Foam Generation and Sample Composition Optimization for the FOAM-C Experiment of the ISS

Rodrigo Carpy¹, Gerold Pickera, Benjamin Amanna, Hans Ranebo, Sébastien Vincent-Bonnie, Olivier Minster, Josef Winter, Jan Dettmann, Luigi Castiglione, Reinhard Höhler, Dominique Langevin

¹ASTRIUM Space Transportation, Department of Fluid Physics, Friedrichshafen, Germany
²European Space Agency, Human Spaceflight, ESTEC, The Netherlands
³Laboratoire de Physique des Matériaux Divisés et des Interfaces FRE 3300 CNRS-Université Paris-Est, France
⁴Laboratoire de Physique des Solides, Université Paris Sud, Orsay, France
⁵Institut des NanoSciences de Paris, UMR 7588 CNRS-UPMC Université Pierre et Marie Curie - Paris, France

FOAM-C Science Team Members
Université Paris Sud (FR), Université Pierre et Marie Curie (FR), Trinity College (IR), Université de Liège (BE), Université Paris-Est (FR), University of Pennsylvania (US), University Kyoto (JP), Moscow University (RU), MPI Golm (DE), IFP (FR), IENI Genova (IT), Unilever (UK), Nestlé (CH), Twente University (NL), St Petersburg University (RU), UTC (FR), Florence University (IT), Lafayette College (US), Alberta University (CA), Marseille University (FR), University Madrid UCM (ES), Thessaloniki University (GR), Loughborough University (UK), DLR (DE), MPI Goettingen (DE), Duke University (US)

Abstract: End of 2009 and early 2010 a sealed cell, for foam generation and observation, has been designed and manufactured at Astrium Friedrichshafen facilities. With the use of this cell, different sample compositions of "wet foams" have been optimized for mixtures of chemicals such as water, dodecanol, pluronic, aethoxisclerol, glycerol, CTAB, SDS, as well as glass beads. This development is performed in the frame of the breadboarding development activities of the Experiment Container FOAM-C for operation in the ISS Fluid Science Laboratory (ISS). The sample cell supports multiple observation methods such as: Diffusing-Wave and Diffuse Transmission Spectrometry, Time Resolved Correlation Spectroscopy [1] and microscope observation, all of these methods are applied in the cell with a relatively small experiment volume <3cm³. These units, will be on orbit replaceable sets, that will allow multiple sample compositions processing (in the range of >40).

1. Introduction
Foaming processes are used on a large scale in the mining industry, for fire fighting and food production, but they can also be limiting factors for improved efficiency in many chemical industries like food and cosmetics production, but also in the oil industry. The experiment FOAM-C (Foam and Optics Mechanics - Coarsening) studies the coarsening process of aqueous wet foam as a function of liquid volume fraction and liquid characteristics. Microgravity allows investigating highly wet foam, which cannot be studied in detail in the earth laboratory due to drainage. Previous experiments have been performed in the frame of the FOAM project, such as parabolic flight campaigns, the Foam-S on the ISS (focused on foams stability) or the experiments in the MAXUS 6 rocket [2]. Now an extensive foam coarsening experiment under microgravity conditions for several types of probes and...
measurement periods as long as 24hrs for each sample experiment foam is foreseen to be performed on
the ISS.

For the experiment on the ISS, where the storage times before experiment execution can be of
several months, one of the crucial development points is the foam generation and quality of the
generated foam. The foaming device shall be capable of generating wet foams with different surfactants
and with a homogeneous initial size of foam bubbles (<100 µm), as described later in the materials and
methods section.

More than 40 samples are foreseen to be processed for the first experiment mission to ISS. A
concept of on-orbit replaceable sealed samples has been developed, avoiding the need of a fluid waste
reservoir or on orbit sample cleaning.

The foreseen experiment sequence for the on-orbit execution is: 1) ground sample preparation with
pre-defined filling procedures, concentrations and liquid fraction, 2) on-orbit foam generation, 3) foam
coonsering observation with overview camera, diffusing wave spectroscopy in reflection (DWS) and
transmission (DTS) and time resolved correlation spectroscopy (TRC), 4) repeat steps 2 and 3 for all
samples is present.

The summary of breadboarding tests performed to demonstrate the foam generation capabilities of
the system with the different experiment liquids is presented within the following chapters, additionally
the initial system characterization to verify compatibility of the optical diagnostics concept to the foam
coonsering observation methods have been performed.

2. Materials and Methods

The materials used for the experiment are: Dodecanol, increasing the surface viscoelasticity of the
bubbles and probably decreasing the coarsening rate; Glycerol increasing the bulk viscosity and
decreasing the coarsening rate; TTAB ionic surfactant, chemically very stable; and SDS as backup of
the TTAB. Additionally, the following chemicals were tested: C12G2, as non-ionic surfactant in backup
of TTAB; Pluronics a polymeric surfactant that adsorbs irreversibly at the air-water surface;
Aethoxisclerol a pharmaceutical product for varicose veins; and Glass beads to study how a network of
particles, linked by attractive capillar bridges, affects coarsening and bubble rearrangement dynamics.
All of these chemicals, except Aethoxisclerol were tested as mixtures with different pure water
concentrations. For the Diffusing Wave Spectroscopy Backscattering and Transmission measurements,
Gillette shaving foam was used.

The setup for the foaming tests consists of a polycarbonate cell with thickness of 2mm and outer
dimensions 53 x 25 x 20 mm (see Fig. 1), which contains a moving piston. The cell is cleaned with
ethanol and an ultrasonic bath prior to filling. After the cleaning, the cell is filled with the desired
concentration and liquid fraction and sealed. The sealing of the sample with a viton o-ring and screws,
has three main advantages, which are: the liquid volume and concentration, are well defined and kept
known during all phases of the experiment. The tests can be repeated with the same sample, as often as
needed; and additionally there is no liquid waste, which would limit the experiment life on-orbit, due to
limited available volume for liquid waste.

The foam is generated by a shearing force, occurring at the gap (1mm on each side) between the
moving piston and the sample cell body. The piston, which contains a set of magnets, within its body, is
magnetically coupled to the outside of the cell. The piston is driven with a frequency of 10Hz in all
cases. The foam sample thickness L=1.1cm, height is 1.1cm and width 1.4cm. All experiments are
carried out under normal gravity conditions at a temperature of 21±0.5°C.
Fig. 2 (Left) Test Setup of the sample under observation. (Right) cross section of the experiment sample

The methods used for the observation (see Fig. 2) of the foam coarsening are, a CCD-camera for top-view observation of the first layer of bubbles, in the upper window of the sample cell, with six LEDs accurately placed below the sample, to provide both enough contrast and illumination for bubble observation. The additional light-scattering measurements (DWS, DTS and SVS) were illuminated with an expanded laser light beam (0.8mm on the foam surface), with a wavelength $\lambda=532$nm. The wavelength has no influence for the extrapolation ratio $z_0$, or the transport mean free path, $l^*$ for aqueous foams as known from [3].

3. Results

The foams were prepared in different concentrations, such as: Dodecanol 2% of total mass, Glycerol 25% volume fraction, SDS 8g/l, TTAB 4.5g/l, C12G2 0.2g/l, Pluronics 17.5g/l, and the glass beads 15% of fraction of liquid. This means, a total of 13 sample compositions were tested. For each composition, different liquid fractions (LF) were tested with increments of 1% of liquid fraction for the 5-10% range and increments of 10% for 10-50%. Each test has been repeated 3 times to verify reproducibility. This sums up 390 measurements.

The success criterion was based on overview pictures of the foam sample cell (Fig. 3) for the study of the coarsening process, the required initial sample characteristics, have been as follows: an average bubble size <100 µm, maximum bubble size <5*average diameter, and a standard deviation between 0.3-3times the average bubble size.

Fig. 3 (Left) Example of homogeneous foam, (Right) Non-homogeneous foam. TTAB+Dodecanol+H$_2$O.
The samples with SDS provided the widest range of liquid fractions for which the foam generation is possible, in some cases with liquid fractions as low as 5%. Note that SDS is not as chemically stable as the TTAB (hydrolysis is present), which may be a problem if the solutions are studied only weeks after preparation. Tests carried out for the samples with TTAB have provided also high foaming properties and compatibility to the success criteria.

![Graph 1](image1.png)  
*Fig. 4* Characteristics immediately after foaming of (left) TTAB + Water, (right) TTAB + Dodecanol + water.

![Graph 2](image2.png)  
*Fig. 5* Characteristics immediately after foaming (left) TTAB + Dodecanol + glycerol + water, (right) TTAB + glass beads + water.

The results obtained with solutions containing C12G2, C12G2+Dodecanol + glycerol + water, pluronic surfactants and Aethoxisclerol were similar.

After the experiments performed to identify the liquid compositions and liquid fractions where foams of the required characteristics could be obtained, additional experiments with the setup, were executed for the additional light scattering methods. In this case, measurements under normal gravity conditions have been performed (Fig. 6) similar to [4], where comparison with other validated test setups and calculation of the average bubble size diameter using Gillette shaving foam has been performed.

From the output of the multiple tau autocorrelation the Siegert equation is used, then the formulas for $g_1(\tau)$ for backscattering and transmission are used in line with [5] and [7].
Fig. 6 Multiple-Tau Autocorrelation function of Gillette foam after 20mins for Diffusing Wave Spectroscopy Backscattering (upper-left) and Transmission (upper-right) and comparison. The logarithm of the correlation function g1 roughly scales linearly with delay time in the case of transmission, and as the square root of delay time in the case of backscattering. This is consistent with previous light scattering experiments with coarsening foams. The sample is Gillette shaving foam, at an age of 20min.

Following the reference measurements, following tests have been performed for functionality of optic and light scattering diagnostics. In this example, the coarsening of a probe of SDS+water with a liquid fraction of 20% has been evaluated. Following on the simplification applied in [6] where $T=5l^*/3L$ the sample shows a linear behavior between the transport mean free path of light ($l^*$) versus the average bubble diameter (Fig. 7). The relationship for this probe was $l^*=(1.2\pm0.05)d$. The coefficient of this law will be refined in further analyses, taking into account a more accurate description of the optical boundary conditions. Out of this graphs, a clear short-time coarsening of the foam SDS+water (within 5 minutes), compared with other foams where times above 1000min [7] is observed. The bubble growth illustrated in Fig. 7 is different (linear) from the parabolic law usually observed in coarsening foams, possibly due to drainage effects. The growth rate of the bubbles under microgravity where drainage will not be present is one of the parameters to be evaluated during the ISS Foam-C experiment. The results are comparable to similar measurements performed within [8] where a bubble size of $\approx140\mu m$ is measured for a SDS sample with LF15% after 120 seconds.
Fig. 7 (Left) Transport mean free path vs. average bubble diameter obtained by viewing first plane of bubbles for SDS+water LF 20%. (Right) Continues line shows the diameter of bubbles over time observed on the first plane of bubbles, dashed line shows the calculated diameter from measured static light transmission. Note: All measurements under gravity conditions.

4. Conclusions
In summary, we have described series of measurements for foam generation within a sealed volume, with different samples varying the composition, concentrations and liquid fractions with an objective of generating homogeneous foams with an average bubble diameter below 100µm. At the beginning of the measurements, it was not possible to define, which of these samples composition could be used for foam generation to fulfill the target foam homogeneity and size. After this campaign, an envelope containing the ranges and compositions of fluid, for which wet foams can be generated with the described test setup, has been defined and will be used as a baseline for the future development of the Experiment Container Foam-C for the International Space Station. In this sense, the results of these investigations have been successfully finished. The optic diagnostics have provided as well initial measurements and compatibility with previous theories or measurements with e.g. shaving cream.

An additional parabolic flight campaign is foreseen in spring 2012 to continue the investigations of the generation of aqueous foams under microgravity, as well as, the use and calibration of multiple light-scattering methods, in view of the Foam-C mission preparation for the ISS.

Acknowledgements
The industrial activities of the FOAM-C project are funded, and the science team is supported, by ESA. We are thankful to the support of Laboratoire de Physique des Matériaux Divisés et des Interfaces for the development of the optical diagnostics methods.

References
[1] Cipelletti -et al J. Phys Cond Mat 15, 257(2003).
[2] Saint-Jalmes, A., Marze, S., Safouane, M., Langevin, D., Cox, S., Weaire, D. Proceedings of the 17th ESA symposium on European rockets, Sandefjord, Norway, ESA SP-590 573.
[3] Moin U.Vera, Arnaud Saint-James, and Douglas J. Durain, Applied Optics 40, 4210 (2001)
[4] S. Cohen-Addad and R. Höhler, Phys Rev. Lett. A86, 4700 (2001)
[5] D.J. Pine, D.A. Weitz, J.X. Zhu, E. Herboldzheimer, J. Phys (Paris) 51, 2101 (1990)
[6] D. J. Durian, D.A. Weitz, and D.J. Pine, Science 252, 686 (1991)
[7] D.J. Durian, D.A. Weitz, and D. J. Pine, Phys Rev. A 44, 7902 (1991)
[8] A. Saint-Jalmes, M.L. Peugeot, H. Ferraz, D. Langevin, Surfaces A, 263, 2 (2005)