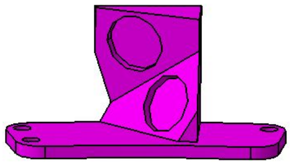


Figure 5.4: CAD Design for an Aluminium Holder.

Figure 5.5: Aluminium Holder.

5.1.4. SOLUTIONS TRADE-OFF

In order to select the better solution to implement in the SCU design a trade-off among the concepts described is carried out. The four possible holders are evaluated according to the following criteria:

- **Assembly Procedure.** The simplicity in the assembling reduces the possibility of mistakes and unexpected behaviours in the system performances.
- **Manufacturing Time.** The production and manufacturing time affects the schedule of the project. Delay in the development will increase the project costs and could provoke delay in fulfilling the deadlines.
- **Cost.** The manufacturing cost represents an important criteria considering the limited available budget in the demonstrator phase of the project.
- **Flight Model Implementation.** An applicable concept on the future FM will reduce the verification evaluations and development analysis of the next phases of the project.

Table 5.2: Holder Solutions Graphical Trade-Off.

Options\Criteria	Assembly Procedure	Manufacturing Time	Cost	Flight Model Implementation	Reliability
Flexible Tube	yellow Medium-High Difficulty	red Long	red High	green Applicable	yellow Medium
3D Printed Holder	green Low Difficulty	green Short	green Cheap	red Not Applicable	yellow Medium
Aluminium Holder	green Low Difficulty	yellow Medium	yellow Low-Medium	green Applicable	green High
Putty Material Holder	red High Difficulty	yellow Medium	green Cheap	red Not Applicable	red Low

green = Excellent yellow = Good red = Unacceptable

- **Reliability.** This criteria enhances the feasibility of the operations (redirecting and detecting the beams) among the concepts.

The graphical trade-off representation is provided in the Table 5.2. There, for each option the single criterion is evaluated and the colours are utilized to easily visualize the excellent compliance in green; the good compliance in yellow; and the non-compliance in red. The result of the graphic trade-off are based on the evaluation of the unacceptable parameters. The putty material holder and the flexible tube present more than one critical parameters, while the 3D printing option is not compliant with the FM implementation. Consequently, the aluminium holder is the optimal solution with respect to the criteria defined.

5.2. MULTI-LAYER MEMBRANE SOLUTION

One of the components of the REFOAM SC is the sealing rheology membrane. Its aim is to prevent the leakage of the liquid and gas composition of the SC, and ensuring the magnets coupling during the rheology experiment. In the first demonstrator design the membrane was implemented using a custom circular shape cut from a Nitrile Butadiene Rubbers (NBR) sheet. During the preliminary development tests, the design showed that it could not stand the maximum design pressure (4 bar) with the necessary safety factors (see Section 6.2). To this end, a new design was developed to deal with a potential future FM. The final solution was a multi-layer diaphragm developed together with an external company. In this analysis a trade-off evaluation was not performed, due to the confirmed unacceptability of the NBR membrane with respect to the required pressure.

The selected diaphragm is characterized by a manufactured of coated fabric, called Reciflex®. This solution has proven its reliability and high performance in many industrial applications. The main assets of the Reciflex® diaphragms are[EFFBE, 2016]:

- Sensitive operating due to lack of friction even in difficult conditions
- Great reliability thanks to the use of coated fabric especially conceived
- Economical conception for an operating without any maintenance
- Optimal lifetime

The Reciflex® multi-layer diaphragms are made of a fabric coated on both sides with elastomer. The material is fully compatible with the chemical solution utilized in the REFOAM experiment (TTAB and C4F14). The shaped diaphragms are formed under pressure and temperature, allowing better stroke in comparison with flat diaphragms [EFFBE, 2016]. The membrane shape designed for REFOAM is presented in the Figure 5.6 (grey colour) in its non-deformed configuration, while in Figure 5.7 it is shown its deformation during the strain application and magnets coupling scenario.

This design requires a customize rod cap, which is perfectly fitted in the membrane shape. The circular cap prevents to damage the diaphragm with the motor rod sharp edges. The estimated cost to produce such a membrane (including all manufacturing tools and processes) is about 16000€, with a total time of production of two weeks. At the moment, the membranes are under procurement. Once available, they will be assembled in the SC with the same procedure used for the NBR option (pressure ring and closing screw) and tested to qualify their performances.

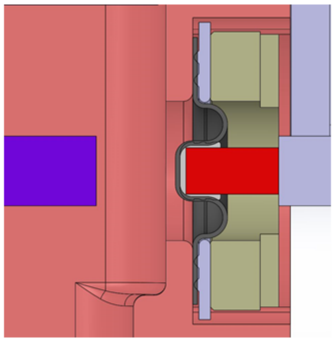


Figure 5.6: Diaphragm Assembly Proposal.

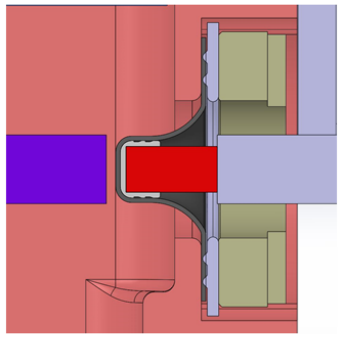


Figure 5.7: Diaphragm Assembly Proposal Under Deformation.

5.3. ACTUATION SYSTEM IMPROVEMENTS

The actuation system is designed to perform a 3 mm stroke for the rheology tests. The first actuation design concept includes a LL10 piezo actuator motor, an encoder foot attached to the motor rod edge and a RLC2IC encoder reader (further details are given in Section 3.3.5). This solution is theoretically able to provide the required stroke with the needed accuracy. The encoder allows the closed loop driving with a theoretical resolution of 0.25 μm. However, the main issue related to this solution is the complexity in the assembly procedure. The encoder foot needs to be perfectly aligned to the encoder reader in order to achieve the optimal performances, a condition difficult to get considering the small dimensions of the part: the encoder dimensions are 20 mm × 13 mm. During the development tests, it was proved that an incorrect assembly prevents the system to be compliant with the requirements of accuracy and repeatability in closed loop mode. To this end, a new concept was evaluated.

Table 5.3: Technical Specifications [PiezoMotor, 2016] [PiezoMotor, 2017].

Parameters:	**LL10**	**LL06**
Maximum Stroke [mm]	5.2 ($L = 26$ mm)	3.1 ($L = 30$ mm)
Speed Range [mm/s]	0-15	0-15
Step Length [μm]	4	4
Sensor Resolution [μm]	NA	1.25
Sensor Accuracy [μm]	NA	± 3
Sensor Repeatability [μm]	NA	1.2
Stall Force [N]	6.5	6.5
Maximum Voltage [V]	48	48
Power Consumption [mW/Hz]	5	5
Size [mm]	22 x 19.3 x 10.8	17 x 19.6 x 7
Weight [gr]	23	23
Operational Temp. [°C]	-20 to +70	-20 to +70

An embedded encoder system was the main requirement in the research of the new solution. Nowadays, the best option available on the market is the LL06 Piezo LEG motor. It is a compact linear motor with an integrated encoder with 1.25 μm position sensor for closed loop control. The LL06 delivers up to 6.5 N force and its friction drive ensures full-force, power-off locking [PiezoMotor, 2017]. The Piezo LEGS® technology is the same of the LL10, and it is ideal for any 'move-and hold' application able to benefit from high precision, instant response and low power consumption. In the Table 5.3 the technical specifications for the two motors are presented.

The LL06 has the same functional characteristics compared to the LL10, with the advantages of small dimensions, less weight and an embedded encoder system. The model selected for the REFOAM application is provided with a customized rod of 30 mm length, which ensures a maximum stroke of 3 mm in accordance with the experiment requirements. In addition, the theoretical accuracy and repeatability of the sensor are compliant with the requirements. In conclusion, this concept turns out to be the best achievable, as long as its simplicity in the assembly and its outstanding performances. The LL06 has been assembled in the SCU and a series of qualification tests have been carried out. The results obtained are discussed in Section 6.2.1.

6

ASSEMBLY, INTEGRATION & TESTING

Once the hardware components are delivered, checked and tested with respect to the design specifications (dimensions, tolerances, roughness, correct functioning of electrical components for e.g.), the Assembly, Integration and Testing (AIT) phase starts. The integration differs from the assembly process: the former is the process of physically and functionally combining component equipments, while the latter is the process of mechanically bringing together hardware components, large and small parts from many suppliers to build up the deliverable system [Fortescue et al., 2011].

The AIT follows a bottom-up strategy which enables testing of individual components during the whole process. This approach aims to identify, isolate, and recover possible faults. In fact, systems characterized by numerous components can easily fail if the subsystems are simply brought together. A fast identification of the source of this failure is impossible, considering the multitude of unknowns, uncertainties, and ill-functioning parts that define the system. A bottom-up approach is the key to cope with unforeseen problems, analysing and testing the single components before and after the mechanical assembly. Another issue is related to the difficulty in the integration management for all the possible configurations. When hundreds or thousands of engineers are working on a system, most are busy with changing implementations. Detailed procedures for integration reduce the management problem, and helps the cooperation among the teams involved in the project.

The AIT of the REFOAM SCU demonstrator was performed in the laboratory, workshop and clean room dedicated for FSL project. The SE strategy was applied in order to reduce risks and unforeseen failures in the subsystems functionality. The AIT phase was started from the mechanical assembly of the SCU main structure with a parallel assembly of the SC and its components; then the two parts were tested and integrated. At the same time the electronics involved in the actuation subsystem was separately tested in a dedicated bench and finally integrated into the SCU. The AIT was an iterative process: after the first iteration the test results were analysed and the different problems were identified. According to that, design improvements were made and a new iteration of the AIT process was carried out.

In this chapter the assembly, integration and relative tests for the REFOAM demonstrator are described. In particular, in Section 6.1 the AIT procedure is presented with the relative details and figures of the involved parts and subsystems. In Section 6.2 a series of tests performed during the AIT are presented with procedures, set-up and results. Finally, the SCU integration into the VTF is described in Section 6.3.

6.1. Sample Cell Unit Assembly, Integration and Testing Procedure

The REFOAM SCU was assembled following the experiment requirements, design specifications and the constrains imposed by the VTF. In order to have a successful assembled and working hardware an AIT was developed, taking in consideration all the processes involved in this phase. Figures 6.1 and 6.2 show an ideal way of the first iteration of the assembly and integration for the SCU. As REFOAM project is still on a feasibility study stage, it was not really needed to deeply develop a detailed AIT plan with allocation of resources. The figure presents two parallel ways of actions to perform in order to have the SCU assembled and ready to be integrated in the VTF.

In the procedure the following phases were identified: inspection, assembly, integration, test and check. The AIT process started with the inspection of the components, which were carefully controlled in dimensions, tolerances and operational status. Then, the assembly was related to the mechanical installation of the parts, while the integration dealt with the functional subsystems combination. The tests were established when the hardware subsystems correct functionality needed to be evaluated. Finally, continuous checks were carried out during the entire AIT process to keep track of the possible problems and critical issues.

First Iteration:
The assembly first iteration started from the upper part of the SCU main structure with the insertion of the pin, connector and interface screws. Then, the encoder was assembled through two screws. The actuation subsystem was integrated in two phases. The encoder was installed before the SC integration and successively the motor was positioned in the operational position. This choice was driven by the encoder small dimensions (20 mm × 13.5 mm) and the consequent difficulty in screwing it accurately. To this end, it was firstly installed, and only in the second part of the assembly it was positioned at the correct height and distance with respect to the encoder foot (glued to the extremity of the Piezo Motor rod). In fact, one of the critical issue of the SCU assembly was the adequate alienation of all the parts.
The SC was assembled in parallel with the SCU main frame. The correct magnet orientation was one of the critical issues to take into consideration, which might affect the performance of the foaming system and the experiment results. When the SC was assembled, it was integrated in the SCU upper part, together with the motor and the optics subsystem. Finally, the top cover and, after the filling, the lower part were screwed via five and two screws respectively.

Second Iteration:
The second iteration assembly process was similar to the first one, with exception of the actuation system. In fact, the Piezo LL10 was substituted by the Piezo LL06 with embedded encoder (see Section 5.3). Consequently, the actuation system assembly changed totally. The external encoder and the encoder foot were no longer necessary, a choice that simplified drastically the assembly procedure. The new motor was clamped via four pressure screws in the same way of the LL10. However, the issues concerning the magnet orientation and alignment of the rod and piston magnets remained the same. The entire procedure is presented in Appendix C.

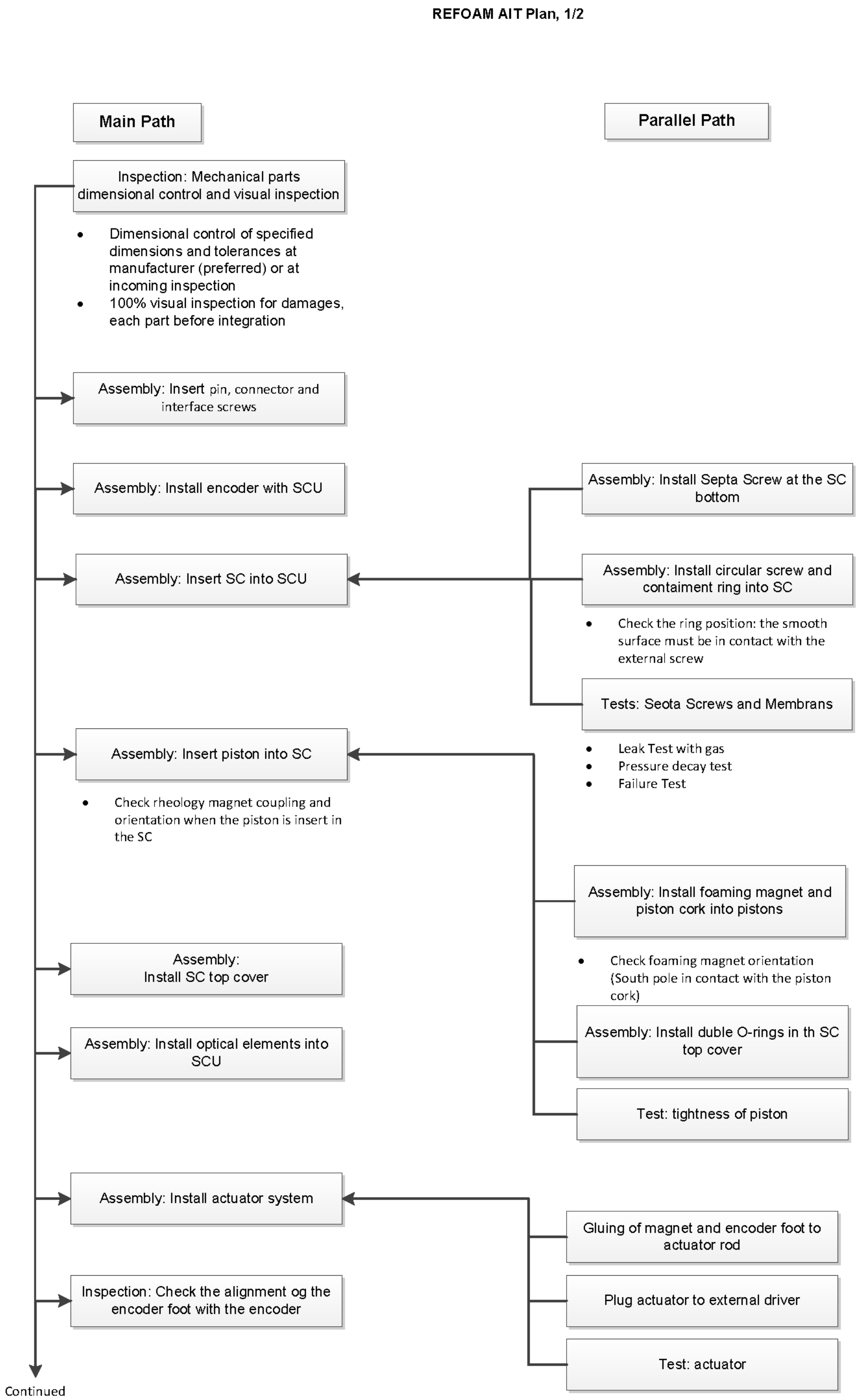


Figure 6.1: REFOAM AIT Procedure 1/2.

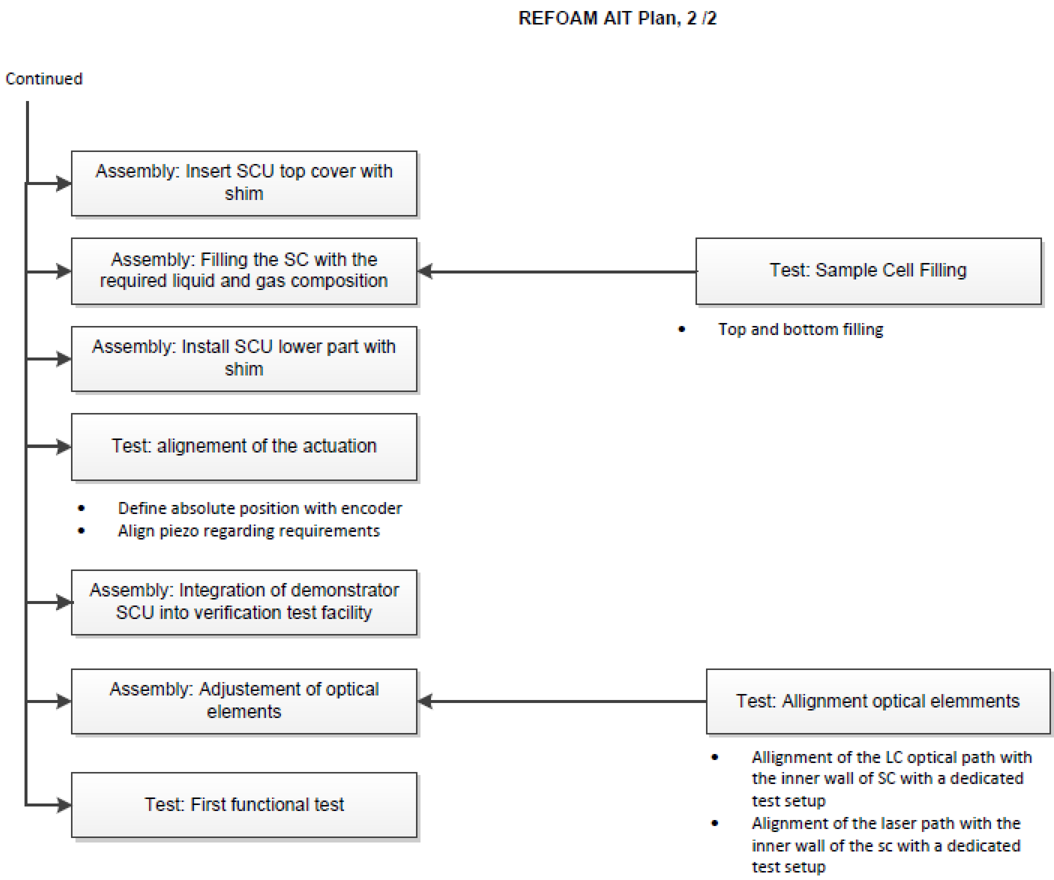


Figure 6.2: REFOAM AIT Procedure 2/2.

In the next sections a detailed description of the subsystems assembly is provided and documented with images of the followed steps. It is concluded with the problems identified during the first iteration process, which represents the crucial aspect to be improved in the development of an EM and FM hardware.

6.1.1. MIRRORS ASSEMBLY

The mirrors assembly was composed by two flat mirrors, whose aim is to redirect the laser rays, to the end that they cross the observation window in the centre of the SC inner wall. The mirrors had a simple cylindrical shape: diameter 7 mm and thickness 2 mm and a silver coating and were directly glued to the two holders available (see Section 5.1).
The assembly procedure changes with respect to the support utilized:

- **Aluminium Holder.** The Aluminium holder was characterized by a single support where the mirrors were glued into circular grooves. It was manufactured taking into consideration the mirrors height and orientation as shown in Figure 6.3. It was simply installed in the SCU optics location and fixed with 3 screws.

Figure 6.3: Assembly Aluminium Holder.

- **3D Printed Holder.** The 3D Printed Holder was manufactured as an additional support to be mounted on top the mirror plate in the SCU. Also in this configuration the mirrors were glued in the operational positions and the plastic support was then fixed on top of the aluminium plate (see Figures 6.4 and 6.5) and together put in the SCU optics location and fixed with three screws.

Figure 6.4: 3D Printed Holder and Mirror Plate.

Figure 6.5: 3D Printed Holder Assembly.

6.1.2. SAMPLE CELL ASSEMBLY

The SC assembly was manufactured by companies with rapid prototyping methods. The main advantages of choosing this method were the flexibility of design offered by additive manufacturing technology and the impressive leading time to get the manufactured parts (10 calendar days from order to delivery). The SC assembly (containing SC body, top cover, piston and membrane attachment) were manufactured in CNC machining and in PC material. The machined parts were fully transparent (see due to material itself and also to the vapour polishing process made after the machining). Another set of SCs was made in vacuum casting technology (Figure 6.6). The master parts (for creating the silicone mould) were directly printed in stereolithography material. The functional surfaces, which were used as optical window characterized by perfect roughness and transparency, were re-machined and surface treated after the vacuum casting process.

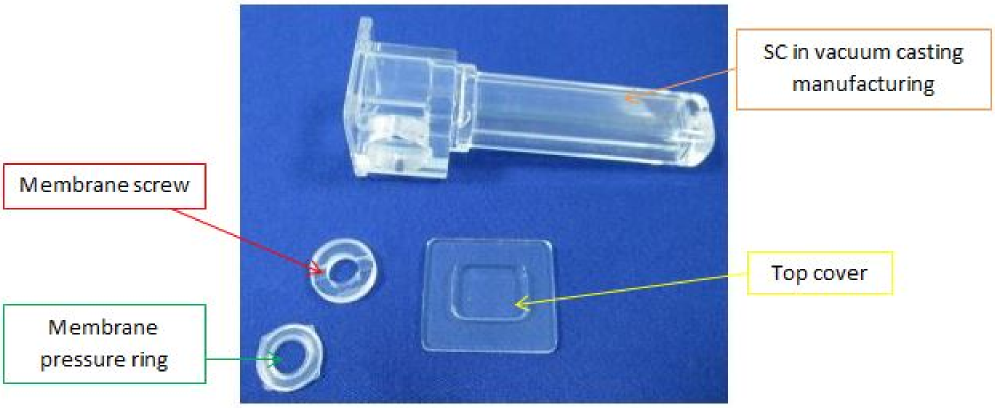


Figure 6.6: Sample Cell Assembly Components.

The SC was assembled from the bottom, the septa screw was installed with two septa membranes that ensured the two levels of containment required from the design specifications. The septa needed a specific screw driver to be assembled correctly. Then, the membrane was set-up. At this design level the membranes were manufactured cutting a thin sheet of NBR plastic at the required diameter. It was assembled fixing its position with the customized pressure ring, and blocked with the external customized membrane screw. The SC assembly was completed mounting the two O-rings at the top surface inside dedicated grooves. The complete SC is presented in Figure 6.7.

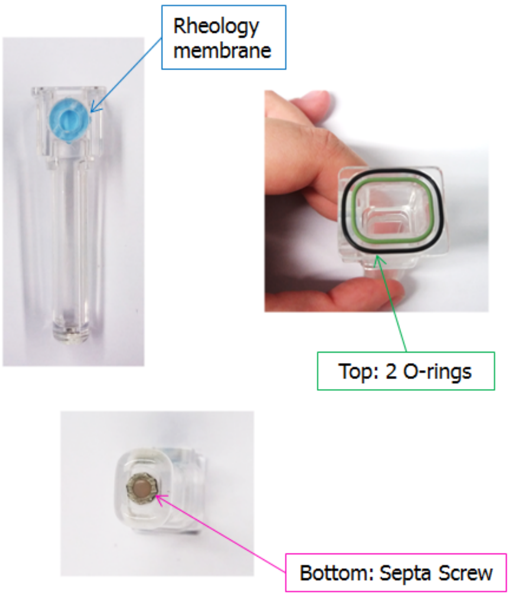


Figure 6.7: Sample Cell Assembly.

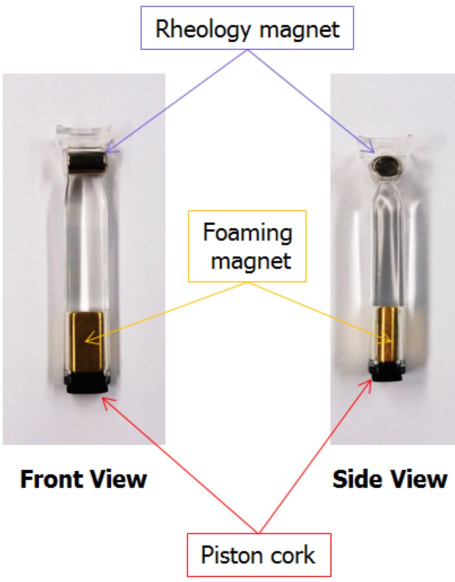


Figure 6.8: Piston Assembly.

In parallel, the piston was assembled. It was manufactured in polycarbonate transparent material with the rheology magnet already installed in its upper part. Therefore, the piston assembly involved only the foaming magnet and the insertion of the piston cork. The correct orientation of the foaming magnet poles was one of the critical issue. The magnet South pole has to be positioned in contact with piston cork, in order to guarantee that the piston stands in the coupling position, at the end of the foam generation phase (see Section 3.4.3). Once the magnet was inserted, the piston cork was fitted at the piston bottom. The final piston assembly is shown in Figure 6.8.

Finally, the piston was put into the SC. It was positioned taking in consideration the rheology magnet orientation. When the piston was installed the coupling between the rheology magnet and the actuation magnet at the tip of the motor rod was checked. An incorrect orientation could provoke the experiment failure. However, the assembly was not completed until all the other subsystems were installed. Only at that moment, the SC top cover could be positioned on top of the SC managing the O-rings and fixed, screwing the SCU top cover.

6.1.3. ACTUATION SYSTEM ASSEMBLY AND INTEGRATION

In the AIT phase two different actuation systems were evaluated and integrated in the SCU: a Piezo Motor LL10 and a Piezo Motor LL06. In this section both the solutions are presented with the relative advantages and drawbacks. During the assembly the systems were also tested in a dedicated test bench at the UPMC in Paris. The tests set-up, procedures and results are discussed in the following sections.

Piezo Motor LL10 Actuation System:

The Piezo Motor LL10 actuation subsystem is essentially composed by two parts: a Piezo Motor and an encoder. The assembly started from the installation of the encoder screwed in the SCU upper structure, then the motor was installed. However, before clamping the motor in the SCU the rheology external magnet (magnet rod) and the encoder foot need to be glued on the motor rod as it is shown in Figure 6.9.

Two main requirements had to be fulfilled in the motor installation: first the motor rod and magnet had to be perfectly aligned with the SC membrane window and the coupling between the external and piston magnet had to be checked. Then, he encoder foot had to be parallel aligned to the encoder at a distance of $0.1-0.8\,\mathrm{mm}$, according to the data sheet [RLS Product, 2016]. To this end, the first installation was the motor clamping in accordance with the magnet coupling. Once it was fixed in its operational position the encoder was correctly positioned at the required distance from the encoder foot (it was achieved using a A4 paper with a $80\,\mathrm{gr/m^2}$ grammage).

Piezo Motor LL06 Actuation System:

The Piezo Motor LL06 is an unique part, which includes the motor system, the optical encoder and the index magnetic band. The assembly started with the gluing of the rheology magnet on the motor rod. In this phase, it was important to check the orientation of the motor. It was integrated with the wires plugs in the opposite side with respect to the SC, and the open part (see Figure 6.10) in contact with the SCU back wall.

The motor was fixed in the SCU via four pressure screws. A thin PC layer was glued on both the motor sides to avoid possible damages due to the clamping. Then, the coupling with the inner piston rheology magnet had to be checked to achieve the correct operation.

Finally, both the actuation systems were in communication with the VTF through a Glenair (MRM16311-15) 15 pins connector. Once the parts were correctly installed in SCU the cables could be connected in accordance with the input-output defined in the system scheme for the electrical interfaces (see Section 4.3).

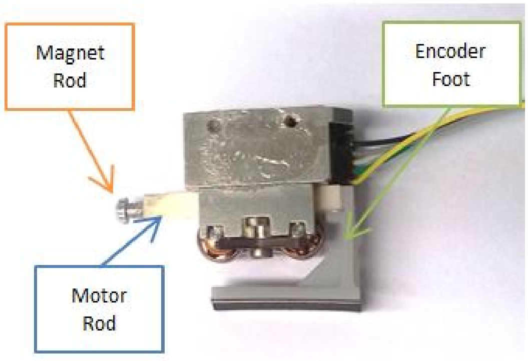


Figure 6.9: Piezo Motor LL10 Assembly.

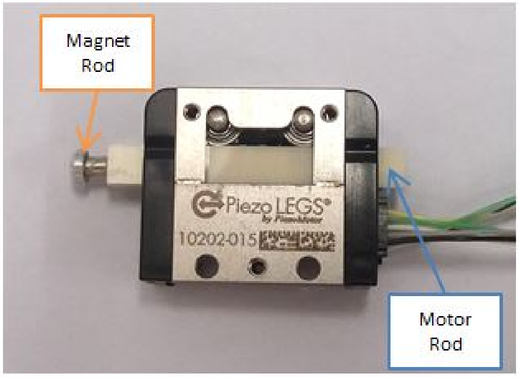


Figure 6.10: Piezo Motor LL06 Assembly.

6.1.4. SAMPLE CELL UNIT ASSEMBLY

When all the subsystems were correctly assembled in the SCU upper structure, it was possible to install the SCU top cover with the upper Shim, which compensates the assembly tolerance between the SC and the SCU top. In this configuration, Figure 6.11, it was possible to fill the SC from the bottom through the septa membranes. Then, the lower part of the SCU was installed. At that point, the hardware was considered ready to be operated and integrated in the VTF.

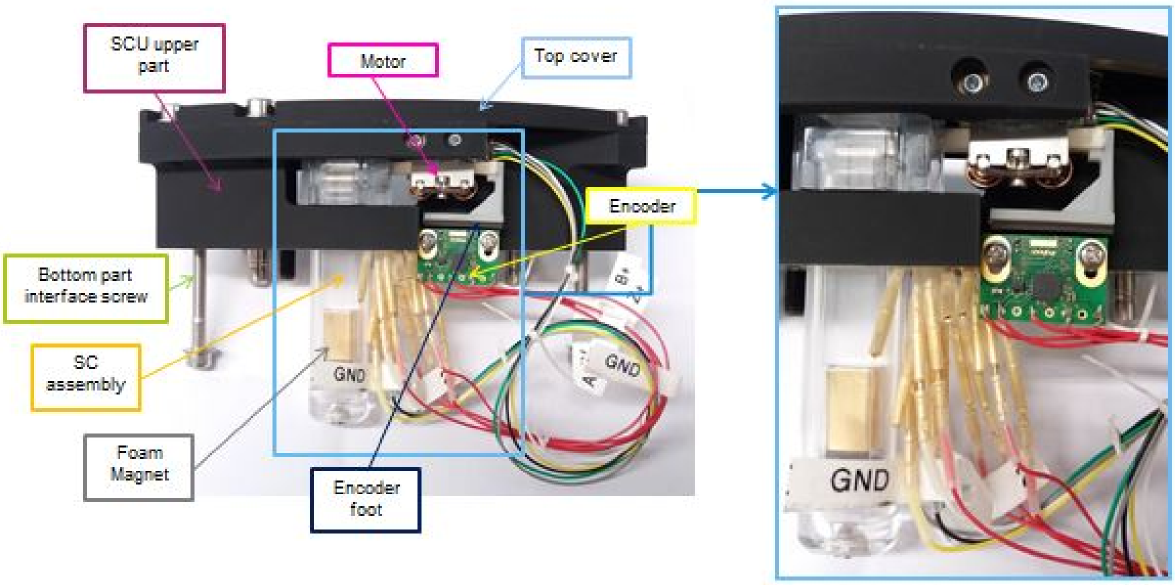


Figure 6.11: Sample Cell Unit Assembly Components.

In Figure 6.11 an overview of the different parts is presented and labelled, and a zoomed-in view prospective of the integrated Piezo Motor LL10 actuation subsystem is given. It is easy to see how the encoder is installed and the small dimensions of the parts involved.

The complete assembled SCUs are displayed in Figures 6.12 and 6.13, respectively for the Piezo Motor LL10 and Piezo Motor LL06 actuation systems.

Figure 6.12: Sample Cell Unit Assembly with LL10.

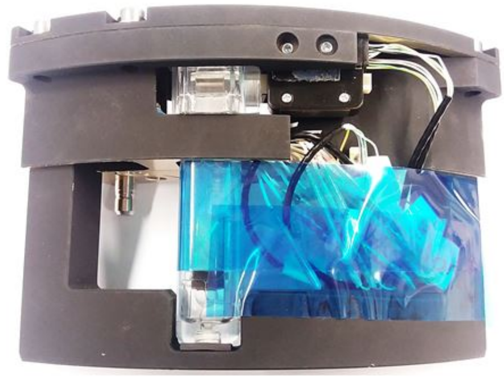


Figure 6.13: Sample Cell Unit Assembly with LL06.

6.1.5. IDENTIFIED PROBLEMS

During the AIT some design problems were noticed. An early identification of critical aspects helped to obtain successful results without compromise the project schedule. In particular, three main issues needed to be highlighted in order to be improved in the next steps of the project.

1. **Sample Cell Septa Screw.** In the assembly of the polycarbonate SC a problem occurred in the installation of the septa screw. The thread hole was not accurately manufactured, and it made impossible to screw the septa and achieve the required sealing. However, the vacuum casting SC presented a good thread and the septa was correctly installed in it.

2. **Motor Clamping.** The motor was installed in the SCU with four pressure screws, which were able to fix the motor in the operational position for long working time. However, the clamping required affected the SCU provoking a permanent deformation of the upper part. Since the SCU dimensions were strictly defined by the VTF design a permanent deformation might prevent it to fit into the VTF experiment location. To this end, an improvement in the SCU design or a different clamping methods needs to be investigate to prevent future failures.

3. **Actuation Alignment.** The actuation assembly was the most critical assembly phase. In particular, the correct alignment of the encoder and its foot required time and patience. Even a small deviation from the operational position might affect the experiment results. The encoder misalignment might affect the closed-loop actuation performances. This problems was overcome in a design solution that involves the Piezo Motor LL06 actuation system. The motor with the embedded optical encoder improved the hardware performances and reduced the assembly critical aspects.

6.2. TESTING PHASE

The AIT allows to identify erroneously specified or incomplete interface definitions. In particular, the testing phase has the main aim to define if a system or a part works as expected and to verify its behaviour [ECSS, 2002]. Different tests are definable, as the development tests in the early project phase, qualification tests and acceptance tests in the late development phase. In particular, development tests validate new design concepts or the application of proven concepts and techniques to a new configuration.

However, the procedural, control, and documentation effort for development tests is usually moderate since development testing still depends on the design level. The test can be considered successful if the result fits the specified behaviour and performance, otherwise it fails. The mindset of testing in this phase is completely different from that in Verification and Validation phase. During AIT, the attention is focused on the identification of system unknown problems. On the other hand, testing during verification and validation emphasizes the system performance with respect to predefined requirements. In this section the testing activities developed during the AIT phase are analysed.

6.2.1. ACTUATION MECHANISM TEST

During the development, different concepts regarding the choice of the actuation and its implementation into the system were evaluated. The main concerns were about the overall repeatability of the mechanism and the alignment of the stack of components from the rod end tip to the rheology plate: magnet D2L4, membrane and piston cylindrical neck. A simple test bench for the LL10 Piezo Motor was designed and built (Figure 6.14) in CNC manufacturing via a three axis machine of the workshop of Airbus DS. The tests were conducted at the UPMC optical lab (in Paris) from Pr. Höhler with his specific equipment and set-up adequate for measuring precise displacement and rheology of wet foams. The tests was developed during the first assembly iteration phase. The test configuration and set-up is presented in Figures 6.15 and 6.16.

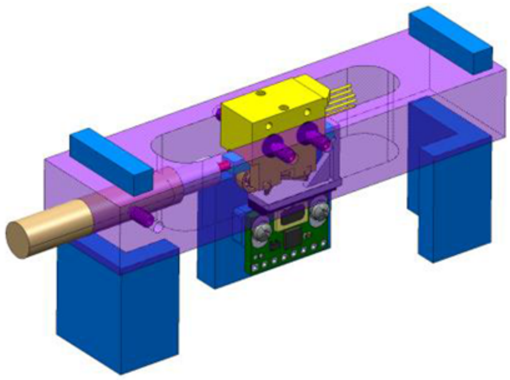


Figure 6.14: CAD Designed Test Bench.

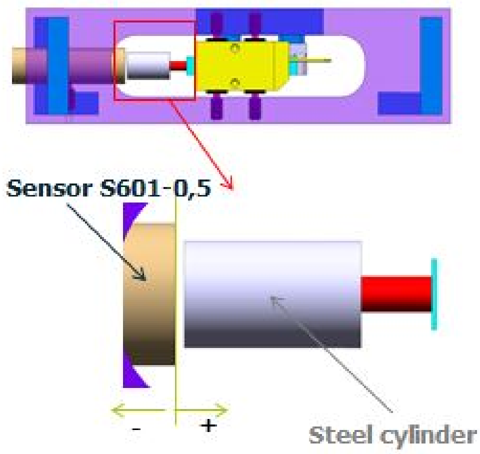


Figure 6.15: CAD Top View with Sensor and Target.

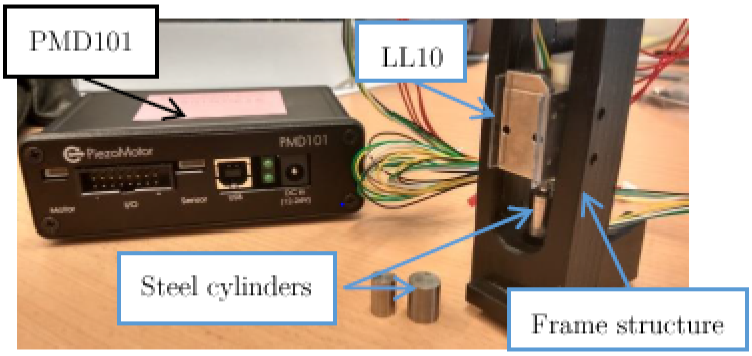


Figure 6.16: Test Set Up with PMD101 and Cylinders.

In Figure 6.14, the LL10 actuator with the encoder foot and the D2L4 magnet glued on each end tips of the actuator rod were clamped into the test plate with the four pressure screws M3 and the protection disks. The encoder was screwed below to the plate and its position is adjusted with washers and two M2 screws so that it fitted the installation tolerances of the encoder data sheet for an optimal measurements [RLS Product, 2016].

During the second iteration, the tests were repeated for the LL06 actuator. In this case, the test was carried out directly on the optical test bench fixing the motor horizontally with an aluminium target, which was coupled to the magnet rod at about 1 mm from the sensor as shown in Figure 6.17. The tests were performed with a grounded and un-grounded target.

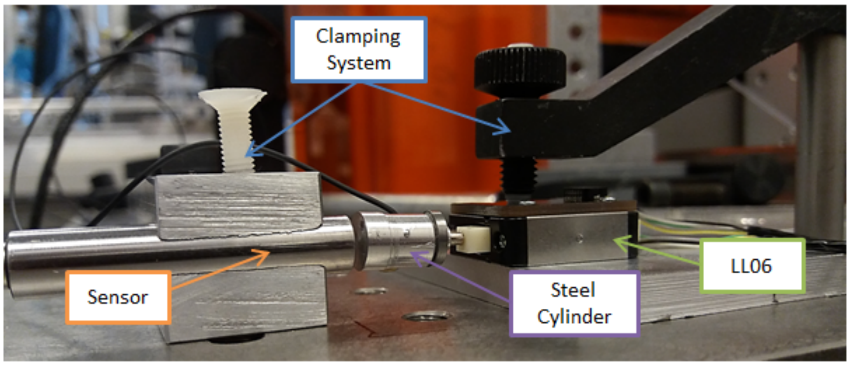


Figure 6.17: LL06 Test Set-up.

In the alignment of the piezo rod a Non-Contact capacitive displacement measurement sensor (brown colour) was used. It is capable of a 0.25 μm resolution on a 0.500 mm measuring range. The sensor works only with electrical conductors as targets (Figure 6.19). The measuring principle of the system is based on the ideal parallel plate capacitor and the high linearity by evaluating the reactance (X_c) of the capacitor which changes directly and only in proportion to the distance [Micro-Epsilon, 2016]. The two plate electrodes are composed by the opposite target and the sensor. If an Alternating Current (AC) current with constant frequency flows through the sensor capacitor, the amplitude of the AC voltage on the sensor is proportional to the distance between the capacitor electrodes (see Figure 6.18); an adjustable compensating voltage is simultaneously generated in the amplifier electronics [Micro-Epsilon, 2016]. After demodulation of both AC voltages, the difference is amplified and an analog signal is the output [Micro-Epsilon, 2016]. The reactance is linked to the distance with the following formulas:

$$X_c = \frac{1}{j\omega C} \tag{6.1}$$

with,

$$C = \epsilon_r \cdot \epsilon_0 \cdot \frac{area}{distance} \tag{6.2}$$

that gives:

$$X_c = \frac{1}{j\omega \cdot \epsilon_r \cdot \epsilon_0 \cdot area} \cdot distance \tag{6.3}$$

finally,

$$X_c = Constant \cdot distance \tag{6.4}$$

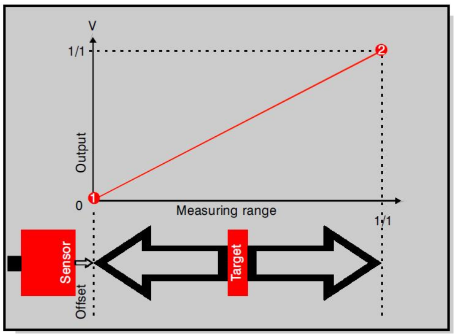


Figure 6.18: Output Voltage Versus Range [Micro-Epsilon, 2016].

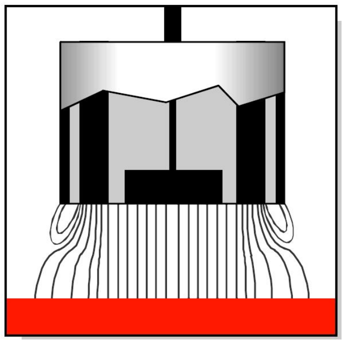


Figure 6.19: Sensor Electrical Principle [Micro-Epsilon, 2016].

The output voltage range is located between 0 to 10V. The linear function between the voltage is represented in Figure 6.18, for which the gradient is close to 50μm/V. As the target for the sensor needs to be metallic, three steel cylinders of diameter 6, 7 and 8mm and length 10mm were manufactured to simulate the piston cylindrical neck (made of PC). The piston neck originally had a diameter pf 6mm, but the sensor could only measure the distance against a minimum diameter of 7mm. The choice of a steel material was also made to let the magnet hold the cylinder in the alignment. The test set-up was designed in a way that it could be tested by laying it along the three axes and to avoid the effect of gravity on the measurement values.

Test procedure.

1. Verify and document test article configuration
2. Set up the test configuration assembling the encoder and the motor in the test frame structure in horizontal position
3. Connect the PMD101 microstepping driver to the REFOAM Ground Test Equipment (GTE) laptop, to the RLC2IC encoder, and LL10 motor or to the LL06 motor and sensor

4. Set-up the test configuration by running manually and carefully the steel cylinder against the sensor's tip end.
5. Verify the alignment of all the parts
6. Set-up the test initial procedure on parameters (StepsPerCount (SPC) and WaveForM (WFM) step-length calculations) by the "PiezoMotor Motion System 2.0.2" software
7. Set-up the initial test position "zero position" and reset encoder position
8. Set-up the test sequence in a closed loop
9. Perform the first test sequence of 100 μm forward and reverse x times (in closed loop mode)
10. Document the test results in the test data sheet
11. Restore the encoder to the initial position
12. Perform a second test positioning the encoder to 2000 and to 10 μm (limit position) in closed loop mode
13. Document the test results in the data sheet
14. Restore the encoder to the initial position
15. Perform a third test in open loop mode to study microsteps performances
16. Document the test results in the data sheet
17. Restore the encoder to the initial position
18. Disassembly all the parts
19. Repeat from step 2 to 17
20. Set-up the test configuration assembling the encoder and the motor in the test frame structure in vertical position
21. Repeat from step 3 to 19
22. Set-up the test configuration assembling the encoder and the motor in the test frame structure in lateral position
23. Repeat from step 3 to 19
24. Set-up the test configuration assembling the encoder and the motor in the test frame structure in vertical position
25. Set-up a PC window sheet of a thickness of 0.75mm in front of the cylinder
26. Set-up the camera alignment
27. Place a small sample (drop) of ready-made-reference foam (~ Gillette Foam) on the PC sheet
28. Perform a compression strain (uniaxial deformation) on the foam sample
29. Record the bubble distribution of foam with the camera (camera performances: 8 mm FoV and a minimum focal length of 20 mm)
30. Perform an extension of the foam sample
31. Record the bubble positions with the camera

Remarks: Tests can be repeated following the same steps provided above changing the velocity and other parameters of driving electronics loop through the software interface. The same procedure was followed to check the performance of both the actuators systems: LL10 and LL06. The procedure from the 27^{th} step to the 31^{th} was not performed with the LL06 system.

LL10 Actuation System: Test results and discussion.
The first driving tests were conducted in closed loop mode. The LL10 actuators was moved to 100 μm in both directions and 2000 μm in forward direction. These showed that the installation of the encoder regarding the magnetic tape of the encoder foot was crucial for

the repeatability of the mechanism. The instruction guidelines of the manufacturer for the encoder RLC2IC suggests a parallelism between encoder upper corner and magnetic tape with max 2° error along the three axes (roll, pitch, yaw angles) [RLS Product, 2016]. The distance between the upper part of the sensor and the magnetic tape should be between 0.1 to 0.8mm, to guarantee the correct thickness and alignment. During the screwing of the encoder, the position might change due to the rotation of the washers; this has to be done really carefully by the operator to prevent any misalignment.

The closed loop mode showed that even if the encoder resolution was relatively fine (= 0.2441 μm) the absolute error of the system was around 5 μm when it was moved to the target and 1 μm, when it came back to the zero position. These results were dependent from a hysteresis of the magnetic encoder that prevented accurate repetitions of the same stroke: a critical requirement for the intended science. The results were consistent with this phenomenon, in fact the hysteresis provoked a maximum inaccuracy of 5 μm, the same values measured during the tests and it was confirmed by the encoder supplier and their technical support staff.

The second series of tests in open loop driving of the LL10 actuators, which means without re-using the encoder readout for the command, gave better results. The microsteps were tested for different WFM typical step length: 4.5–5.5 μm and several velocities: 50 or 500 wfm/s. The theoretical value of a single microstep-length, with a 2048 resolution given by the PMD101 and a waveform Delta (M3) [PiezoMotor, 2016], should be around 0.0025 μm = 2.5 nm. The calculated ones via the measurement of the external sensor were really close to the theory: only 1 nm delta. Figure 6.20 illustrates the smoothness of displacement of the rod for a small series of 1000 microsteps at 500 wfm/s with 5.2 μm WFM-typical-step-length.

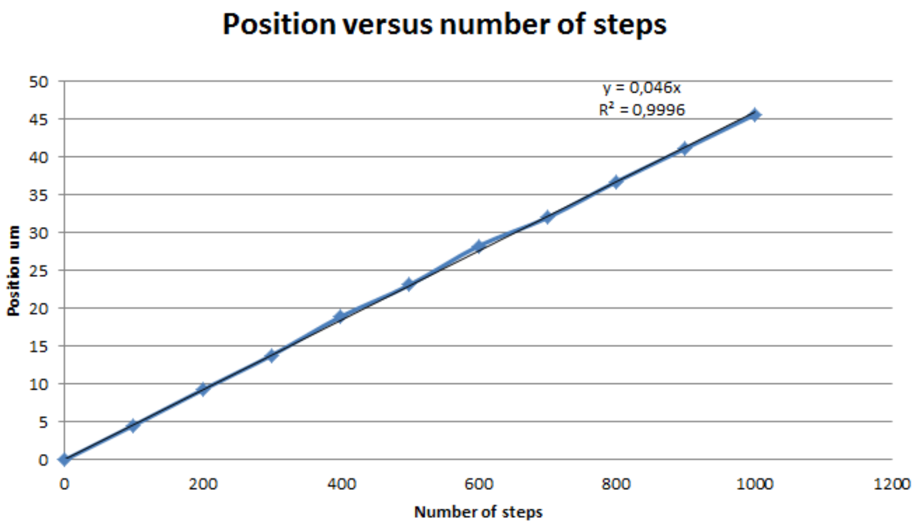


Figure 6.20: LL10 Open Loop Driving, Microsteps Performances Plot.

These results and the use of a 2048 microsteps per WFM-step and a Delta wave form represent the most favourable solution for an optimal actuation to conduct future rheology experiments. During the second test with a drop of ready-made-foam from TTAB and C6F14 gas, compression and extension of the foam were studied. Figure 6.21 shows the experiment set-up, while in the Figure 6.22 the tip end of cylinder immersed in the white foam is presented(same appearance and texture as a shaving foam). The deformation stroke and velocity were studied to figure out the impact of these parameters on the displacement of the foam bubbles. The main output from this test was that the bubble displacements (due to compression or extension via the steel cylinder) were concentric. This means that the alignment of the actuation elements (stack) was extremely robust and reliable to conduct rheology experiment according to Professor Höhler´s claims.

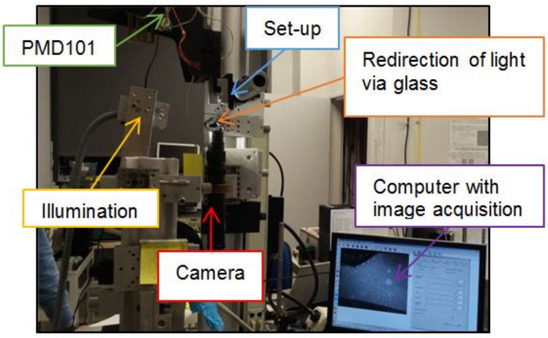


Figure 6.21: Rheology Experiment with UPMC's Lab Set-up.

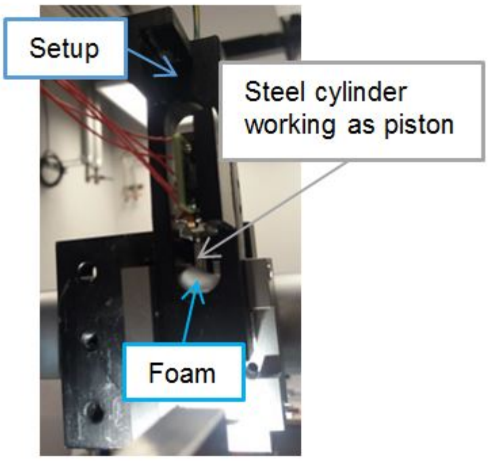


Figure 6.22: Foam Experiment.

LL06 Actuation System: Test results and discussion.
In a second test campaign the actuation tests were repeated with the LL06 actuation system with the integrate encoder with a resolution of 1.25 μm

The first test of the LL06 actuation system was performed in closed loop, with a cycle of displacements. It started from the absolute encoder zero position (found out with the index mode in the Piezo Motor Software) and moved forward to 100 μm back to 0 μm. Then, it was moved backward to $-100\,\mu$m to 0 μm. The entire cycle was repeated several times to observe the repeatability of the actuation system. The analysis of the results showed that the new system had a positioning error of less than 3 μm in the full range of stroke. While the repeatability of the strain cycle was of 1 μm, both better than the required performance. A second closed loop test was performed with the same set-up as with a cycle of displacements of 10 μm at two different speeds (500 wfm/s corresponding to 2.4375 mm/s and 1000 wave frame/s corresponding to 4.875 mm/s). The test was carried out starting from the absolute encoder zero position. The target was moved to 10 μm and back to 0 μm several times. Also in this configuration, the results provided an error of 1 μm between the sensor potion and the given command. In addition, the standard deviation σ was computed on seven displacements cycles on the absolute zero position. The obtained value equal to 0.38 μm is in accordance with the actuation system requirements.

Then, an open loop test was performed with the same test set-up. The test started from the zero absolute position and a single microstep command was sent to the motor. The test was repeated with 100 micro-step size. The command to move forward was sent eleven times and a single backward command of 1000 micro-step size was given. The error measured was less than 1 nm delta, a result that confirmed the performances of the system in accordance with the values obtained in the LL10 test campaign. The Figure 6.20 illustrates the displacement of the LL06 rod for a small series of 1000 microsteps at 500 wfm/s with 5,2 μm WFM-typical-step-length already computed with the LL10 (see Figure 6.20).

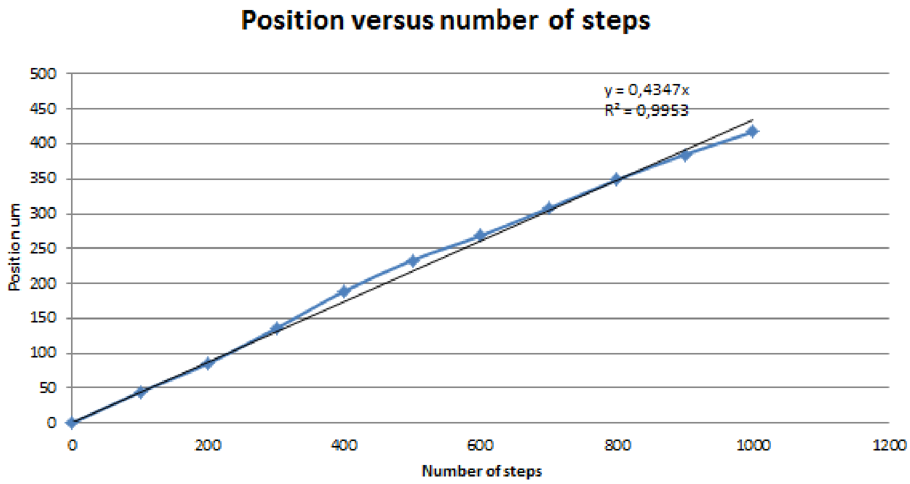


Figure 6.23: LL06 Open Loop Driving, Microsteps Performances Plot.

A final test was carried out recording the trend with a digital scope. In this way the step rise time from a command to another was evaluated. The observed rise time was about 0.1 s, in a test in closed loop with a cycle of displacements of 10 μm with a cylindrical steel target with a mass of about 6 gr. This target was utilized to reproduce the experiment operational mass pushed in the SCU (i.e. the assembled piston mass). The obtained results defined less than 1 μm delta in the encoder position.

6.2.2. SAMPLE CELL LEAKAGE AND PRESSURE DECAY TESTS

A critical aspect in the development of the SC was the evaluation of its leakage. This issue was critical due to two main reasons. First of all, the utilization in space requires to fulfil the safety regulations concerning the dispersion of liquid/gas particles on-board the ISS. At the same time, the scientific requirements, defined for the foam rheology experiment, have to be respected and a constant liquid concentration in the SC must be provided.

In light of the REFOAM design, the rheology membrane and the bottom septa screw were the two critical apertures that need to be tested. To this end, a leakage and a pressure decay test of the REFOAM SC were conducted in the Airbus DS controlled laboratory environment. In this section, the set-up, procedures, and the analysis of the results are discussed.

Sample Cell Leakage Test.

The SC leakage test consisted in the evaluation of the membrane and septa screw apertures. It was carried out with the utilization of a vacuum pump and helium detector. The aim of the test was to evaluate the quantity of helium particles that could penetrate inside the SC, once the vacuum was performed, and the consequent pressure decay. The test was considered successful if the measured pressure decay was in the order of $1 \cdot 10^{-5}$ mbar/s.

The REFOAM SC was insert in the SCU and an adapter was mounted on the test samples. It was compressed by the SCU top cover and assembled with the O-rings, awith the same procedure used for the REFOAM top window and body. Then, the SCU was connected to a flange fitting going outside of the vacuum device. The final test set-up is shown in Figure 6.24.

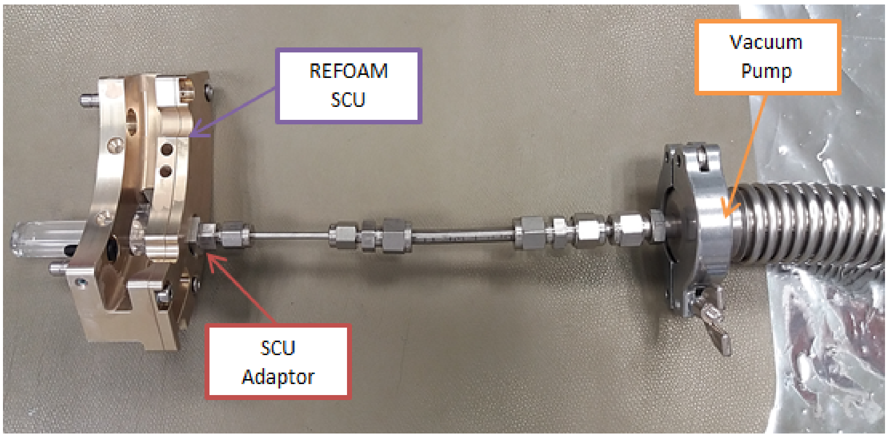


Figure 6.24: Sample Cell Leakage Test Set-up.

Once the SC was connected to the vacuum device, a plastic bag was used to isolate the SCU from the outer environment and not to disperse the helium particles in the laboratory. After the calibration of the device, the helium was sprayed close to the membrane and the septa. The test procedure is presented hereafter, followed by the test results.

Test Procedure:

1. Calibrate the vacuum pump and detector
2. Connect the SCU to the vacuum pump and detector tool
3. Perform vacuum in SC
4. Put SC in a bag to isolate it from the outside environment
5. Spry the Helium particles around the SC apertures
6. Measure the leakage
7. Record the results

Results and Analysis.

The results were quite good. The test was considered successful since the measured pressure decay in 2-3 seconds was in the order of $5 \cdot 10^{-8}$ mbar/s. All the useful parameters recorded during the test are reported in Table 6.1.

Table 6.1: Sample Cell Leakage Test Results.

Parameters:	**Values:**
p_1	$4.3 \cdot 10^{-3}$ mbar
Δp	1 bar
Starting pressure time rate	$4.9 \cdot 10^{-8}$ mbar/s
He Max Pressure Time Rate	$3 \cdot 10^{-5}$ mbar/s
Final Decay	$5 \cdot 10^{-8}$ mbar/s

However, the test was not sufficient to assess the fully validity of the design with respect to the scientific requirements. The test was valid only to confirm the sealing of the bottom septa screw. But, it was not possible to evaluate the leakage of the membrane: the vacuum performed during the experiment deformed permanently the membrane, making it unsuitable for the operational scenario. To this end, a pressure decay test was carried out to evaluate the system decay and the maximum design pressure of the membrane.

Pressure Decay Test.
The pressure decay was carried out to evaluate the membrane behaviour at its blast pressure. Thank to this, it was possible to have a more accurate overview of the system leakage and membrane performances. In this set-up the SCU was connected with the same adaptor used in the Leakage Test to a Nitrogen tank. The connection system was composed by two valves and a digital manometer (LEO 5 Keller Manometer), which was connected via USB to the REFOAM laptop as shown in Figures 6.25 and 6.26.

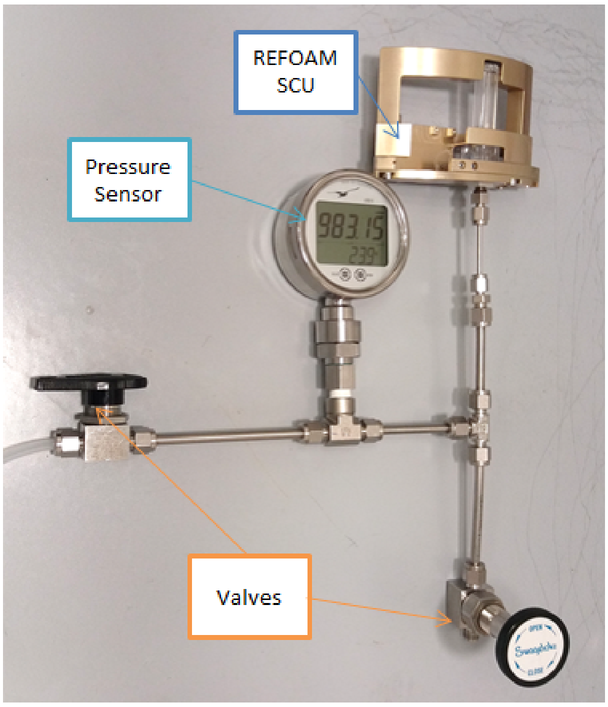


Figure 6.25: Pressure Decay Test: Sample Cell Unit Set-up.

The test started connecting the SCU to the required instrumentations and to the Nitrogen tank, with the relative connection valves opened. Then, the system was brought to a pressure equal to the design value of 4 bar. Once the pressure value was considered stable, it was closed and the pressure decay curve was recorded. Two different configurations were used. The first one involved the SCU connected to the tank with two closing valves as sketched in the Figure 6.27. In this way the total system decay was analysed together with the SCU.

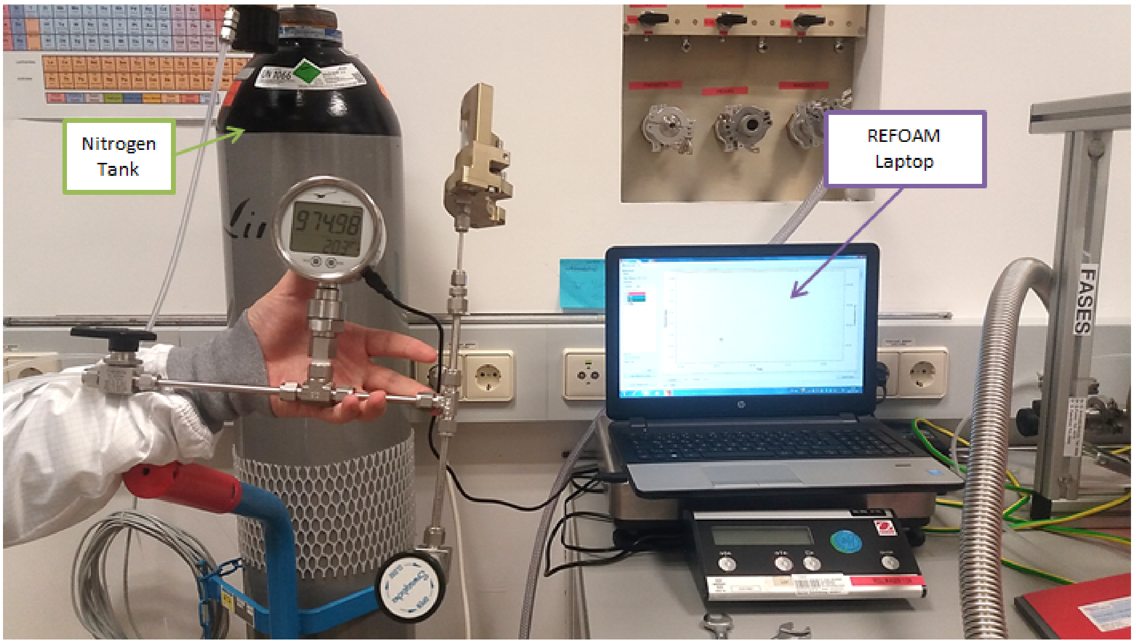


Figure 6.26: General Test Set-up.

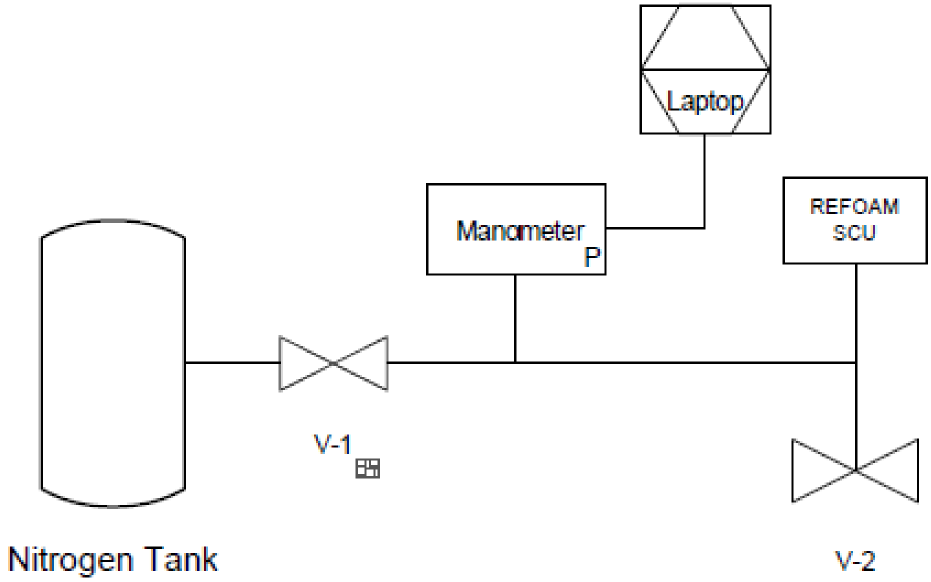


Figure 6.27: Sketch of the Test Set-up with the Sample Cell Unit.

In the second configuration, the SCU was removed and substituted with a third closed valve (see Figure 6.28). The experiment was repeated with the same procedure used for the previous one. In this set-up the system decay was recorded without the SCU. Then, the two results were analysed and the final SCU decay was computed.

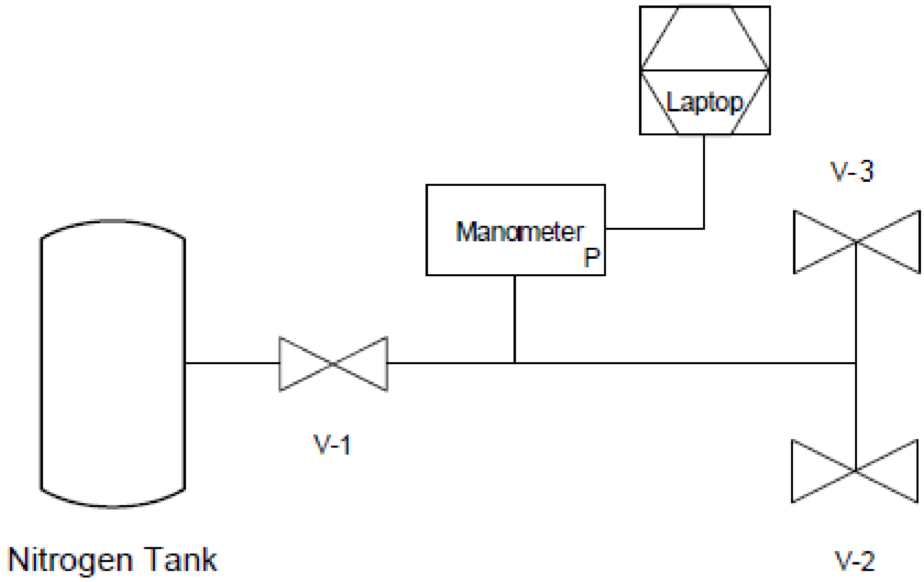


Figure 6.28: Sketch of the Test Set-up Without the Sample Cell Unit.

Hereafter the test procedure and the analysis of the results obtained from the two measurements are reported and a final evaluation is given.

Test Procedure:

1. Connect the SCU to the pressure system
2. Close the valves
3. Open the valve V-1 connect to the tank
4. Open the Nitrogen tank
5. Bring the system at a 4 bar pressure
6. Close the valve V-1
7. Record the pressure decay curve for the needed time
8. Remove the SCU from the set up
9. Close the system with a third valve V-3
10. Repeat the same procedure without the SCU to evaluate the system decay

Results and Analysis.

The results were recorded real time through the digital manometer. The pressure decay curves for the total system and for the system without the SCU were obtained. The plots shown in Figures 6.29 and 6.30 were used to compute the analysis of the leak rate of the single SCU, starting from the measurement of the volume and the relative pressure decay versus time.

The membrane blast test was performed in conjunction with the pressure decay test. The pressure selected for the decay analysis was equal to the nominal system pressure. This choice made possible to evaluate the resistance of the NBR plastic membrane versus time. In Figure 6.29 it is clearly shown that the membrane was able to bear with a 4 bar pressure for a time frame of about 3.5 minutes. The drastic fall in the plot is representative of the membrane explosion and the consequently rebalancing of the system with the outer pressure.

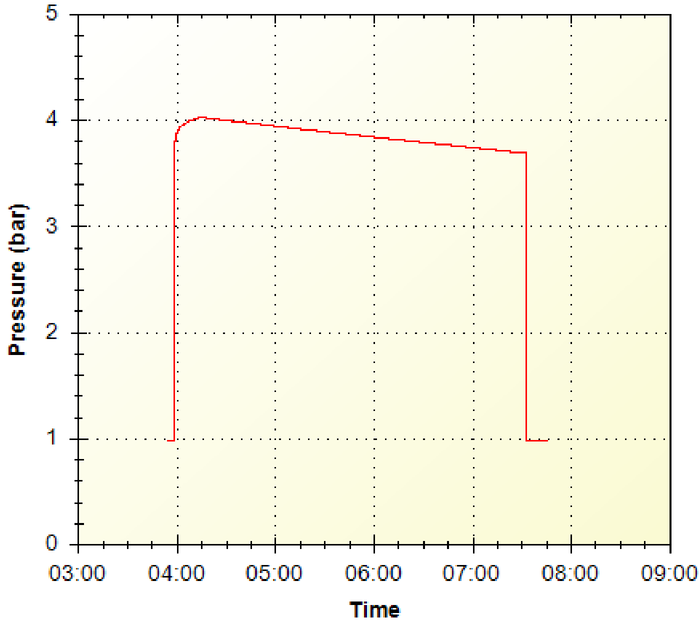


Figure 6.29: System and Sample Cell Unit Pressure Decay Curve.

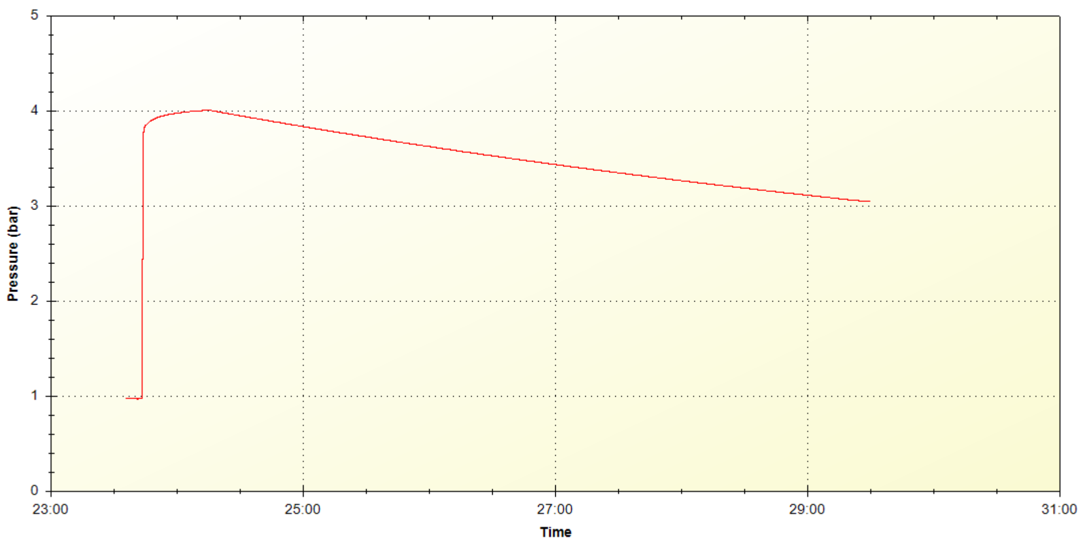


Figure 6.30: System Pressure Decay Curve.

A leakage rate of the SCU was determined from the values recorded by the digital manometer. First of all the SC and system volumes needed to be computed. The SC is known by design at it is equal to:

$$V_{SC} = 6\,\text{cm}^3 = 6000\,\text{mm}^3 \tag{6.5}$$

Then, the system volume can be computed starting from the geometrical dimension of the pipes and the total system length.

$$A_{tube} = \left(\frac{D}{2}\right)^2 \cdot \pi \tag{6.6}$$

with $D = 3\,\text{mm}$ the diameter of the pipe, and considering the length of the system equal to $L = 500\,\text{mm}$ it is possible to compute the system volume (without the SC):

$$V_{system} = L \cdot A = 3500\,\text{mm}^3 \tag{6.7}$$

Finally the total volume can be computed.

$$V_{tot} = V_{SC} + V_{system} = 9500\,\text{mm}^3 = 9.5\,\text{cm}^3 = 9.5 \cdot 10^{-3}\,\text{l} \tag{6.8}$$

The pressure rate is then computed from the volumes and the pressure variation versus time recorded during the tests. The first computation concerns the total system (first test configuration).

$$p_{rate_{System+SC}} = \frac{\Delta p \cdot V_{tot}}{\Delta t} = 0.01357\,\frac{\text{mbar} \cdot \text{l}}{\text{sec}} \tag{6.9}$$

with $\Delta p = 0.3\,\text{bar}$ and $\Delta t = 210\,\text{sec}$
The value computed at 3 mbar is then converted to 1 mbar.

$$p_{rate_{@3\,\text{mbar}\Delta p}} = 0.01357\,\frac{\text{mbar} \cdot \text{l}}{\text{sec}} \tag{6.10}$$

$$p_{rate_{@1\,\text{mbar}\Delta p}} = 1.357 \cdot 10^{-3}\,\frac{\text{mbar} \cdot \text{l}}{\text{sec}} \tag{6.11}$$

The pressure rate of the pipes system is calculated. The pressure variation in the equation is relative to the record of the second test configuration.

$$p_{rate_{System}} = \frac{\Delta p \cdot V_{system}}{\Delta t} = 0.01357\,\frac{\text{mbar} \cdot \text{l}}{\text{sec}} \tag{6.12}$$

with $\Delta p = 1\,\text{bar}$ and $\Delta t = 345\,\text{sec}$ Also in this case the value is converted from 3 mbar to 1 mbar pressure.

$$p_{rate_{@3\,\text{mbar}\Delta p}} = 1 \cdot 10^{-2}\,\frac{\text{mbar} \cdot \text{l}}{\text{sec}} \tag{6.13}$$

$$p_{rate_{@1\,\text{mbar}\Delta p}} = 1 \cdot 10^{-3} \cdot 10^{-3}\,\frac{\text{mbar} \cdot \text{l}}{\text{sec}} \tag{6.14}$$

In conclusion, the SC pressure rate is computes subtracting the system leakage from the total one.

$$p_{rate_{SC}} = p_{rate_{System+SC}} - p_{rate_{System}} = 4 \cdot 10^{-4}\,\frac{\text{mbar} \cdot \text{l}}{\text{sec}} \tag{6.15}$$

This result together with the blast test conducted at the design pressure revealed that the membrane had a too low pressure limit and a leakage not compatible with the requirement of $1 \cdot 10^{-5}$ mbar/s. This proved that the design was not able to support the maximum design pressure with the necessary safety factors. And consequently, the NBR plastic membrane could not be implemented for a potential future FM. A possible improvement was the utilization of a multi-layer membrane customized for the specific application, as discussed in Section 5.2. When the new membrane will be assembled and integrated in the SC, a new leakage and pressure decay test campaign will be carried out.

6.3. INTEGRATED SYSTEM TESTS

The key test following the assembly stage is the Integrated System Test (IST), a test that verifies the performance of all the elements working together at system level, in all operational modes. The IST is sometimes known as the System Functional Test (SFT). The first IST sets the baseline against which the results of later Integrated System Tests (ISTs) are compared, to identify any trends in performance that might detect failures induced during the test programme (and to clearly identify the particular activity that caused the failure)[Fortescue et al., 2011].

For the REFOAM SCU hardware the main IST involved the testing of the electronics interfaces of the actuation system, and its performances after the SCU insertion in the VTF. The first step was checking the cable connections, then the SCU was plugged in the eBB and the REFOAM laptop was connected to the Piezo driver through the outer eBB connector. When the links were completed the laptop was able to identify the motor and the encoder, and control them. To confirm that the integration was successful, the motor was run in open and closed loops. The index finder was an ulterior test useful to provide a feedback for the correct encoder installation. It is a specific software function thanks to which is possible to identify the absolute encoder index position and set it as a the zero position for a closed loop run.

When the actuation system was considered successfully tested, the magnet coupling was checked. To carry out this functional test the SCU had to be moved to the experiment position N.2, where the rheology magnet and the rod magnet were observed from the SC top window via the overview camera. In this configuration, it was possible to verify if the two magnets were in contact, if the piston provided the correct strain when the rod pushed against it, and if the alignment of the stack of components from the rod end tip to the rheology plate was obtained.

7
Verification & Validation

Validation and Verification phase is an essential aspects of all the project from its beginning to the end. A good V&V approach is the so called "V" Model. In which, it is clearly shown the relationship between the definition/ decomposition/ validation process (on the left side of the "V") and the integration/ verification process (on the right side) [Haskins et al., 2006]. The approach points out that in a project development the two processes of the two V sides are dependent, and a continuous correspondence exists between them. In the Figure 7.1 the sketch of model is given.

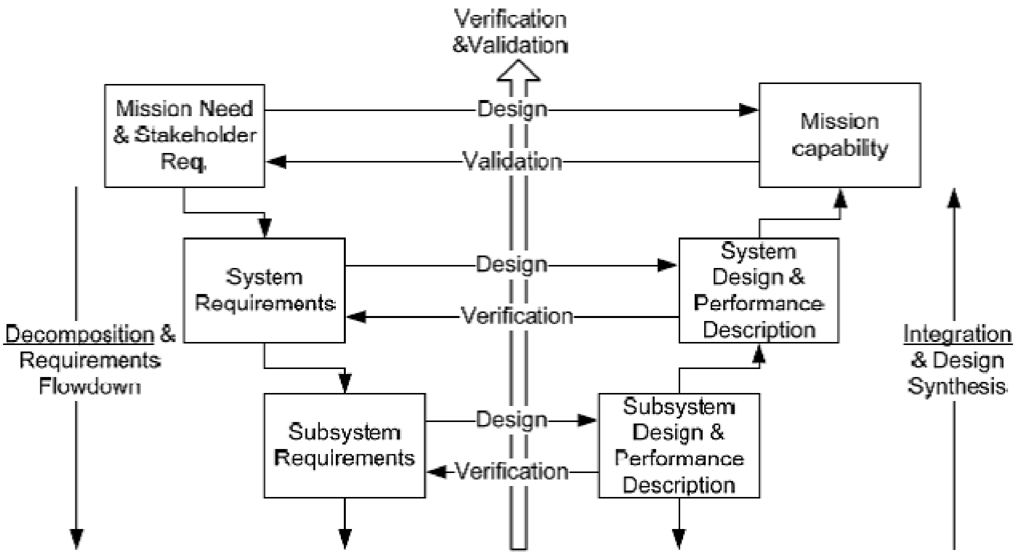


Figure 7.1: System Engineering "V" Model [Gill, 2015].

System verification and validation activities (V&V) can be easily confused, but they address specific different issues. *Verification* addresses whether the system and its elements satisfy their requirements; *Validation* confirms that the system, as built satisfy the user's needs. The primary function of the verification process is to ensure conformance of the system with the derived requirements, and that the planned development process has been followed. The second function is to document that the system and subsystem representations at each level are fully compliant with the specifications and requirements. In this way, each phase of the development process is completed, and the next phase can be started [Haskins et al., 2006]. The final result is a verified item that has been qualified to meet all design specifications and the contractual requirements.

The objective of the validation process is to ensure the implemented product functions as needed in its intended environment. It includes its operational behaviour, maintenance, training, and user interfaces [Haskins et al., 2006]. Successful verification and validation results confirm that the development process has provided a system consistent with customer expectations. Both validation and verification activities often run concurrently and may use portions of the same environment.

In this chapter the SE approach of the verification and validation is applied to the REFOAM project. In Section 7.1 the first iteration of the Verification Compliance Matrix (VCM) is presented. It is developed starting from the Project Requirements presented in Appendix B. In Section 7.2 the Verification and Validation Plan is described in accordance with the results obtained from the VCM. In Section 7.3 the Verification tests are described and the results are analysed. Finally, in Section 7.4 the future Validation test camping is described.

7.1. VERIFICATION COMPLIANCE MATRIX

A first Verification Compliance analysis was performed in the light of the design and development tests carried during the AIT phase. It started from the REFOAM requirements established in cooperation with the science team (see Appendix B). For each requirements one or more verification methods are defined and additional thoughts about the verification activity and reasons to select a certain methods have to be annotated.

The results are presented and discussed in the following paragraphs, each for every subsystem. Each requirement is enclosed in a title box, where the requirement categorization, number, name and strategy are presented. The last column of the box refers to the compliance of the demonstrator requirements. C stands for Compliant, C* Compliant for now but will require additional verification, PC for Partially Compliant, NA for Not Applicable in this phase of the study, and NC for Non-Compliant. If "—" is stated, that means there is no input at the moment for this requirement. This layout was developed with the aim to highlight the requirements characteristics and compliance, and present them in the clearest possible way.

7.1.1. DEMONSTRATOR OBJECTIVE

M	R1	Rheology of Foam	Validation Test	—

The demonstrator was designed to allow the uni-axial deformation of foam and support the assessment if and how a rheology experiment cell can be implemented in the Soft Matter Dynamics (or following) FSL EC. To really see if the demonstrator is able to conduct rheology test, we need to run the final validation test in the real environment test.

NH	R101	Rheology of Emulsions	Validation Test	—

Additionally, the demonstrator shall allow the deformation and support the assessment for emulsions. This needs also to be tested during integration in the VTF of SMD. As the requirement was agreed in a NH flexibility level, if the demonstrator fails to conduct Rheology on emulsions, this should not compromise the whole project.

7.1.2. EXPERIMENT DEFINITION

M	R2	Jamming Transition	Validation Test	NA

The transition from jamming induced solid-like to liquid-like behaviour in soft matter shall be investigated. Jamming transition, according to the science team, cannot be tested during the Validation Tests of the demonstrator.

M	R3	Characterisation and Control Parameters	Validation Test	—

The transition shall be characterised in terms of elastic/ plastic response of the sample with liquid-fraction ϕ to a temporally applied strain ϵ.

M	R31	Critical Yield Strain	Validation Test	—

For a given liquid fraction ϕ lower than the critical liquid fraction ϕ_c, upper limits to the critical yield strain ϵ_y shall be determined.

O	R102	Critical Liquid Fraction	Analysis, RoD	C

RoD: The design allows to investigate one liquid fraction per SCU. The design of Soft Matter Dynamics EC allows to exchange SCU on orbit to study several liquid fractions.

O	R32	Strain Relaxation	Analysis, RoD	C*

RoD: The design allows to investigate one liquid fraction per SCU. The design of Soft Matter Dynamics EC allows exchanging SCU on orbit to study several liquid fractions. The Soft Matter Dynamics EC LC used for the observation can be recorder for several hours of experiment time. Analysis: Exact number of sample liquid fractions and measurement duration need to be assessed by science team.

O	R33	Plastic Rearrangement	Similarity, Development Test, Test	C*

Similarity: SMD supports offline processing of the raw data, this allows implementing arbitrary algorithms. The LC of Soft Matter Dynamics EC supports line rates up to 10 kHz. Development Test: Reference for a successful demonstration of this experiment in the laboratory needs to be supplied by the science team. Test: Reference test needs to be repeated with the REFOAM demonstrator and VTF.

7.1.3. SAMPLE MATERIAL PROPERTIES

M	R4	Generate Foams	RoD, Test	C*

RoD: During operational scenario, the piston shakes vertically in order to create in-suit foam. This phase is called the foaming phase. Test: Foaming test needs to be performed with the REFOAM demonstrator and VTF.

M	R5	Maximum Liquid Fraction	RoD	C

RoD: During filling of the SC, the filling occurs through the septa screw which allows to evacuate the residual gas in the SC volume. Therefore liquid fractions up to 100% can be realized. Similarity: During the Parabolic Flight Campaign of the Soft Matter Dynamics EC VTF foaming of liquid fractions up to 50% has been demonstrated successfully.

M	R103	Minimum Liquid Fraction	RoD	C

RoD: During filling of the SC, the filling occurs through the septa screw which allows to evacuate the residual gas in the SC volume. Therefore liquid fractions down to 0% can be realized. Similarity: During the Parabolic Flight Campaign of the Soft Matter Dynamics EC VTF foaming of liquid fractions down to 5% has been demonstrated successfully.

M	R104	Liquid Fraction Accuracy	RoD, Similarity	C

RoD: Internal volume of the SC can be determined by filling with a 100% liquid fraction of water (see R5 above) and weighing of the cell. The amount of liquid added during filling can also be determined by weighing. Similarity: During the science test campaign of Soft Matter Dynamics EC it has been demonstrated that the required accuracy of liquid fraction can be met.

M	R105	Liquid Fractions	Analysis, RoD	C

RoD: The design allows to investigate one liquid fraction per SCU. The design of Soft Matter Dynamics EC allows to exchange SCU on orbit to study several liquid fractions. Analysis: at least six liquid fractions need to be investigated, which means at least six SCUs need to be processed on orbit. The science team needs to assess if lower and upper limits to the critical liquid fractions (see above R102) can be defined with the six explicitly required liquid fractions.

M	R6	Initial Average Bubble Size D	Similarity, Test	C*

Similarity: During the Science Test Campaign of the SMD EM adjustment of foam properties by changing the FGS parameters has been demonstrated successfully. Test: test needs to be repeated with the REFOAM demonstrator and VTF.

M	R7	Bubble Size Distribution	Similarity, Test	C*

Similarity: During the Science Test Campaign of the SMD EM adjustment of foam properties by changing the FGS parameters has been demonstrated successfully. Test: test needs to be repeated with the REFOAM demonstrator and VTF.

M	R106	Composition chemicals	Similarity	C

Similarity: During the Science Test Campaign of the SMD EM pure water, TTAB and air have been used successfully for foaming. Science team is using reference foam made from pure water, TTAB, nitrogen and C6F14.

M	R107	Liquid Compositions	Similarity, Analysis, Test	C*

Similarity: During the Science Test Campaign of the SMD EM pure water, TTAB and air have been used successfully for foaming. Science team is using reference foam made from pure water, TTAB, nitrogen and C6F14. Test: The leakrate for the gaseous components of the composition needs to be measured in a relevant configuration of the SC. Vapour pressure of C6F14 inside SC needs to be measured. Foaming of liquid compositions that contain liquid drop of C6F14 needs to be demonstrated with the REFOAM demonstrator and Verification Facility. This test can be performed only when the multi-layer membrane will be integrated. Analysis: Necessary amount of liquid C6F14 in the liquid composition has to be calculated from the measured leakrate.

M	R108	Gas Compositions	Development Test	—

Development Test: The filling procedure for gas into the SC needs to be qualified. Achievable volume fraction of gas must be determined.

M	R109	Gas Pressure	Similarity	C

Similarity: Filling sample with gas at ambiance pressure through the septa screw has been performed many times within other project applications projects.

O	R110	Liquid Fractions	Similarity	C

Similarity: The design allows in principle creating any liquid fraction between 0 to 100% in step of 1% with an accuracy of 0.5%.

NH	R111	Generate Emulsions	Test	—

Test: The test needs to be performed with the REFOAM demonstrator and VTF. Emulsion properties needs to be defined by science team.

7.1.4. DIAGNOSTICS

M	R9	Characterisation of Plastic Deformation	Similarity	C

Similarity: During the Science Test Campaign of the SMD EM, the suitability of the Speckle Visibility/Variance Spectroscopy (SVS) detection and observation channel to perform time resolve correlation measurements has been demonstrated successfully. The science team has used time resolve correlation measurements in the laboratory for the characterization of plastic deformation.

M	R8	Multi-Speckle DWS	RoD	C

RoD: The SMD SVS Detection and Observation channel implements homodyne multi-speckle DWS.

M	R20	Observation Volume (L^3)	RoD	C

RoD: The observation volume is defined by the initial gap size of the deformation volume (2mm) and the FoV of the LC (3.30 mm diameter).

M	R22	Backscatter DWS	RoD	C

RoD: The SMD SVS Detection and Observation channel is performed in backscattering configuration.

M	R23	Optimized Illumination / Detection	RoD, Development Test, Test	C*

RoD: The design of the redirecting elements (mirrors) allows for adjustment of the beams. Development Test: The feasibility of accurate adjustment of the optical paths has to be assessed during integration. Test: Optimum parameters of the acquisition chain (laser intensity, LC exposure time, etc.) need to be assessed with the REFOAM SCU and VTF.

M	R25	Coherence Length	Similarity	C

Similarity: The SMD laser has a spectral bandwidth (Full Width at Half Maximum (FWHM)) of less than 1 MHz this corresponds to a coherence length larger than 95.4 m in air at ambient temperature and pressure.

M	R26	Intensity Stability	Similarity	PC

Similarity: The SMD laser states a power stability over 8 hrs of less than 2%.

M	R28	Number of Speckles	Similarity	C

Similarity: During the Science Test Campaign of SMD EM, it has been estimated by the science team that between two and four speckles are recorded by each pixel of the LC. Therefore a total of at least 4000 speckles are recorded by the detector.

M	R24	Detected Intensities	Demonstrator Test	—

Demonstrator Test: test needs to be performed with the REFOAM demonstrator and VTF.

M	R27	Detector Resolution	RoD	C

RoD: The Soft Matter Dynamics EC LC uses a 12bits Analog to Digital Converter (ADC) Bit Depth.

M	R29	DWS Detector Frame Rate	RoD	C

RoD: The sensor has a maximum line rate of 51kHz.

M	R119	DWS Recorded Frames	Similarity	C

Similarity: The Soft Matter Dynamics EC LC used for the observation can be recorder by the FSL Video Management Unit (VMU) for several hours of experiment time.

M	R113	Measurement of Bubble Size	RoD	C

RoD: Bubble size can be measured after foaming using the overview camera of the Soft Matter Dynamics EC.

M	R114	FoV (2L x 2L)	Similarity	C

Similarity: The Soft Matter Dynamics EC overview camera observes an area approximately 12x14mm. The REFOAM SC Top Cover and SCU Top Cover allows to observe foam in the full FoV of the imaging optics.

M	R115	Optical Resolution	Similarity	C

Similarity: The Soft Matter Dynamics EC overview camera resolves the FoV with better than 10µm.

M	R116	Intensity Resolution	RoD	C

Similarity: The Soft Matter Dynamics EC overview camera uses a 12bits ADC.

M	R117	Camera Frame Rate	RoD	C

Similarity: The Soft Matter Dynamics EC overview camera has a frame rate of 8 frames per second.

M	R201	Camera Exposure	Similarity	C

Similarity: The Soft Matter Dynamics EC has a global shutter. Exposure time is adjustable between 0.03 ms to 32 seconds.

O	R118	DWS Detector Frame Rate	Similarity	C

Similarity: The Soft Matter Dynamics EC LC sensor has a maximum line rate of 51kHz.

O	R120	Synchronization	RoD	C

RoD: The Soft Matter Dynamics EC does not provide interfaces necessary to implement a recording of images synchronized with the strain cycle. The line rate of the camera is 1000 times faster than the rise time of the strain cycle. This allows synchronizing the measurements with the actuation during data post-processing.

O	R121	Measurement of Bubble Size	RoD	PC

RoD: For the REFOAM demonstrator, the optical/illumination product used to redirect the laser and LC optical paths can be replaced by a special part to redirect the overview camera FoV thereby allowing the observation of the same boundary with both optical diagnostics but not at the same time. This will most likely not be possible for the potential FM.

O	R122	FoV	Similarity, RoD	C

Similarity, RoD: The Soft Matter Dynamics EC overview camera observes an area approximately 12×14 mm. The REFOAM SC Top Cover and SCU Top Cover allow observing foam in the full FoV of the imaging optics.

O	R123	Optical Resolution	Similarity	C

Similarity: The Soft Matter Dynamics EC overview camera resolves the FoV with better than 10 μm.

NH	R124	DWS Detector Frame Rate	Similarity	C

Similarity: The Soft Matter Dynamics EC LC sensor has a maximum line rate of 51 kHz.

NH	R125	Epi Illumination of Optical Images	Similarity	NC

Similarity: Neither the VTF nor the Soft Matter Dynamics EC support Epi illumination of the overview camera.

7.1.5. ACTUATION SYSTEM

M	R19	Strain Mechanism	RoD	C

RoD: The strain is applied by an additional feature implemented into the former foaming piston of FOAM-C.

M	R15	Deformation Volume (L x 3L x 3L)	RoD	C

RoD: The deformation piston is centred around the observation volume, which has an initial gap width L of 2 mm (corresponding to 20 average bubble diameters D) from the rheology plate to the inner opposite wall of the cell before deformation stroke. The deformation volume has circular shape of 6mm diameter (=3L) and leaves sufficient free space L to the bounding walls to allow an undisturbed flow of foam around the piston during the strain cycle.

M	R126	Gap Width Accuracy (L)	RoD	C

RoD: The error and the repeatability of the initial gap width L is initialized during integration and then ensured by the performances of the Piezo actuator LL06 with the micro stepping driver PMD101. The whole system can achieve a position with 0.5 μm error and 0.5 μm repeatability for unlimited number of strokes.

M	R14	Uniaxial Deformation	RoD	C

RoD: The strain applied by the piston by design provides a local homogeneous uni-axial deformation of the foam sample.

M	R10	Strain Amplitude	RoD	C

RoD: The strain amplitude of $|\epsilon|$ can be achieved up to 200 μm. This value is limited by the smallest distance between the piston and the SC.

M	R127	Strain Direction	RoD	C

RoD: As the piezo LEGS LL06 actuator allows both ways of direction, it is possible to whether compress or expand the foam sample starting from the original gap width L and with the stroke amplitudes defined from R10.

M	R11	Strain Resolution	RoD	C

RoD: The resolution of the applied strain ϵ is ensured by the performances of the Piezo actuator LL06 coupled to the micro stepping driver PMD101. The whole system can achieve a position with 0.5 μm error and 0.5 μm repeatability for unlimited number of strokes.

M	R17	Strain Accuracy	RoD	C

RoD: The resolution of the applied strain ϵ is ensured by the performances of the Piezo actuator LL06 coupled to the micro stepping driver PMD101. The whole system can achieve a position with 0.5 μm error and 0.5 μm repeatability for unlimited number of strokes.

M	R18	No Overshoot	Depends on Concept	C

RoD: The Piezo LEGS LL06 has no backlash due to its technology used inside the actuator. The electronic control and feedback loop also limit the overshoot of the actuator rod during the displacement as follows:

- The position encoder gives an update of the position every 0.5 μs to the microstepping driver.
- Velocity of the rod by design has to be minimum 2mm/s.
- This corresponds to an overshoot of 1nm.
- Therefore the overshoot is limited to the resolution of the encoder 1.25 μm.

M	R12	Rise Time	RoD	C

RoD: The velocity of the piezo LEGS LL06 is adjustable in the range of 0-15mm/s. The control loop velocity is limited by the counting frequency of the encoder position (2 Mhz) and the desired resolution (1.25 μm is the best reachable). For this resolution, the encoder position can be used up to 230 mm/s linear application. The maximum reachable speed is limited by the Piezo LEGS to 15 mm/s, which is larger than the 2 mm/s required.

M	R13	Strain Duration	RoD	C

RoD: For the demonstrator the software to control the strain cycle allows automatic sequences of instructions. The command RunToTarget provides the functionality to pause for 0–10 seconds with 1 ms accuracy. For the potential future FM same functionality is expected.

M	R128	Volume Change	Analysis	C

Analysis: During the strain cycle with a deformation stroke of 200 μm (Target of R10) the total volume of the sample material changes by 2.836 mm^3 (=0.002836 ml) which corresponds to 0.08930% volume change of the available volume for liquid and gas inside the SC.

M	R129	Velocity Field Homogeneity	Test	C*

Test: The test needs to be performed with the REFOAM demonstrator and VTF.

O	R130	Strain Duration	Similarity	C

RoD: For the demonstrator the software to control the strain cycle allows automatic sequences of instructions. The command RunToTarget provides the functionality to pause for 0 – 600 seconds with 1 ms accuracy. For the potential future FM same functionality is expected.

7.1.6. SAMPLE CELL PROPERTIES

M	R131	Sample Cell Filling	RoD, Analysis	C*

RoD: According to the operational scenario the SC can be filled whether from the top with ready-made reference foam or via the septa screw with a syringe from the bottom with specific mix of gases and liquids. Analysis: The lifetime analysis of leak rate.

M	R132	Sample Material Containment	RoD, Development Test, Demonstrator Test	C*

RoD: By design the SC provides two levels of containment. Development Test: Containment of water by the membranes was assessed by visual inspections. Test: Test needs to be performed with the REFOAM demonstrator and VTF with the multi-layer membrane considering the failure of the development tests with the NBR membrane.

M	R133	Material Compatibility	Similarity, Demonstrator Test	C

Similarity: As far as possible materials with known compatibility was used in the design of the SC. Test: Material compatibility tests were performed for demonstrator materials not previously used. The results of the tests assess the compliance of the new material utilized for the SC.

M	R134	Surface Treatment	Similarity	NA

Similarity: Suitable surface treatments TBD by science team.

M	R135	Diagnostics Compatibility	RoD	C

RoD: The REFOAM SC design is derived from FOAM-C SC. The original SVS diagnostic channel of the Soft Matter Dynamic EC is reused for the REFOAM experiment. Compatibility of FOAM-C SC design with Soft Matter Dynamic EC diagnostics has been shown during the SMD test campaign.

7.1.7. OPERATIONAL SCENARIO

M	R34	Soft Matter Dynamics Compatibility	RoD	C

RoD: As design system is compatible with the interfaces of the FSL Soft Matter Dynamic EC and it is well- suited for on-orbit replaceable SCU.

M	R35	Operational Environment	Analysis	NA

Analysis: The Demonstrator will only be operated in controlled laboratory conditions by trained personal on ground. The future potential FM aims to run experiments under microgravity conditions in human space flight.

M	R136	Lifecycle	Analysis, RoD	C*

RoD: The demonstrator will be operated and transported inside VTF. The design of the future potential FM will need to take into account the whole lifecycle. Analysis: The demonstrator lifecycle is limited to Ground Operations and Transport. Full lifecycle will be considered and analysed in future development tests.

7.2. VERIFICATION & VALIDATION PLAN

Verification and Validation plan begins with the requirements that need to be verified in accordance with the results of the VCM. These are reorganized in a Verification Requirements Matrix (VRM) Table 7.1, starting point for verification planning.

Table 7.1: Verification Requirements Matrix.

Req. ID	Req. Title	Strategy	Test ID	Phase Study
R1	Rheology of Foam	Validation Test	T1	Validation Test
R3	Characterisation and Control Parameters	Validation Test	T2	Validation Test
R31	Critical Yield Strain	Validation Test	T3	Validation Test
R32	Strain Relaxation	Analysis, RoD	T4	Verification Test
R33	Plastic Rearrangement	Similarity, Test	T5	Verification Test
R4	Generate Foams	RoD, Test	T6	Verification Test
R6	Initial Average Bubble Size D	Similarity, Test	T7	Verification Test
R7	Bubble Size Distribution	Similarity, Test	T8	Verification Test
R107	Liquid Compositions	Similarity, Analysis, Test	T9	Verification Test
R108	Gas Compositions	Test	T10	Verification Test
R129	Velocity Field Homogeneity	Validation Test	T11	Validation Test
R131	Sample Cell Filling	RoD, Analysis	T12	Verification Test
R132	Sample Material Containment	RoD, Test	T13	Assembly
R23	Optimized Illumination / Detection	RoD, Test	T14	Verification Test
R24	Detected Intensities	Test	T15	Verification Test
R136	Lifecycle	Analysis, RoD	T16	Verification Test

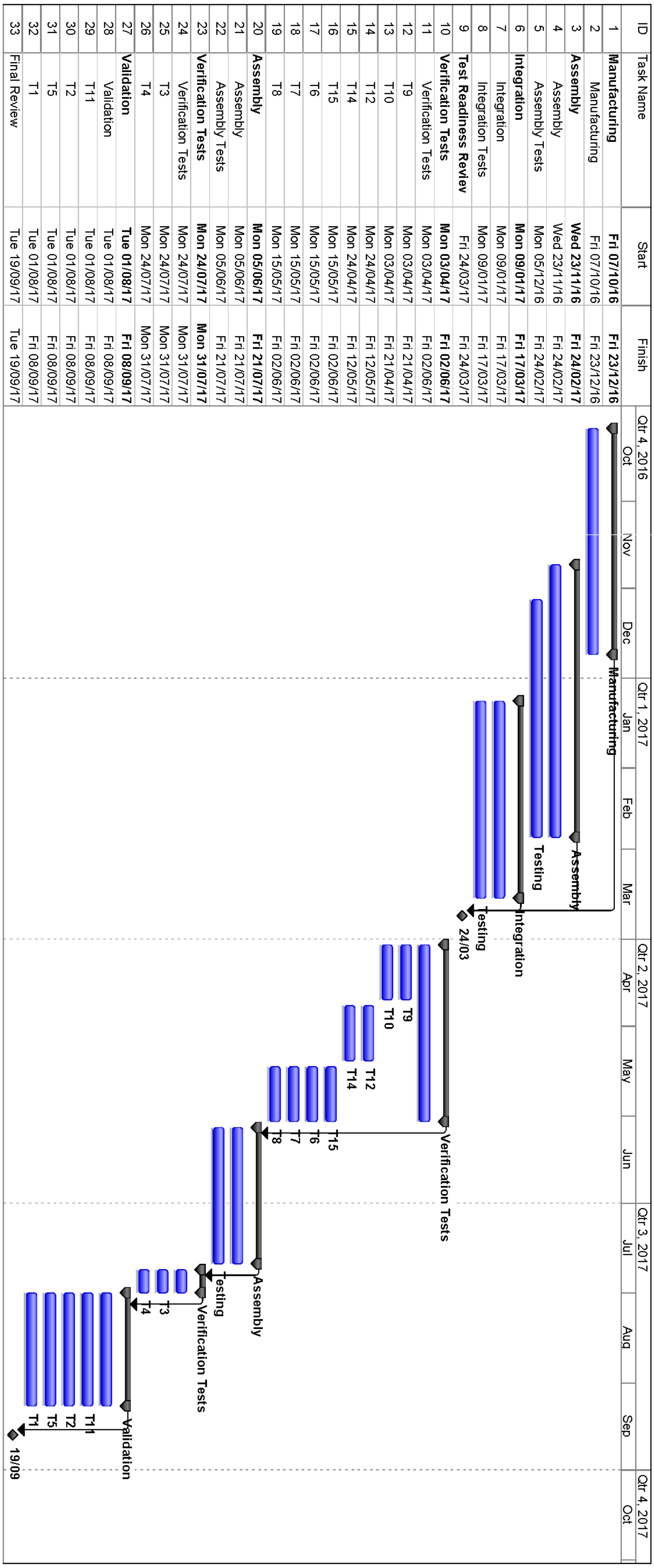


Figure 7.2: REFOAM Project Plan.

The VRM aim is to determine the method of verifying each system requirement, when it is done within the life cycle of the system and the specific procedure according to which the verification will be accomplished. The criteria to provide evidence that the system complies with the requirements were established in collaboration with the science team. In the VRM the validation tests are also mentioned. This choice was driven by the requirements themselves, which were related to the final hardware performance and were only complaint at the end of the Validation campaign.

Finally, a Test ID is added for each requirement to simplify the planning procedure and the correlation between the tests and the requirements. In Figure 7.2 the latest version of the REFOAM Gantt Chart is presented. In particular, the attention is given to the Verification and Validation test plan. However, the V&V process is totally dependent on the AIT phase, consequently it was not possible to develop a V&V plan not taking into account the AIT time frames and iterations.

7.3. VERIFICATION TEST CAMPAIGN

The Verification Test Campaign (VTC) has the aim to verify the compliance of the design with the requirements through system and subsystem tests. The REFOAM VTC was developed in agreement with the VRM, dividing the tests with respect to their context and aim.

In particular the campaign was focused only on the minimal requirements, which were considered necessary to asses the feasibility of the REFOAM experiment utilizing the Soft Matter Dynamic EC (hence, the optimum requirements R32 and R33 are not part of this study). To this end, a revisited version of the VRM was developed as presented in Table 7.2. In the following sections the tests developed during the VTC are presented. Each paragraph is dedicated to a specific set of tests.

Table 7.2: New Version of Verification Requirements Matrix.

	Req. ID	**Test ID**	**Test Details**
Filling Test	R131	T12	Sample Cell Filling
	R107	T9	Top Liquid Filling
	R108	T10	Bottom Gas Filling
Foam Generation	R4	T6	Foam Generation in the VTF
	R6	T7	Average Bubble Size
	R7	T8	Bubble Size Distribution
Optimized Detection	R23	T14	Optimized Detection and Illumination
	R24	T15	Line Camera Detected Intensity

7.3.1. FILLING TESTS

The first tests in the Verification Plan concerned the SC filling. Their aim was to prove that the SC could be filled by a specific quantity of liquid composition from the top of the SC, and a certain amount of gas could be inserted from the septa screw using a syringe. The procedure followed was the same utilized to fill the SC in preparation for the actual rheology experiments. However, a preliminary test was needed to evaluate the SC available volume.

This parameter required an experimental evaluation in order to asses the real capacity of the SC. The result of the measurements was compared with the nominal volume defined by the CAD model. In the light of these results, the computations related to the chemical composition were carried out with respect to the selected liquid fraction.

The filling tests were performed in the chemistry laboratory at Airbus DS. Pure water was used to evaluate the SC volume and the filling was performed using a syringe from the top window. Then, the mass of the system was computed with a high precision scale. The measurements were repeated several times, in order to obtain a set of values to be analyses via statistical evaluations. The procedure is presented hereafter, and it is followed by the test results and analysis.

Test Procedure

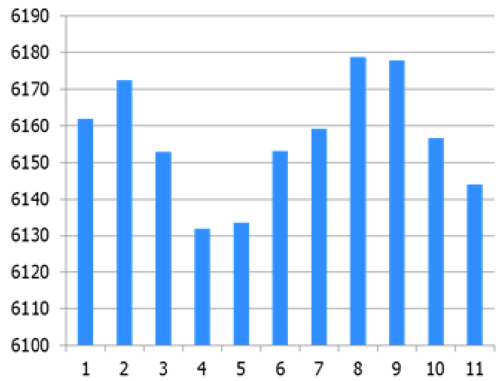
1. Assembly the SC without the piston
2. Calibrate the high precision scale (waiting time 30 minutes)
3. Measure the mass of the empty system
4. Fill certain amount of pure water into the SC
5. Measure the mass of the filled system
6. Report the measurement
7. Evacuate the SC
8. Repeat from 4 to 7 at least ten times

Results and Analysis

The measurements performed during the tests were recorded for each step. The final result was a set of values used in the estimation of the available inner volume of the SC. In Table 7.3 the volumes are reported. The first performed measurement was the SC empty mass (M0), followed by the volume recorded for each measurement. The net inner mass was computed subtracting the SC empty mass to the measured mass, these values are reported in the second column of the table. Finally, the mass in grams was converted in volume. The measured mass was pure water, and the conversion was obtained with a multiplication of the factor 10^3 to obtain the final volume.

Table 7.3: Top Filling Measurements and Histogram

Measurement	Mass [g]	Net Mass [g]	Volume [mm^3]
M0	11,7755	0	0
M1	17,9374	6,1619	6161,9
M2	17,9481	6,1726	6172,6
M3	17,9285	6,153	6153
M4	17,9074	6,1319	6131,9
M5	17,90901	6,13351	6133,51
M6	17,92872	6,15322	6153,22
M7	17,9347	6,1592	6159,2
M8	17,95419	6,17869	6178,69
M9	17,9533	6,1778	6177,8
M10	17,93207	6,15657	6156,57
M11	17,9195	6,144	6144



In the light of these values the variance, standard deviation and mean were calculated. These evaluations are reported in the Table 7.4. The test was considered successful since the

SC volume measured was in the 3σ range, a statistic rule to expresses that "nearly all" values are taken to lie within three standard deviations of the mean.

Table 7.4: Statistic Evaluation

Variance	0.000232
Standard Deviation	0.015239
Mean	6.156581

The obtained mean value was considered the SC available volume, when the piston was not inserted. The same evaluation was repeated with the piston inside the volume. Then, the liquid fraction ϕ was selected equal to the 40% and the liquid volume was computed.

$$\phi = \frac{V_{liq}}{V_{tot}} = 0.4 \tag{7.1}$$

with $V_{tot} = 3.35\,\mathrm{gr}$ computed with the same procedure of the described filling test, but considering the volume occupied by the piston inside the SC. From this relation, the volume of the liquid fraction was equal to:

$$V_{liq} = 1.32\,\mathrm{gr} \tag{7.2}$$

This value represents to the total amount of liquid present in the SC. The required liquid fraction was composed by a mixture of TTAB dissolved in water in a fraction of 5 g/l. Once the SC was filled with the liquid fraction, the SC top window and the SCU top cover were assembled. In this configuration, a drop of C6F14 was inserted in the SC through the bottom septa screw using a syringe. When the filling phase was completed, the SCU bottom was assembled and the REFOAM SCU was considered ready to perform the next Verification Tests. The detailed procedure is presented hereafter.

REFOAM Filling Procedure

1. Assembly the SCU upper part with the relative subsystem
2. Insert the SC
3. Inset the piston in the SC
4. Fill the SC with the required liquid composition
5. Close the SC with the top cover and the two O-rings
6. Close the SCU top cover with the shim
7. Fill the SC from the bottom septa screw
8. Install the SCU bottom part

REFOAM Filling Results

The procedure was repeated several times with different liquid compositions and different amount of C6F14 and C8F16. In all the experiment the SC was filled successfully. The syringe needle was inserted and extracted without any problem and the quantity released was controlled and checked via visual inspection. In conclusion, the design and the filling procedure were considered compliant with the requirement R131. With the available design was not possible to carry out the leakrate analysis defined to evaluate the R107 and R108. The main reason was the non-compliance of the NBR plastic membrane available at that time. Considering the high leakrate measured during the development test, it was decided to postpone the verification tests when the new multi-layer membrane will be available and assembled in the SC.

7.3.2. FOAM GENERATION TESTS

The SCU assembled and filled was ready to be integrated in the VTF, where the second foam generation was carried out. The aim of these tests was to asses the capability of the system to generate foam with an average diameter around 100 μm with a poly-disperse distribution of 0.3 to 2 times the average diameter. The experiment was performed in the eBB, the SC was filled with the procedure described in the previous section. The liquid fraction used was equal to $\phi = 40\%$ composed by TTAB (5 g/l) and a drop of C8F16.

The foam was generated shaking the piston inside the SC via the FGS available in the VTF. The FGS was controlled by the eBB laptop and the shaking parameters were selected in the STMO software. The piston was shaken for 30 seconds at 10 Hz. Then, the foam was recorded by the overview camera and the required illumination was provided by the six LEDs. The procedure, after the completed filling, is presented hereafter.

Foam Generation Procedure

1. Integrate the SCU in the eBB
2. Close carefully the upper eBB cap
3. Switch the eBB EGTE
4. Connect the REFOAM laptop to the eBB
5. Switch on the LEDs with the eBB laptop
6. Switch on the overview camera
7. Move the SCU with MT to the foam generation position (N.1)
8. Check the position of the SCU with the overview camera
9. Regulate the overview camera shot and exposure
10. Switch the FGS on
11. Set the parameters and the shaking time in the STMO software
12. Start the foam generation process
13. Shoot and record the bubble obtained
14. Analyse the average diameter and average bubble distribution

Results and Analysis

The bubbles were recorded in a set of shoots from the SC top window. The images obtained were processed in MATLAB to get an evaluation of the bubbles average diameter and their distribution. The computation was carried out with a simple MATLAB script based on the function "`imfindcircles`". The diameter of the bubbles was computed in pixel and converted in μm. The conversion factor was obtained through a proportion between the top window dimension 13.5 mm × 10.5 mm and the image size in pixel 1600 × 1250. In Figures 7.3 and 7.4 one of the images recorded and the related diameter analysis are shown.

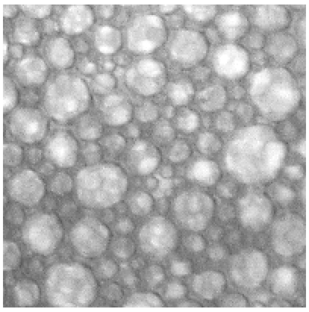


Figure 7.3: Overview Camera Bubble Record.

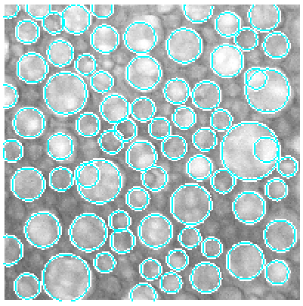


Figure 7.4: Bubble Processed Image in MATLAB.

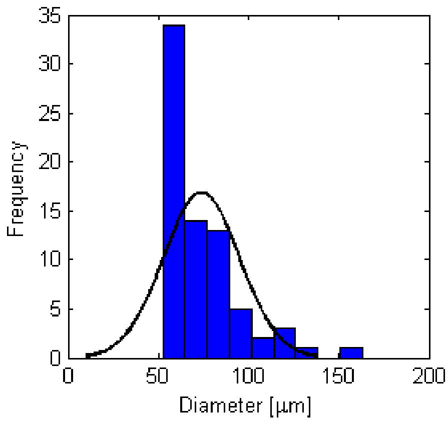


Figure 7.5: Bubble Diameters Distribution Histogram.

In the script the mean and the static distribution were computed. The histogram of the distribution is presented in Figure 7.5. The computed mean is equal to 74 μm and the bubbles distribution is in the range of [30 μm - 200 μm]. However, this analysis was the only performed since the foam generation was not considered a critical aspect of the system. The same process was tested and verified for previous experiments performed in the Soft Matter Dynamic EC. In the light of this, the science team accepted the test results and considered the test successful, certifying the compliance with the requirements R4, R6 and R7.

7.3.3. ILLUMINATION AND DETECTION

The last verification test concerned the qualification of the illumination and diagnostic system. The aim of the test wast to asses that the design of the redirecting elements (mirrors) was able to redirect the laser beam and detect the required intensity. The test was developed in the optic laboratory at Airbus DS. The experiment was conducted in the VTF, operating the eBB without the top cover in order to check the laser beam redirection. The speckle pattern was recorded by the LC and the analysis of the spectra was performed via the ImageJ software.

In order to verify the validity of the results the speckle histogram distribution was compared with the one obtained from a FOAM-C SCU. In fact, its design provided a direct illumination and detection of the speckle, without any reflecting mirror. To this end, two tests were carried out in the eBB with two different SCUs. The tests were conducted in two different sessions: the FOAM-C SC was filled and recorded right after, while the REFOAM pattern

was recorded after two days from the filling.
The foam utilized for both the experiments was the ready made Gillette foam, and the SCs were filled from the top cover. Consequently, the process did not require a foam generation system. The experiments were performed with both the design solutions available: 3D printed and aluminium holders. The test procedure for all the experiments is reported hereafter.

Procedure

1. Fill the SC with ready made Gillette foam
2. Insert the SC in the SCU
3. Assemble the SCU according to the procedure
4. Insert the SCU in the VTF
5. Connect the laser key to the laser port
6. Wear the laser protective goggles
7. Switch the eBB EGTE and the laser
8. Connect the REFOAM laptop to the eBB
9. Switch on the LC
10. Move the SCU with MT to the laser/acquisition position (N.2)
11. Check the laser beam spot on the SC observation window
12. Regulate the LC parameters
13. Record the speckle pattern
14. Analyse the results obtained

Results and Analysis

The experiment set-up ensured that the laser beam reached the SC observation window. The laser lights generated a speckle pattern, which was recorded by the LC. The final output was a grey spectrum band representing the foam speckle pattern. The spectra recorded for FOAM-C and REFOAM are presented respectively in Figures 7.6 and 7.7. The delay in the recording is clearly visible in the spectra obtained. In fact, the resulting pattern shows that the REFOAM foam is more dry and stable compared to the FOAM-C one.
From the spectrum bands the statistical analysis was carried out. The speckle histograms were computed with the ImageJ software. The obtained distribution was represented in a logarithmic scale for both the experiments (see Figures 7.8 and 7.9).

The results were comparable in the distributions, ensuring that the mirror holder, used to redirect the beam, provides the similar results to those obtained without any beam redirection. However, some differences in the plots occur, which can be associate to a possible light backscattering that can be reduced with an optimization of the SCU position in the VTF.

Finally in the light of the obtained results, the design solution was considered compliant with requirements R23 and R24. In fact, the mirrors were able to illuminate the observation window redirecting the laser beam, and to allow the record of the speckles pattern with the LC at the required intensity.

Figure 7.6: FOAM-C Grey Spectrum Band.

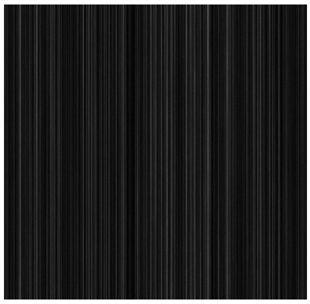


Figure 7.7: REFOAM Grey Spectrum Band.

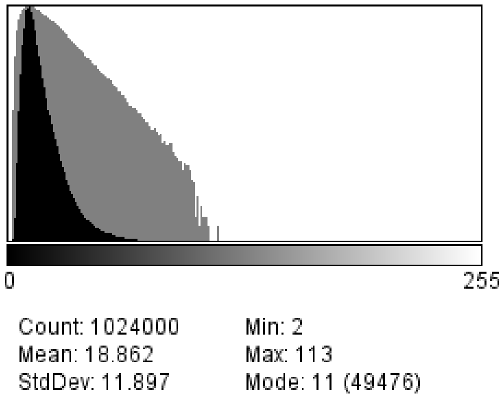


Figure 7.8: FOAM-C Speckle Histogram.

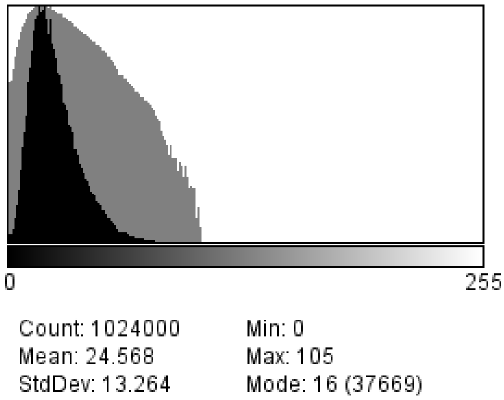


Figure 7.9: REFOAM Speckle Histogram.

7.4. VALIDATION TEST CAMPAIGN

Validation is interpreted as the validation of the design. It determines that the system does all the things it should and does not do what it should not do. It is usually performed in the operational environment or a simulated operational environment. The performed functions are similar to verification tasks, such as test, analysis, inspection, demonstration, or simulation [Lightsey, 2001]. Validation activities start with a verified end product and its success depends on the compliance of the project requirements, which are the measures of effectiveness and success criteria. These criteria are based on the details about how the product will be used, and how it will work. A detailed validation plan is developed to achieve a validated product, supported by the test reports generated as part of verification.

Within this thesis framework, a validation campaign was not performed. It was out of the aim of this study since some design issues were still in development. Once the REFOAM assembly will be completed with the insertion of the new membrane, new development tests will be carried out to asses the SC leakage and material containment (R132). Then, a second verification campaign will be opened to ensure the final requirements compliance and the validation tests will be performed when the system will be successfully verified.

III

Conclusions and Future Prospects

8

Final Compliance Analysis

The final results of the Verification phase are discussed in this chapter. The test campaign had the aim to verify the requirements, whose compliance was not assessed during the design review and system development. To this end, several tests were performed in order to close the VCM (see Table 7.1). The attention was focused on the verification analysis of the Minimum requirements. All the performed tests were successful and the compliance was assessed for the requirements related to the SC filling, foam generation system, optics detection and illumination systems.

However, some requirements are still under analysis. In particular, the tests dedicated to the gas and liquid compositions were not carried out due to the unavailability of the multilayer membrane. Consequently, the R107 and R108 will be closed in the second campaign iteration, when the SCU will be provided with all the design improvements introduced in this study. Finally, the Optimum and Nice to Have requirements R31, R32 and R111 were not taken into account in this framework, but their compliance will be assessed in future investigation over the next project phases.

The compliance assessed during the Verification Tests is reported in Table 8.1. The fully compliant requirements are denoted with a C, and the report sections, where tests aims, procedures and results are discussed, are recalled in the table last column. The requirements denoted with a C* and with — will require further analysis and investigations.

The Validation Tests are also reported in the table, even if the validation campaign was not performed since the verification analysis was not completed. This decision was made considering that this VCM will be not only the starting point of the second iteration of the Verification Campaign, but also the first indication to develop and perform the final Validation Tests.

Table 8.1: Final Verification Compliance Matrix.

Req. ID	**Req. Title**	**Strategy**	**Status**	**Report Section**
R1	Rheology of Foam	Validation Test	—	—
R101	Rheology of Emulsions	Validation Test	—	—
R3	Characterisation and Control Parameters	Validation Test	—	—
R31	Critical Yield Strain	Validation Test	—	—
R32	Strain Relaxation	Analysis, RoD	C*	—
R33	Plastic Rearrangement	Similarity, Test	C*	—
R4	Generate Foams	RoD, Test	C	Sec. 7.3.2
R6	Initial Average Bubble Size D	Similarity, Test	C	Sec. 7.3.2
R7	Bubble Size Distribution	Similarity, Test	C	Sec. 7.3.2
R107	Liquid Compositions	Similarity, Analysis, Test	C*	Sec. 6.2.2
R108	Gas Compositions	Test	C*	Sec. 6.2.2
R111	Generate Emulsions	Test	—	—
R23	Optimized Illumination/ Detection	RoD, Test	C	Sec. 7.3.3
R24	Detected Intensities	Test	C	Sec. 7.3.3
R131	Sample Cell Filling	RoD, Analysis	C	Sec. 7.3.1
R132	Sample Material Containment	RoD, Test	C*	Sec. 6.2.2
R136	Lifecycle	Analysis, RoD	C*	—

9 CONCLUSIONS

The present thesis project was dedicated to the development and qualification of the REFOAM, a system aimed to study the implementation of the rheology investigation on wet foams within the Soft Matter Dynamics EC. The idea was to build up a Sample Cell Unit(SCU), which was able to interface with the available optical and diagnostics systems. Airbus DS is working in collaboration with ESA in order to design and verify this concept through the development of a prototype hardware with appropriate system capabilities, to provide valuable results form a scientific point of view.

The aim of the project was the evaluation and verification of the available design, via a series of tests conducted on a demonstrator under laboratory conditions. Part of the study was devoted to assess the functionality of the prototype within the Verification Test Facility (VTF), called elegant Bread Board (eBB). The thesis started from the analysis of the project requirements, written in accordance with the customers expectations and in cooperation with the scientists from the Institut des NanoSciences de Paris (Pierre and Marie Curie University (UPMC) of Paris). Then, a preliminary evaluation of the system design was conducted. During this phase, the design critical areas were identified and possible improvements analysed. Once all the design issues were considered potentially solved, the assembly phase started. The first output was an AIT procedure, which was developed taking into consideration the necessary development tests. During this phase, each critical subsystem was carefully tested to prevent unexpected behaviours in the integration. However, some failures occurred in the testing and a design re-evaluation was necessary. New concepts were analysed and finalised to complete the assembly together with the final AIT procedure, which was concluded with the hardware integration in the VTF. Once the integrated system tests were successfully completed, the verification phase started.

The verification aim was to assess the experiment feasibility, in compliance with the proposed requirements. A Verification Compliance Matrix (VCM) was worked out and the verification methods were selected for each requirement. On the first outputs obtained, the Verification and Validation Plan was established and the verification tests campaign began.

In this chapter the improvements introduced in the design are summarized in Section 9.1, followed by the final consideration illustrated in the Section 9.2. Finally, the recommendations for future developments are presented in Section 9.3.

9.1. DESIGN IMPROVEMENTS

The thesis project started with the analysis of the first proposed design concept for the development of the REFOAM SCU The aim of the study was to determine the assembly and integration with the related development tests. During these phases some open issues were identified.

The first problem was related to the optical system concept. A valid solution for the mirror holder was not available, but only the suggestion to use a hand-made putty material holder to orientate the mirrors was given in the design report. Then, thanks to a deep analysis of the CAD model, different alternatives came up. The possibility to manufacture a 3D printed holder and an aluminium holder was evaluated. Both the concepts were developed and tested and a trade-off was performed to select the option with the best characteristic in terms of costs, manufacturing and performances. The trade-off analysis showed that the optimal concept was the aluminium one, also considering that it is the only solution available at the moment, which is compatible with the future FM requirements. However, also the 3D printed solution was very valuable in the project development: thanks to its rapid prototyping, it allowed to perform a first series of tests during the manufacturing of the final aluminium holder.

Other issues arose during the assembly procedure. The PC SC presented critical problems in the installation of the bottom septa screw, due to an error in the hole threading. Consequently the SC sealing was not achieved, and only the vacuum casting SC was utilized in the assembly tests. The solution to the problem remains an open issue and it will be investigated for future implementations. An other complication concerned the fixation of the motor. According to the design, it was fixed via four pressure screw, however the clamping provoked a permanent deformation of the SCU upper part. A variation in the dimensions of the SCU is a critical issue and it could result in a unsuccessful integration of the SCU in the VTF. The complication can be solved with an improvement in the clamping system or in a change of the SCU designed structure. However, it remains an open issue to be investigated in the next project phases. The last problem faced during the AIT dealt with the assembly of the first actuation system solution. An inaccurate alignment of the encoder foot with the encoder sensor drastically affects the closed loop driving system performances, as proved during the development tests. An improved solution was then introduced. A more compact motor with the same actuation characteristics and an integrated optical encoder was installed in the SCU. The tests proved that the new concept provided the accuracy required by the rheology experiment.

The last critical aspect of the design concerns with the SC membrane. During the development tests the NBR membrane installed in the SC did not withstand the maximum design pressure, and a high leakage rate was measured. To this end, a procurement of a multi-layer elastomer diaphragm was carried out. The new membrane compliance will be assessed after its integration in the SC, when new development and Verification Tests will be performed.

9.2. FINAL CONSIDERATIONS

The objective of this research project was to develop and qualify a new demonstrator SCU dedicated to foam rheology experiments. In particular, the study was focused on the manufacturing and subsequent analysis of the performances of a demonstrator prototype supported by a series of tests. The main research question of the thesis was referred to the possibility of implementing such system in the available Soft Matter Dynamics EC. The answer to that question was provided through different steps developed according to the systems engineering methodologies, which helped in the evaluation of the proposed design. The system and subsystems developed were tested with a bottom-up approach, in order to find out possible critical areas. Test procedures and a test plan were defined to assess the quality of the design proposed. The results were discussed and analysed in collaboration with the science team, in order to determinate the pass/fail criteria. From these evaluations, possible improvements in the design were introduced and a new iteration of the testing phase was finalised. The study was concluded with a verification test campaign. All the results obtained were converted into a VCM, thanks to which the design compliance with the project requirements was assess.

The systematic approach defined by the use of the SE methodologies was tremendously helpful. The division in WPs was extremely useful in the division of the work tasks and and their time frames definition. The Gantt Charts supported the project and test planning thanks to the visualization of the links among the tasks, the time dedicated to each activity and the deadlines tracking. The AIT procedures were fundamental tools in the hardware assembly, and essential in the identification of critical areas and development tests. The bottom-up approach made clear the need of design improvements, reducing the number of unexpected failures during the AIT phase. Finally, the compliance analysis carried out through the VCM was immensely supportive in the verification strategies characterization, the requirements identification and tests development. Thanks to this tool, a continuous evaluation of the open requirements was possible, and in the light of the final results the next steps of the project were evidently specified.

However, during the research some delays occurred in the procuring and manufacturing phases, which prevented the possibility to complete the verification and validation of the system in the established thesis time frame. But, the fully functionality of the hardware was proved and the needed improvements in the design were defined. The ultimate system will be assembled and integrated in the following weeks. The changes introduced in the design will ensure the success of the Verification and Validation campaign. The REFOAM SCU will be presented at ESA experts in September, with the improvements and suggestions for a potential FM. This thesis will be part of the Airbus DS deliverables to ESA and will be handed in with the hardware at the end of the study. The final agreement on the eventual beginning of a REFOAM EM and FM will be based on the results obtained.

9.3. Recommendations

In the light of this work and future EM and FM development, some recommendations are required in the hope to optimize the next REFOAM project phases.

As discussed in the previous chapters, the Validation tests were not performed. However, these are essential in the system qualification and an accurate planning and test procedures need to be defined. Considering the scientific output of the project, it is really recommended to develop them in close collaboration with the science team, which will help in the analysis of the results, identification of possible problems and required improvements. In addition, the science experts could be involved in the second iteration of the verification campaign, adding valuable advice in the process.

In this thesis the attention was focused on a minimum number of tests considered essential for the hardware qualification. However, it is suggested to increase the number of tests in the available time in order to provide a more reliable proof to prove the performances of the system.

With regard to the future design development, a first recommendation is about the SC top cover. It is held by the SCU top cap, fixed via five screws, a solution proved to be inconvenient during the assembly. To this end, it is highly recommended to fix it via 4 screws positioned at the four top window corners. It will prevent possible leakage problems, caused by adjustments made to the other subsystem after the SC filling. Another suggestion concerns the SCU design. In particular, the deformation in the SCU due to the motor clamping can be overcome with a new design solution in the SCU upper part. It can be modified in a way that the arm supporting the motor is not terminated at the motor edge, but it is substituted with an unique stripe structure that ends at the right SCU side. This will improve the structure stiffness preventing any possible deformation in the clamping.

As far as the project management concerns, keeping track of the schedule is a fundamental aspect in order to respect the deadlines imposed. To this end, a continuous risk mitigation analysis can help in dealing with possible unforeseen in a systematic way. In addition, the implementation of the SE methodologies are strongly suggested, together with monthly progress reports considered a good way to monitor the project evolution and to arrange the following steps. Finally, it is highly recommended to have a direct communication with the suppliers ensuring trusting relationships to avoid misunderstanding and delays in the delivery.

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APPENDICES

A
Project Planning

This Appendix presents the MSc Thesis Gantt Chart in Figure A.1. There, each bar is related to a specific work package. A different amount of time to accomplished each task was estimated. This schedule was utilized to keep progress of the work development and deadlines.

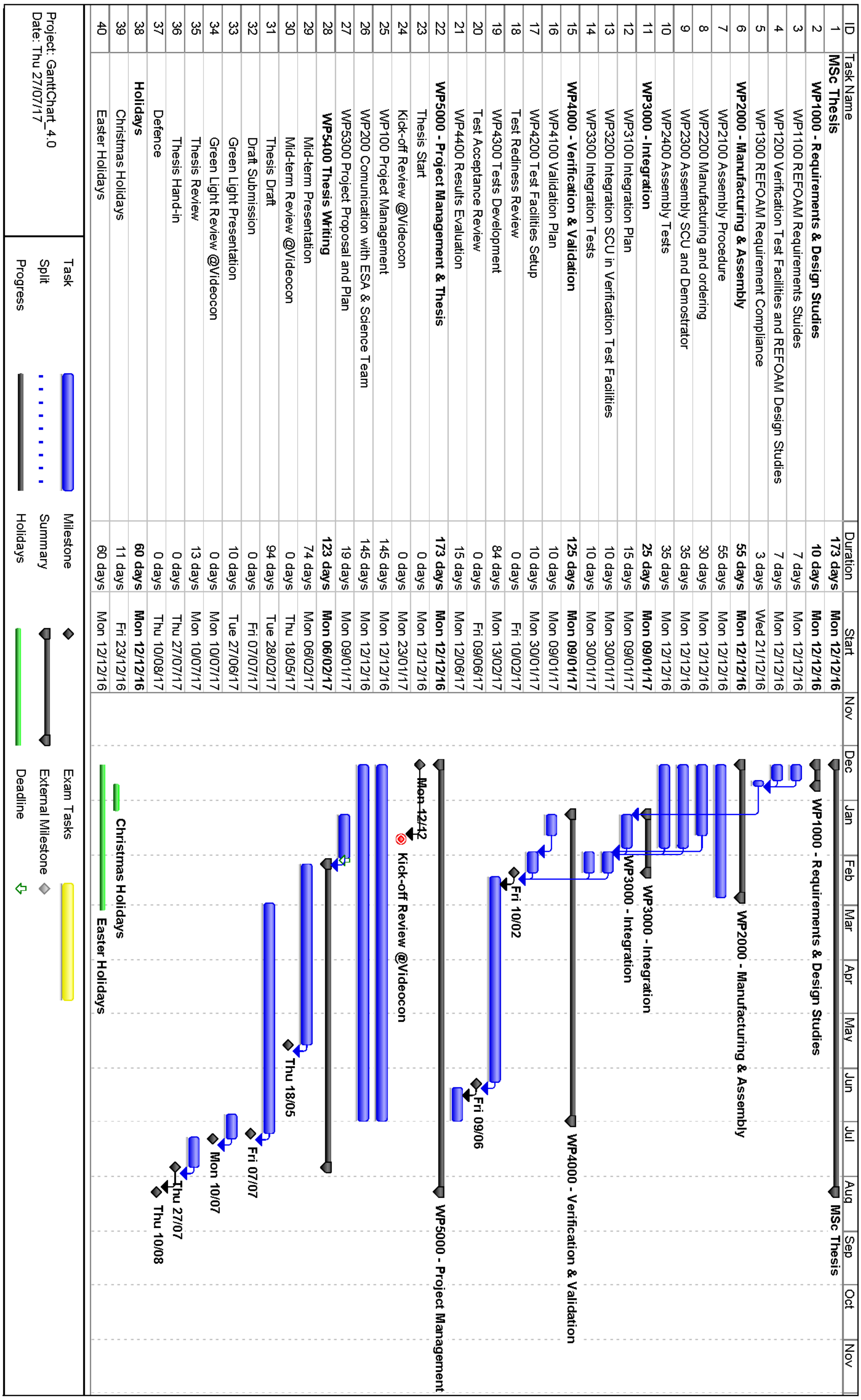

Figure A.1: MSc Thesis Gantt Chart.

B

REFOAM Requirements

In this Appendix the REFOAM project requirements are attached. The requirements are presented through the *"Scientific Requirements and Concept Trade Off"*, Airbus DS internal report [Höhler, 2016]. The report was written in collaboration with Prof. Höhler, who was responsible for the scientific aspects of the research. The tables are divided per function and subsystem, and the requirements are categorized as Minimum, Optimum and Nice to Have.

The pdf report, from page 12 to 21, follows.

3 Scientific Requirements

All requirements are recorded in format given in Table 3-1.

Table 3-1: Requirement Format

Requirement ID	**Title**	**Closeout**
Text		

The requirement ID shall be unique through all issues of this document. Requirement IDs established before the start of this study (i.e., during proposal preparation) are preserved and the numbers from 0 to 99 are reserved for these. Requirements established in issue N of this document will get numbers in the range N00 to N99. In this issue 2 the new requirements will have IDs larger than R200. This allows tracking changes to one requirement even if the layout / outline of the document change drastically.

The title and text describe the requirement.

The Closeout specifies the Verification Strategy for the requirement. Possible Closeouts are Analysis, Development (Breadboard) Test, Review of Design, Inspection, (Demonstrator) Test, and Validation Test. A note of "depends on concept" means that the exact verification is expected to depend on the specific concept / design of the Demonstrator. A notion of Similarity means that solutions from other experiments shall be transferred as-is.

The difference between the three test categories is:

- Development or breadboard test need to be mostly concluded before selection of the best concept or latest before the design review. Some can be performed with the Demonstrator for parameter optimization or selection between design alternatives.
- (Demonstrator) Test is the typical test after integration to verify all functions and performance of the Demonstrator. Such tests generally rely on the evaluation of engineering values.
- Validation Tests have to be defined by the scientist. They will conclude the study by validating the feasibility of the original intended Objective and Experiments. These are usually tests which produce a scientific result, instead of raw engineering values.

The requirements are grouped in topical sections. Within each section requirements are categorized as Minimum, Optimum, Nice to have. Where minimum means an absolutely critical requirement, optimum expands the science scope, and nice to have enhances the flexibility of the experiment.

Note: Unless explicitly specified the requirements presented here are those that shall resemble as close as possible those that will apply to a potential flight model of the REFOAM experiment. The Demonstrator and the Verification Facility will not fulfil all of these requirements.

3.1 Demonstrator Objective

3.1.1 Minimum

R1	**Rheology of Foam**	**Validation Test**
The demonstrator shall allow the uniaxial deformation of foam and support the assessment if		

and how a rheology experiment cell (see requirements below) can be implemented in the Soft Matter Dynamics (or following) FSL EC.

3.1.2 Nice to have

R101	**Rheology of Emulsions**	**Validation Test**
The demonstrator shall allow additionally the deformation and support the assessment for emulsions.		

3.2 Experiment Definition

3.2.1 Minimum

R2	**Jamming Transition**	**Validation Test**
The transition from jamming induced solid like to liquid like behaviour in soft matter shall be investigated.		
R3	**Characterisation and Control Parameters**	**Validation Test**
The transition shall be characterised in terms of elastic or plastic response of the sample to a temporally applied strain ε, depending on liquid-fraction φ		
R31	**Critical Yield Strain**	**Validation Test**
For a given liquid fraction φ lower than the critical liquid fraction φc the critical yield strain εy shall be determined above which irreversible plastic strain response sets in.		

3.2.2 Optimum

R102	**Critical Liquid Fraction**	**Analysis, RoD**
Lower and upper limits to the critical liquid fraction φc, where the critical yield strain εy vanishes, shall be determined.		
R32	**Strain Relaxation**	**Analysis, RoD**
For liquid fractions φ close to φc and strain steps of ε < εy the relaxation time after the strain cycle shall be measured. These cycles shall be repeated many times (of the order of 100) to study strain induced self-organisation in the packing. *Notes: This investigation involves* → *many (order of 20) liquid fractions below and close to φc,* → *long measurements (order of 10 minutes) are necessary to confirm scaling law,* → *suitable compositions to adjust stability of foam.*		

R33	**Plastic Rearrangement**	**Similarity, Development Test, Test**
For a given liquid fraction φ and strain steps of ε >= εy the duration of plastic rearrangement events and their temporal correlation shall be measured. *Note: Time Resolved Correlations shall be computed, the algorithm will be different from the one required for FOAM-C data processing. This requires frame rates >= 10 kHz* [RDD4 §3.2.1.15, §3.2.3.12].		

3.3 Sample Material Properties

R4	**Generate Foams**	**RoD, Test**
The feasibility study shall consider in-situ foam generation.		
R5	**Maximum Liquid Fraction**	**Review of Design**
Foams with liquid fractions φ up to 45 % of the sample volume (%-full scale, %-fs) shall be investigated.		
R103	**Minimum Liquid Fraction**	**Review of Design**
Foams with liquid fractions φ greater equal 10 %-fs shall be investigated.		
R104	**Liquid Fraction Accuracy**	**Review of Design, Similarity**
The error of the liquid fraction φ shall be smaller than ±0.5 %-fs.		
R105	**Liquid Fractions**	**Analysis, RoD**
At least six liquid fractions shall be used: 30 %-fs, 36 %-fs, 40 %-fs, TBD %-fs, TBD %-fs, TBD %-fs.		
R6	**Initial Average Bubble Size D**	**Similarity, Test**
The foam shall have an initial average bubble diameter D of the order of 100 µm.		
R7	**Bubble Size Distribution**	**Similarity, Test**
The foam shall have an amorphous structure. A poly-disperse distribution of bubble diameters of roughly 0.3 to 2 times average diameter is considered suitable		
R106	**Composition Chemicals**	**Similarity**
The chemicals to be considered for liquid compositions are pure water (TBD), TTAB (TDB), air (TBD) and C6F14 (TBD)		
R107	**Liquid Compositions**	**Similarity, Analysis, Test**
The liquid used for the foam shall be TTAB 5 g / L. That is a mixture composed of 5 gram of TTAB per 1 litre of water. Accuracies are TDB. A drop (volume TBD) of liquid C6F14 shall be added to compensate for losses of C6F14		

vapour over the life time of the sample.		
R108	**Gas Compositions**	**Development Test**
The gas used for the foam shall be 60 vol-% Air and 40 vol-% C6F14 (TBC). Accuracies are TBD.		
R109	**Gas Pressure**	**Similarity**
The gas shall be added to the composition at ambient atmospheric pressure (TBD). Accuracy is TBD.		

3.3.1 Optimum

R110	**Liquid Fractions**	**Similarity**
Additionally all liquid fractions from 28 % to 45 % in steps of 1 %.		

3.3.2 Nice to have

R111	**Generate Emulsions**	**Test**
The feasibility study shall consider in-situ emulsion generation. All characteristics of the emulsions are TBD. The range of continuous phase volume fractions to be investigated is the same as for foams.		

3.4 Diagnostics

R9	**Characterisation of plastic deformation**	**Similarity**
The strength of the plastic response shall be quantified by using the intensity autocorrelation function on scattered laser light speckle patterns and comparing the decorrelation in the strained state as well as in the relaxed state after the strain cycle to a theoretical model.		
R8	**Multi-Speckle DWS**	**RoD**
Elastic / plastic behaviour shall be distinguished using homodyne multi-speckle DWS light scattering.		
R20	**Observation Volume (L^3)**	**RoD**
The deformation / observation volume shall be located at the centre of one outer boundary of the sample. The observation volume shall at least have a size of L x L x L, where L is 20 average initial bubble diameters D.		
R22	**Backscatter DWS**	**RoD**
The DWS measurement should be performed in backscattering configuration.		

R23	**Optimized Illumination / Detection**	**RoD, Development Test, Test**
The laser illumination and scattered light collection optics needs to be adjusted to the detection sensor / optics to optimize image parameters: i.e. speckle number and intensity.		
R25	**Coherence Length**	**Similarity**
The illumination laser shall have a correlation length of at least 1 m.		
R26	**Intensity Stability**	**Similarity**
Intensity stability shall be better than 1 % over ten minutes.		
R28	**Number of Speckles**	**Similarity**
At least 300 (target: 1000) speckles shall be recorded by the detector. Each detector shall record a number of speckles per pixel = 2.5.		
R24	**Detected Intensities**	**Demonstrator Test**
The scattered light should be collected by a line camera in such a way (taking into account illumination, collection optics, sensor sensitivity, ROI, calibration) that analysed intensities → have an ensemble average intensity between 1/6 and 1/4 of the sensor maximum → have an individual temporal mean intensity that is homogeneous over the ensemble (within ±10% of the average). → follow a Poisson distribution with TBD deviations.		
R27	**Detector Resolution**	**RoD**
The sensor shall have at least 8 bit resolution		
R29	**DWS Detector Frame Rate**	**RoD**
The sensor shall allow recording with a frame rate of at least 10 kHz.		
R112	**DWS Recorded Frames**	**RoD**
The sensor and recording system shall allow continuous recording with the maximum frame rate.		
R113	**Measurement of bubble size**	**RoD**
It shall be possible to observe one boundary of the foam sample with imaging optics to determine the average bubble size and size distribution.		
R114	**Field of View (FoV) of the overview camera (2L x 2L)**	**Similarity**
At least an area of diameter 2 L at the centre of the boundary surface shall be observed by the imaging optics (where L is 20 average initial bubble diameters D). Note: Order of 1000 bubbles will be visible in the FoV.		

<table>
<tr><td>R115</td><td>Optical Resolution</td><td>Similarity</td></tr>
<tr><td colspan="3">The FoV of the imaging optics shall be resolved with better than 1/6 of the average initial bubble diameter D.</td></tr>
<tr><td>R116</td><td>Intensity Resolution</td><td>Similarity</td></tr>
<tr><td colspan="3">The sensor used with the imaging optics shall have at least 8-bit per pixel intensity resolution.</td></tr>
<tr><td>R117</td><td>Camera Frame Rate</td><td>Similarity</td></tr>
<tr><td colspan="3">The sensor used with the imaging optics shall be able to record single frames, with a frame rate larger or equal 1 frame per second (fps).</td></tr>
<tr><td>R201</td><td>Camera Exposure</td><td>Similarity</td></tr>
<tr><td colspan="3">The sensor used with the imaging optics shall support exposure times shorter or equal 1 ms with global shutter. Longer exposure times up to 1 s shall be supported.</td></tr>
</table>

3.4.1 Optimum

<table>
<tr><td>R118</td><td>DWS Detector Frame Rate</td><td>Similarity</td></tr>
<tr><td colspan="3">The sensor shall allow recording with a frame rate of at least 10 kHz [Derived from RDD4 §3.2.1.15 and §3.2.3.12]</td></tr>
<tr><td>R120</td><td>Synchronization</td><td>RoD</td></tr>
<tr><td colspan="3">It shall be possible to synchronize the acquired diagnostics data with the actuation of the sample. At least the moment in time (with respect to recorded detector frames) of a state change of the actuation has to be known to less than 1/10 of the maximum rise time (target: resolution of the DWS detector frame rate).
Note: the relevant states are <initial>, <compressed>, <expanded>, <compressing>, <expanding>.</td></tr>
<tr><td>R121</td><td>Measurement of bubble size</td><td>RoD</td></tr>
<tr><td colspan="3">It shall be possible to observe the same boundary of the foam sample with imaging optics as is used for observation with light scattering diagnostics.</td></tr>
<tr><td>R122</td><td>Field of View (FoV)</td><td>Similarity, RoD</td></tr>
<tr><td colspan="3">The FoV of the imaging optics shall contain the whole boundary surface of the foam sample.</td></tr>
<tr><td>R123</td><td>Optical Resolution</td><td>Similarity</td></tr>
<tr><td colspan="3">Target: The FoV of the imaging optics shall be resolved with better than 1/10 of the average initial bubble diameter D.</td></tr>
</table>

3.4.2 Nice to have

R124	**Overview Camera DWS Detector Frame Rate**	**Similarity**
In case the overview camera (OC) is used for multispeckle DWS the camera sensor shall allow recording with a frame rate of at least 30 Hz in the region of interest (ROI)		
R125	**Epi Illumination of Optical Images**	**Similarity**
The optical diagnostics shall record reflected light from the foam sample. For instance via in-line illumination or suitable illumination / camera configuration.		

3.5 Sample Actuation

R19	**Strain Mechanism**	**RoD**
The strain shall be applied by a piston.		
R15	**Deformation Volume (L x 3L x 3L)**	**RoD**
The deformation shall be applied to a part of the sample volume probed by the DWS backscattering diagnostic. The deformation volume / piston design shall consider the following characteristics (know-how by science expert) → be centred around the observation volume → have an initial gap width L (at least 20 average bubble diameters D), → an area with at least 3L diameter (for instance 3L x 3L square or 3L diameter circle) → leave sufficient free space L to the bounding walls to allow an undisturbed flow of foam around the piston during the strain cycle.		
R126	**Gap Width Accuracy (L)**	**RoD**
The gap width L defined by the initial position of the strain piston shall be achieved with an error <= 5% of L and a repeatability <= 0.1 % (target 0.05 %) of L.		
R14	**Uniaxial Deformation**	**RoD**
The strain shall be applied as a well-defined local homogeneous uniaxial deformation of the foam sample. This means the deformation shall ideally resemble that of a perfectly incompressible and elastic piece of rubber, i.e., not change the volume of the sample and the sample shall respond with a symmetric flow perpendicular to the central axis through the deformation area. *Note: Only a part of the whole foam sample is actually deformed in a controlled way. Still the total sample volume shall stay constant.*		
R10	**Strain Amplitude**	**RoD**
A well-defined (repeatable, accurate) step-like strain cycle with amplitude $\lvert\varepsilon\rvert$ up to 5 % (target 10 %) of the original gap width L shall be applied to the foam.		

R127	**Strain Direction**	**RoD**
It shall be possible to apply positive and negative strain. That means it shall be possible to compress as well as expand the foam sample from the original gap width L.		
R11	**Strain Resolution**	**RoD**
The applied strain ε shall be adjustable with a resolution smaller than 0.3% (target 0.1 %) of the original gap width L.		
R17	**Strain Accuracy**	**RoD**
The applied strain shall be adjustable with an error smaller than ±0.15 % (target 0.05 %) and repeatability <= 0.1 % (target 0.05 %) of the original gap width L.		
R18	**No Overshoot**	**depends on concept**
Within the limits of required strain accuracy the actuator implementation and control system shall ensure that → all applied deformations are always smaller or equal to the setpoint. → no intermediate deformations larger than the final deformation are applied. *Note: Several actuator mechanisms have inherent overshoot, for instance almost all stepper motors independent of their technical details overshoot due to inertia. Other actuators might be free of inherent overshoot but the control algorithm or elements in the feedback loop might produce an overshoot. This requirement has been carefully worded to actually allow small overshoot as long as this does not invalidate the measurement of lower limits to* εy.		
R12	**Rise Time**	**RoD**
The rise time to apply and to release the strain each shall be shorter or equal to 0.1 seconds. *Note: This corresponds roughly to 1/10 of the typical time between two "typical" rearrangement events in the foam samples of interest.*		
R13	**Strain Duration**	**RoD**
The duration of applied strain shall be adjustable → between 0 seconds and 10 seconds → in steps of at most 0.1 seconds → with an accuracy of better than ±0.05 seconds.		
R128	**Volume Change**	**Analysis**
During the strain cycle the total volume of the sample material shall change by less than the required liquid fraction accuracy.		
R129	**Velocity Field Homogeneity**	**Test**
The flow velocity of the foam shall deviate from the perfect by less than ±20 % over the observation area. *Note: This is derived from development tests performed by the science expert using high precision laboratory equipment with suitable adjustment capabilities.*		

3.5.1 Optimum

R130	Strain Duration	Similarity
The duration of applied strain shall be adjustable → between 0 seconds and 600 seconds (10 minutes)		

3.6 Sample Cell Properties

R131	Sample Cell Filling	RoD, Analysis
The Sample Cell design shall consider the filling with science sample liquids and gasses or alternatively foam compositions with the required accuracies on liquid fraction over the relevant lifetime.		
R132	**Sample Material Containment**	**RoD, Development Test, Demonstrator Test**
The Sample Material shall be contained within a Sample Cell.		
R133	**Material Compatibility**	**Similarity, Demonstrator Test**
The materials in contact with the sample shall not deteriorate the scientific properties of the sample composition. Known good materials are: Glass, stainless steel, gold, Viton, Polycarbonate, PTFE, cured epoxy resins.		
R134	**Surface Treatment**	**Similarity**
The viscous friction at the cell wall shall not be larger than TBD. The foam wetting angles should be ideally below 10°. Viscous friction can be reduced by hydrophilic surface coating according to TBD process. *Note: The "Linear and non-linear wall friction of wet foams" has been published in Soft Matter, 2015, 11, 368.*		
R135	**Diagnostics Compatibility**	**RoD**
The Sample Cell shall be compatible with the diagnostics: → wave length → optical path → diagnostics concept *Note: Compatible means that neither the sample cell shall be degraded by the diagnostics, nor shall the diagnostics be degraded beyond required performance by the sample cell. Examples of bad design would be the selection of a sample cell material along the optical path that is not transparent for the used wavelength, or the use of material that is destroyed by the observation radiation like excessive absorbed heat or UV light for polycarbonate.*		

3.7 Operational Scenario

R34	**Soft Matter Dynamics Compatibility**	**RoD**
The technical implementation and feasibility study shall consider the capabilities and interfaces of the FSL EC Soft Matter Dynamics and extension concept based on on-orbit replaceable Sample Cell Units.		
R35	**Operational Environment**	**Analysis**
The feasibility study shall consider performance of the experiment under microgravity conditions in human space flight.		
R136	**Lifecycle**	**Analysis, RoD**
The feasibility study shall consider at least Ground Operations, Transport, Launch, On-orbit Operations, Storage and Disposal.		

3.8 Obsolete Requirements

R16 (integrated in R15)	**Deformation Boundaries**	**NA**
To prevent edge effects the observation volume shall be located at least one sample thickness (extent parallel to the deformation direction) away from the edges of the deformation boundaries (that are parallel to the deformation direction).		
R21	**Observation Boundary**	**NA**
The laser illumination and detection paths should be applied at the boundary of the sample where the deformation / observation volume is located.		
R30	**Objectives**	**NA**
The feasibility study shall consider three experiment objectives.		

C
Assembly, Integration and Testing Procedure

In this Appendix the second iteration of the AIT procedure is provided, Figures C.1 and C.2. In this procedure the LL10 is substituted by the LL06, consequently the encoder foot and the encoder sensor installation is not taken into consideration. The LL06 is an unique part and it is assembled in the SCU after the SC integration.

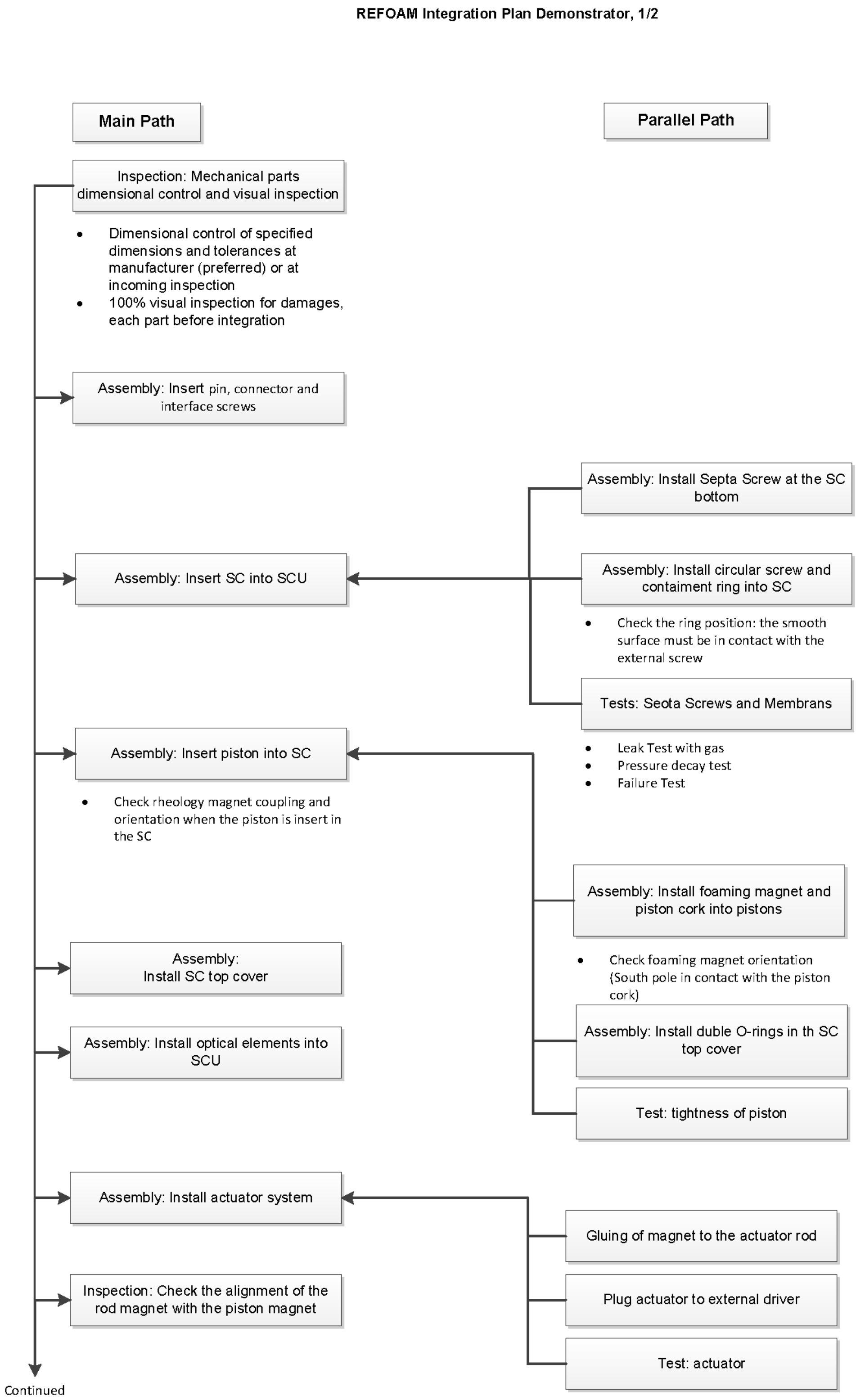

Figure C.1: REFOAM AIT Procedure 1/2 - Second Iteration.

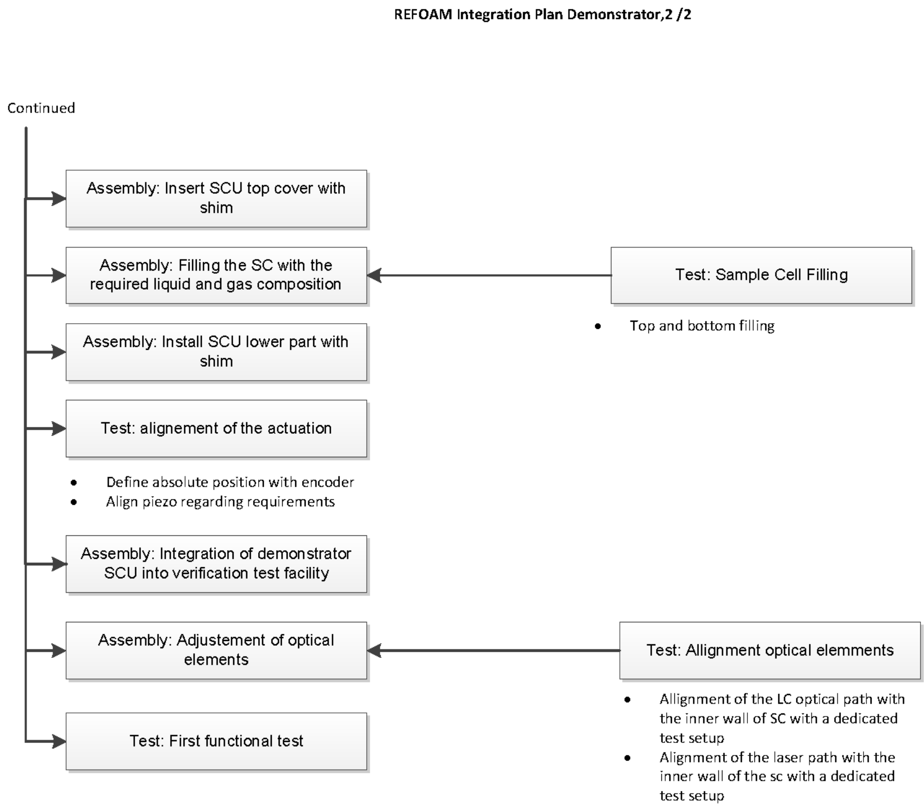

Figure C.2: REFOAM AIT Procedure 2/2 - Second Iteration.