17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.

SpaceOps-2023, ID # 585

The Operational Challenges of the Multiscale Boiling Investigation on the International Space Station

Denis Van Hoof[a*], **Carla Jacobs**[a]

[a] *Services Department, Space Applications Services, Leuvenseteenweg 325, 1932 Sint-Stevens-Woluwe, Belgium.*
* Corresponding Author: Denis.VanHoof@spaceapplications.com

Abstract

Multiscale Boiling is a European Space Agency funded experiment performed on-board the International Space Station between 2019 and 2021 that aimed at studying the basic physics of the boiling process. This paper focuses on the operational aspects of the Multiscale Boiling experiment, from its preparation to the execution on-board of the ISS and the lessons learnt.

Studying boiling in a microgravity environment allows studying the basic physical aspects of the boiling process and allows the observation of effects that are too fast and too faint to be measured under normal gravity conditions. The experiment addresses fundamental questions about two-phase heat transfer during boiling processes. For this purpose, single or few subsequential bubbles are selectively ignited in a nucleation point on a heated substrate using a short laser pulse. A multi-scale experimental approach is adopted, including the application of two external forces (electrical field and shear flow). The diagnostics tools include a multi-thermocouple rack, high-speed black and white and infrared cameras.

More than 3000 data sets have been generated over a 9-month measurement period spread over two measurement campaigns. The experiment was monitored and controlled from ground by the Belgian User Support Operations Centre (B.USOC) and the raw scientific data was further distributed to the Science Teams. The process of boiling heat transfer depends on the environmental conditions, determined by the liquid temperature, the liquid pressure, the heat flux at the substrate heater, the preheating time, the liquid flow rate, and the strength of the electric field. This large number of experiment parameters results in a complex setup which requires careful monitoring and continuous real-time control by the ground operator, preventing a fully automated approach for the science runs. The Multiscale Boiling experiment was operationally challenging, as the conduct and result of the experiment was mainly relying on the expertise of the ground operator.

An assessment was made of the operational issues that had to be dealt with during both the operations preparation and execution phases with recommendations to the processes applied over the lifetime of such a project. In addition, during the operations execution, several hardware anomalies occurred, preventing the complete achievement of all mission objectives while additional objectives were added to compensate for it. Nevertheless, the Science Teams are very satisfied with the data, which are of an unprecedented quality. The data will be used to achieve a much better knowledge about the boiling process and to validate theoretical models and numerical codes.

The success of the mission was made possible thanks to the intense and productive close collaboration between the different instances involved, being the international and multidisciplinary Science Teams, the European Space Agency (ESA), Airbus and the B.USOC.

Keywords: International Space Station – European Space Agency – Operations – Fluid Science Laboratory – Multiscale Boiling

Nomenclature

Symbols

g	Gravity (m s^{-2})
h	Height (m)
Q	flow rate (ml min^{-1})
q	Heat flux (W m^{-2})
p	Pressure (bar)
T	Temperature (°C)
t	time (s)
U	electric field strength (V)

Subscripts

elec	electrode

i	individual
mtcr	micro-thermocouple rack
liq	liquid
pulse	laser pulse
set	target
Sub	subcooling
wall	wall
wait	wait time between substrate heater activation and onset of laser pulse

Superscripts

Acronyms/Abbreviations

Belgian User Support Operations Centre (B.USOC)
Boiling Cell (BC)
Central Experiment Module (CEM)
Columbus Control Centre (Col-CC)
Commercial Off The Shelve (COTS)
Commercial Resupply Service (CRS)
Electrically Erasable Programmable Read-Only Memory (EEPROM)
European Space Agency (ESA)
Experiment Container (EC)
Experiment Procedure (EP)
Fluid Science Laboratory (FSL)
fps (frames per second)
Forced Convection Loop (FCL)
GigaByte (GB)
High Rate Data (HRD)
High Speed Black and White camera (HSBW)
High Speed InfraRed camera (HSIR)
High Voltage (HV)
High Voltage Electrode (HVE)
International Space Station (ISS)
Loss of Signal (LOS)
Micro-ThermoCouple Rack (MTC-R)
Microgravity Vibration Isolation System of the Fluid Science Laboratory (MVIS)
Mission Control System (MCS)
Portable Network Graphic (PNG)
Pressure Control System (PCS)
Processed Parameter (PP)
Rack Interface Computer (RIC)
Secure File Transfer Protocol (sFTP)
Substrate Heater (SH)
TerraByte (TB)
Thermoelectric Cooler (TEC)
Video Management Unit (VMU)
Virtual Private Network (VPN)
Yet Another Mission Control System (Yamcs)

1. Introduction

Everybody is familiar with the concept of boiling, the rapid vaporization of a liquid which occurs when the liquid is heated to its boiling point. Two main types of boiling can be distinguished: nucleate boiling and critical heat flux boiling. One refers to nucleate boiling when small bubbles of vapour form at discrete sites on a heated surface, while critical heat flux boiling refers to a condition where the boiling surface is heated above a certain critical temperature and a film of vapour forms on the surface. Nucleate pool boiling is used in many engineering fields, such as cooling of nuclear reactors, environmental applications, food and chemical processes, thermal management of satellites and many others. It is one of the most efficient heat transfer regimes in which large amounts of heat can be dissipated from a heated surface with small changes in temperature [1].

Even though everyone is familiar with the concept of boiling, it is a complex two-phase heat transfer process influenced by many parameters and physical processes. Due to the complexity of the interactions and phenomena involved, the physics of the boiling process is still poorly understood and most of our understanding of the boiling process is based on empirical studies. On Earth, gravity-driven processes like natural convection and buoyancy are dominant mechanisms in the boiling process. Studying boiling in a microgravity environment allows studying the basic physical aspects of the boiling process and allows the observation of effects that are too fast and too small to be measured under normal gravity conditions (e.g. micro-region effects, Marangoni convection). Having a better understanding of the physics behind boiling does not only improve the application of boiling on Earth, but also in space [2]. Knowing and predicting the thermo- and fluid dynamics of boiling heat transfer in reduced gravity is mandatory for a safe and efficient design of spacecraft thermal control systems.

The Multiscale Boiling experiment, funded by the European Space Agency (ESA), aims to investigate the basics of boiling heat transfer phenomena on a heater surface, in a stagnant pool of liquid (also referred to as pool boiling). Pool boiling is considered as an effective means to remove heat in many application fields. As no moving parts are involved, it is especially attractive for space applications. The International Space Station (ISS) offers a great test environment in microgravity for such experiments. The typical level of micro-gravity on the ISS is of the order of $1x10^{-4}g$ [3]. Although there exist facilities with a better level of low-gravity, the ISS offers the advantage that experiments can be performed over an extended period of time in weightless conditions, and its excellent communication infrastructure offering the near real-time monitoring and control of the experiment. Boiling experiments have already been carried out on the ISS [4-6] demonstrating the significant influence of gravity on the boiling process.

The Multiscale Boiling experiment investigates a single or a low number of several bubbles under microgravity conditions and a multi-scale experimental and analytical approach is adopted, including the application of two external forces (electrical field and shear flow). The external forces are a means to remove the vapour above the heated substrate in microgravity. The experiment data will be used for validation of theoretical models and numerical codes, improving the current theories of boiling heat transfer. Applying a multi-scale approach allows the simultaneous investigation of the different physical phenomena at play on various spatial and temporal scales. The main objectives of the experiment are the measurement of wall temperature and heat flux distribution underneath vapour bubbles with high spatial and temporal resolution by means of infrared thermography accompanied by the synchronized high-speed observation of the vapour bubble shapes. Furthermore, a moveable micro-thermocouple array allows the measurement of the fluid temperature in the vicinity and inside of the vapour bubbles. Additional stimuli available are the generation of an electric field above the heating surface and a shear flow created by a forced convection loop. Besides vapour removal, the objective of these stimuli is to impose forces on the bubbles and investigate the resulting bubble behaviour such as bubble sliding on and detaching from the surface [7].

The Multiscale Boiling project is the result of the intense collaboration between an international science community (13 research groups from eight different countries), ESA, Airbus Defence and Space, and the Belgian User Support and Operations Centre (B.USOC). The experiment hardware has been mainly developed by Airbus Defence and Space Friedrichshafen, while the operational aspects are taken care of by B.USOC. The B.USOC is the ESA designated responsible centre for the preparation and conduct of experiments in the Fluid Science Laboratory (FSL), in ESA's Columbus module of the ISS. The proposal for the Multiscale Boiling investigation was formulated in response to several ESA announcements of opportunity from 1999 and 2004 for Evaporation, Condensation and Multiscale Analysis of Boiling research in microgravity. Work on the design started in 2005 and it was considered as part of a second batch of FSL Experiment Containers. The first batch to be launched together with the FSL facility and the Columbus module had to be completed first. Airbus Defence and Space (then ASTRIUM) was selected as prime contractor for the project in 2008 and a Preliminary Design Review was completed in 2011. No suitable high speed cameras were supported as part of the existing FSL diagnostics support, so the cameras had to be integrated within the Multiscale Boiling EC, interfacing with FSL through a separate high speed video interface. In the meantime, with the batch 1 experiments on FSL coming to completion, it appeared that a failure was building up in the high-rate data (HRD) transmission between the Video Monitoring Unit (VMU) of FSL and the Columbus module. After investigation in 2015 and 2016, the FSL facility was declared incapable of transmitting science data from experiments through the HRD line to the ground due to this VMU issue. It was then proposed to develop a new VMU based on Commercial Off The Shelve (COTS) components and that would modernise the imaging capabilities of FSL. It was also the opportunity to include the interface to the Multiscale Boiling high-speed cameras into the new VMU design, so that an external high-speed video interface would not be needed any more. In parallel with this, several troublesome and outdated diagnostic services of FSL would be de-scoped and retired to improve the operability of the rack. The whole concept gave birth to the FSL-ON project laying down a roadmap for FSL upgrades and the completion of all future FSL experiments. Soon after, the CDR for the Multiscale Boiling design would be completed in 2016 with the flight acceptance review and launch in 2019, almost 20 years after the initial proposal.

The Multiscale Boiling hardware was uploaded to the ISS with the SpaceX CRS-18 mission. The installation of the Multiscale Boiling Experiment Container (EC) inside the FSL was performed by ESA astronaut Luca Parmitano on 9 August 2019 and a first experiment series was conducted between 6 September 2019 and 5 March 2020. A mission extension was granted and a second experiment campaign was performed between 15 October 2020 and 13 January 2021. A total of 3913 experiment runs have been performed, generating almost 10 TB of data. A detailed description of the Multiscale Boiling experiment and first results have been published by Sielaff et al. [8].

In this paper, we focus on the operational aspect of the Multiscale Boiling experiment and the challenges encountered. A more in depth description of the experiment hardware and the experiment philosophy is provided in the next section. Section 3 shortly describes the Operational setup and concept. Section 4 presents an extended overview of the performed operations, including a listing of the problems encountered and their impact on the experiment objectives. In the Discussion and Conclusion sections we present the lessons learnt and summarise the operational aspect of the Multiscale Boiling experiment.

2. Experiment description

2.1 Hardware design and experiment control

The experiment is conducted in a test cell, also referred to as Boiling Cell (BC), with controllable temperature and pressure. The working fluid is fluid FC-72 (C_6F_{14}), a non-conductive, thermally and chemically stable liquid with low boiling point of 56°C under atmospheric pressure, and commonly used in low temperature heat applications. The thermal control system allows to homogeneously condition the working fluid in the range of 30°C to 70°C. The Pressure Control System (PCS) controls the liquid pressure, allowing to adjust it within the range [500, 1500] mbar. The boiling process takes place at the Substrate Heater (SH) inside the Boiling Cell, initiated by locally superheating an artificial nucleation site using a focused laser spot. The temperature distribution of the substrate heater surface is measured from the back side by High Speed Infrared (HSIR) thermography while the shape of the vapour bubbles are observed via a High Speed Black and White (HSBW) camera. The HSIR has a fixed frame rate of 240 fps, whereas the HSBW framerate is controllable between 0-500 fps. The temperature inside the bubble and in the vicinity of the liquid-vapour interface is measured by a rack of four micro-thermocouples (referred to as MTC-R), with a controllable acquisition rate of maximum 10kHz. The MTC-R is mounted on a positioning device to allow the positioning of the rack to a pre-defined location prior to the bubble nucleation as well as retraction after the measurements; the MTC-R tip can translate from 0.2mm to 3cm orthogonal to the heater surface. Two stimuli systems are integrated in the test cell to apply additional forces on the vapour bubbles: 1) an in strength and in position adjustable electric field of a washer shaped electrode above the substrate heater surface, and 2) a shear flow that is created by the Forced Convection Loop (FCL), consisting of a pump and flow meter connected to the test cell. The flow rate can be varied between 0 and 700ml min^{-1}. The field strength of the electrode (referred to as HVE) ranges 0-15kV, whereas the height above the substrate heater can be varied between 6-10mm. Moreover, the electrode can be completely retracted to avoid collision and interference with the MTC-R. An HSBW image is shown in Fig. 1, visualising the test cell and the different components.

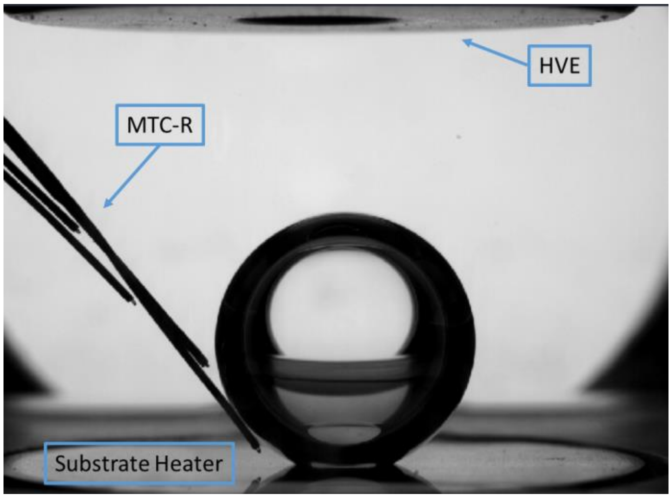

Fig. 1 High-Speed Black and White camera image from the Boiling Cell, showing a growing gas bubble on the substrate heater, the fully extended Micro-Thermocouple Rack (MTC-R), and the retracted High Voltage Electrode (HVE).

The temperature of the BC is regulated by several heaters: three sets of Thermoelectric Coolers (TECs) mounted between the BC main body and support structure which can both heat and cool the liquid, two sets of low power support heaters to establish homogeneous temperature, a preheater conditioning the liquid before it enters the BC, and a subcooler element (TEC) connected to a cold plate to cool the liquid exiting the BC. The purpose of this cooling element is to effectively cool the liquid before it enters the pump, in order to prevent pump cavitation. In combination with a range of temperature sensors, the thermal control system of the BC allows to reach a temperature homogeneity within 0.5°C at an accuracy of ±0.1°C. A schematic of the experiment setup is provided in Fig. 2, and a more detailed description of the experimental setup is available in [8].

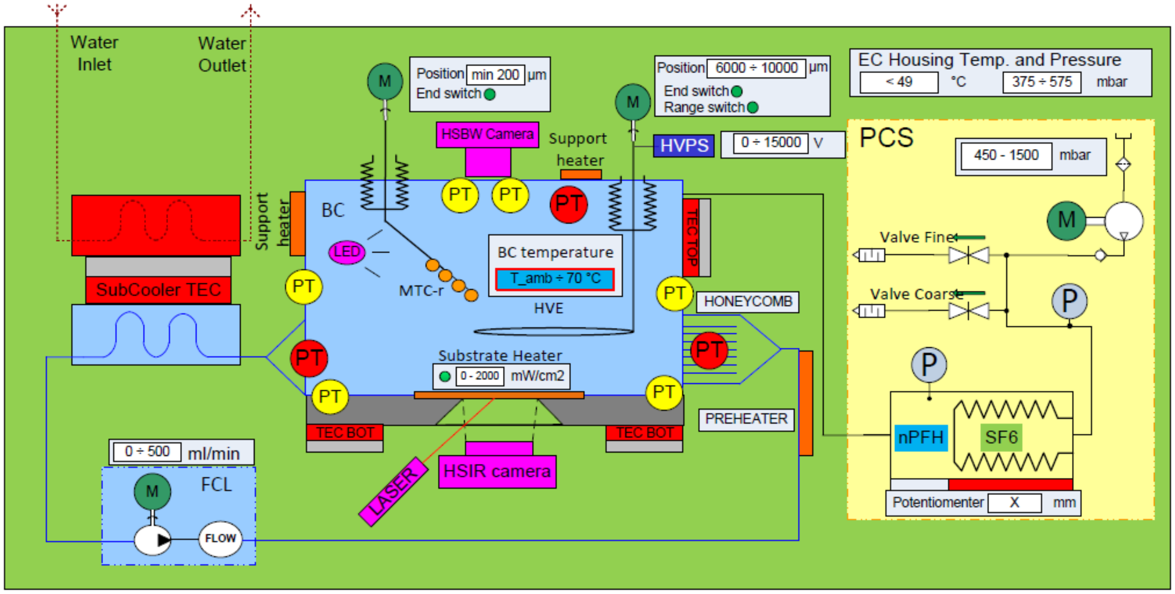

Fig. 2. Multiscale Boiling experiment conceptual diagram. In the diagram, the following nomenclature is applied: PT – thermistor, M –motor, P – pressure transducer, HVPS – High Voltage Power Supply. Credits: Airbus.

The experiment is designed as such that it fits in a so-called Experiment Container (EC) for the Fluid Science Laboratory (FSL). The EC design provides the support structure required for the operational positioning and locking inside the FSL Central Experiment Module (CEM), as well as all EC interfaces with FSL required by the experiment (power supply, different consumer voltages, heating/cooling, data and signal connections, optical and mechanical interfaces). The EC housing as well as parts of the EC avionics are developed as common equipment with a built-in high degree of design flexibility, so that they can also be used for future ECs. See Fig. 3 for an outside and inside view of the Multiscale Boiling EC.

Fig. 3 – Left: Multiscale Boiling EC showing the interfaces towards FSL; Right: Multiscale Boiling subsystem accommodation inside the EC - top side (left) and bottom side (right). Credits: Airbus

The EC interfaces with the VMU of FSL for image and science data acquisition, recording, processing (compression, region of interest, scaling), playback, and downlink to ground. The experiment itself is controlled through a so-called Experiment Procedure (EP), running on the FSL Rack Interface Computer (RIC), i.e. the FSL main computer. The EP is a Tool Command Language (TCL) script that drives the execution of the experiment. The EP can send commands to the FSL RIC via interface functions and can read telemetry values via a mechanism that links telemetry elements to TCL variables through a monitoring table at a rate of one value per second. The EP can also receive on event telemetry from the EC, other FSL subsystems, and messages from ground. The EP contains the main experiment control instructions and the experiment sequence. The EP functions can be called directly by dedicated telecommands, or through a parameter table, which is prepared on ground and uplinked to the FSL RIC. Using parameter tables allows for the semi-automatic execution of the experiment. For VMU specific commands, de-centralised instruction sets can be ran immediately on the VMU with interpreters running locally on a more modern and faster VMU processor, off-loading the slower and older processor of the RIC and speeding up considerably VMU video bus reconfigurations e.g.

On top of the EP, the experiment also uses a so-called Event List, which consists of three configuration tables resident in the EC EEPROM memory defining the acquisition frequency for the high speed channels (i.e. the acquisition frequency of the 4 MTC-R thermocouples), the parameters for the pulsed output generation (i.e. controlling the laser, the substrate heater, and the HVE), and the sequence of events to be processed when a much higher temporal accuracy is needed, not achievable by the typical rate of 1Hz for TM and TC. Up to 50 events can be stored in the sequence configuration table, and the events define among others the on-time for the substrate heater, the electrode and the laser, the start and stop times for the high speed channel acquisition. For each configuration table, 20 instances can be saved in memory.

2.2 Experiment Philosophy

The process of boiling heat transfer will depend on the environmental conditions. The experiment conditions are determined by the liquid temperature T_{liq}, the liquid pressure p, the heat flux at the substrate heater q, the liquid flow rate Q, and the strength of the electric field U_{elec}. Also the height of the electrode h_{elec}, the position of the MTC-R h_{mtcr}, and the settings for the laser have an influence on the results. This results in a 9-dimensional parameter space (see Table 1) and four types of experiment series:

- Series 1: pure pool boiling experiments. The MTC-R is lowered close to the substrate heater in order retrieve information at the bubble contact line.
- Series 2: similar to series 1 but including shear flow. This will allow to investigate the impact of the hydrodynamic boundary layer to the change in heat transfer.
- Series 3: investigate the influence of an electric field on the growth and dynamics of the bubbles. In this case the MTC-R has to be retracted.
- Series 4: study the combined effect of shear flow and electric field on the bubble dynamics.

Table 1 - Summary of the experiment parameters and their values for the first mission

Experiment parameter	Definition	Value range
p	Liquid pressure [mbar]	[500, 600, 750, 1000]
T_{Sub}	Level of sub-cooling [°C]	[1, 3, 5, 10]
q	Heat flux [Wcm^{-2}]	[0.5, 0.75, 1, 1.5, 2]
h_{mtcr}	Height of the MTC-R above the substrate heater [mm]	[0.2, 0.5, 10]
U_{elec}	Voltage applied on the electrode [kV]	[5, 10, 15]
h_{elec}	Height of the electrode above the substrate heater [mm]	[6, 8, 8.5]
Q	Flow rate [ml min^{-1}]	[0, 100, 300, 500]
t_{wait}	Time between the activation of the substrate heater and the onset of the laser pulse [s]	[1,2,3,5,10,20]
t_{pulse}	Duration of the laser pulse [ms]	[5, 10, 20]

2.2.1 Thermalisation phase

Before an experiment can be executed, the liquid has to be conditioned at the desired temperature. The boiling cell is considered thermalized when the following conditions are met:

$$\left|T_{liq} - T_{set}\right| \leq 0.1°C, \qquad (1)$$

$$\left|T_{liq} - T_{wall}\right| < 0.5°C, \qquad (2)$$

$$\max\left(\left|T_{liq} - T_i\right|\right) \leq 0.5°C, \qquad (3)$$

where T_{liq} is the average temperature as measured by various sensors inside the liquid, T_{set} is the desired experiment temperature, T_{wall} is the average temperature as measured by the different temperature sensors near the cell wall, and T_i is the individual temperature measurement of each sensor inside the liquid. As such, expression (1) indicates that the temperature accuracy needs to be within 0.1°C, while expression (2) and (3) ensure a temperature homogeneity within 0.5°C. During the thermalisation phase the pressure is typically kept at 1300mbar, to guarantee no vapour bubbles are residing in the Boiling Cell. The FCL can be applied to actively mix the fluid and speed up the thermalisation process. For the experiments without active flow, the liquid needs to settle to a steady state before the experiment run can start.

2.2.2 Experiment phase

Once the thermalisation criteria are fulfilled and the temperatures show near constant values, the pressure in the boiling cell is lowered to the desired experiment pressure. The experiment sequence is started consisting out of the activation of the high speed data acquisition by the four micro-thermocouples, the activation of the substrate heater, the control of the electric field, and the laser pulse. The exact experiment sequence is controlled via the specific event list. Once the experiment is completed, the pressure is increased to minimal 1300mbar to allow the condensation of the vapour bubbles.

The science data consist of the 1Hz housekeeping telemetry, images of the HSBW and HSIR cameras, and the high rate temperature measurements of the MTC-R. A typical science record consists of 10s of experiment data recorded at 500Hz for the HSBW and 240Hz for the HSIR, and the MTC-R collecting data at 2kHz, where data recording is started 1 second before the laser pulse. One science record in raw format is about 6.5GB in size and the data are stored on the VMU of FSL. The images from the HSBW camera can be lossless compressed to the PNG format during downlink, reducing the record size on-ground to 2.5GB.

3. Operational setup and concept

3.1 Ground Segment

The Multiscale Boiling experiment was monitored and controlled from the B.USOC, located in Brussels, Belgium. All data from the Columbus module, including the payload data, is routed through the Columbus Control Centre (Col-CC) in Oberpfaffenhofen, Germany. Engineering data is archived at Col-CC whereas scientific and facility data is distributed to User Support and Operations Centres for processing and archiving. The main Mission Control System (MCS) used for FSL telemetry monitoring, processed parameter monitoring and tele-commanding is the Yamcs Suite, an open-source, modern, lightweight, and scalable Mission Control System [9,10]. The displays for telemetry monitoring are developed and viewed using Yamcs Studio. Commanding is either performed through the command interface of Yamcs Studio, or directly from the displays. The flexibility of the Yamcs Suite allows for clever display design and command scripting. It was especially useful for building and checking the complex configuration tables for the event lists. The images from the camera systems are streamed in near real-time and directly displayed in Yamcs Studio, allowing the operator to follow closely the ongoing experiment.

One of the challenges of the Multiscale Boiling experiment, and FSL experiments in general, was the downlink and processing of the HRD. The HRD broker on the B.USOC ground segment unwraps the incoming packets in images and science data. In addition, the broker creates Processed Parameters (PP) outlining the HRD stream content, e.g. the data density (i.e. number of images or science data per second), the type of science product (i.e. image or science parameter packets), experiment run unique identifier, etc. These PPs act as placeholders or representatives for a set of HRD in support of the operations. The PPs aim to support the B.USOC operations by providing a data stream that can be handled by the tools and displays initially developed for the medium-rate telemetry. The science team has access to these data via an sFTP interface. In addition, B.USOC provided to all members of the science team a so-called User Home Base, allowing to monitor and extract the telemetry from the experiment through a secured VPN connection.

3.2 Operational concept

The functionality and performance of the flight hardware and software was validated during several test campaigns (Development Tests and Mission Tests), which included the involvement of the engineering, operations, and science teams. In the Mission Tests (November 2018, February 2019, March 2019), various tests have been performed in a representative way (in terms of experiment set-up, thermalisation, experiment performance incl. data recording and data transfer). This defined the realistic timeline for single experiment runs and served as baseline to prepare the mission schedule. One of the Mission Tests also included a Science Validation Test, testing the experiment philosophy for a predefined set of experiment parameters. The tests were performed for two different orientations of the Experiment Container (+1g and -1g) and served as a reference for the in-orbit experiments. Several important insights were discovered during the Science Validation Tests, such as techniques to avoid parasitic boiling and pump cavitation for experiments at higher temperature and low levels of subcooling. The entire operational flow, from experiment setup, to data delivery and the interaction with the science team, was rehearsed in the so-called Experiment Sequence Test (May 2019). The lessons learnt and findings from the different test campaigns were taken into account in the operator training and resulted in updated ground procedures and displays.

The operational phases of the experiment comprised a commissioning and a routine phase. The commissioning consisted out of four main activities, being:

1. The uplink and installation of the necessary software, being the Experiment Procedure scripts and support libraries (both for the main RIC TCL interpreter and de-localised VMU TCL interpreter).
2. A functional checkout of the Experiment Container and its subsystems.
3. Thermalisation tests of the Boiling Cell and HSIR data collection. The aim was to verify that the Boiling Cell can be thermalized in-orbit at the desired level of thermal accuracy and homogeneity and this for different temperatures. At each temperature a series of HSIR images is collected, which are used in the HSIR calibration procedure and to be compared by the results of the on-ground calibration.
4. Science commissioning consisting out of a repetition of a subset of 10 runs also performed during the Science Validation Test.

The routine operations were divided into two phases: fine-tuning and science runs. The aim of the fine-tuning was to characterise the system in micro-gravity conditions. It was expected that the parameter settings for the thermalisation, as well as the time needed to reach the requested thermal conditions within the test cell, would be different from the ground tests due to the absence of gravity. The fine-tuning would result in a viable set of heater settings which provided the desired temperature of the boiling cell (within the level of accuracy and homogeneity as defined in eqs. [1-3]) and also in an updated range of experiment parameters defining the final series of science runs to be executed.

4. Operations execution and challenges

The Multiscale Boiling EC was installed by ESA astronaut Luca Parmitano on 9 August 2019 (Fig. 4).

Fig. 4. Luca Parmitano installing Multiscale Boiling Experiment Container in the Fluid Science Laboratory aboard the space station. Credits: NASA

The commissioning activities were successfully completed on 23 September, 2019 and were followed by the routine operations starting on 01 October, 2020. Based on the findings of the fine-tuning, the science team eventually defined a total number of 674 experiments as a combination of the parameters defined in Table 1, of which 268 pool boiling, 103 shear flow, 255 electric field, and 48 shear flow and electric field. Each experiment had to be repeated at least three times. This resulted in a total of more than 2000 science runs. A reference run was defined as well which was repeated multiple times during the mission duration to check for a possible degradation of the setup. As an example, in Fig. 5 a comparison is shown between undisturbed bubble growth and the impact of the different external forces on the nucleation process. The figure shows images of the HSBW camera, taken at the same point in time and for similar thermal conditions, and different external forces.

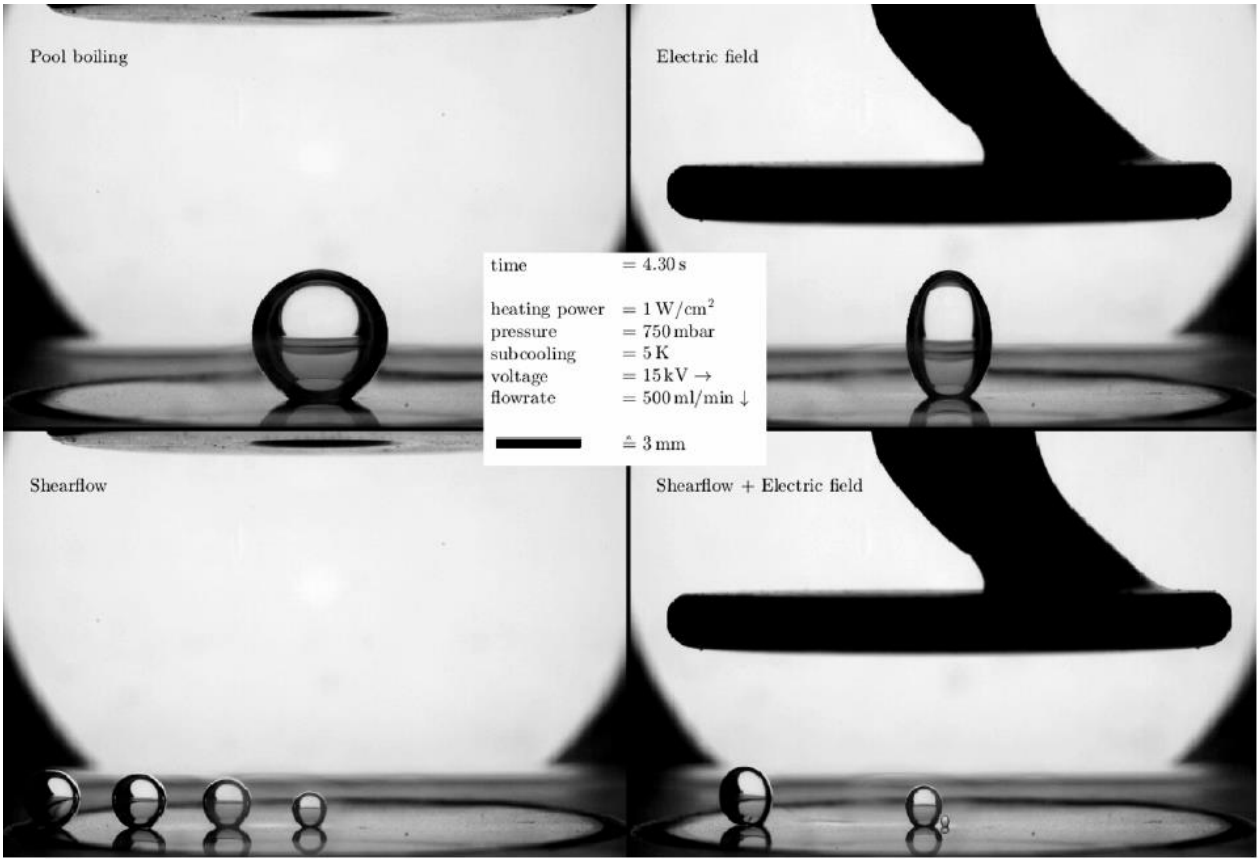

Fig. 5 - Comparison of the impact of different external forces on the boiling process. Top left: pool boiling; top right: electric field; bottom left: shear flow; bottom right: shear flow and electric field. Credits: Multiscale Boiling science team.

A timeline of the mission overview and main issues encountered is provided in Table 2 and described in detail in the next subsection.

Table 2 - Overview of mission phases and main anomalies with operational impact

Dates	Activities	Notes and anomalies
07 Aug 2019	Installation of mission specific EPs and libraries on FSL RIC and VMU	
09 Aug 2019	Installation of the EC by crew and harness reconfiguration with new power cable	Crew activity preparations did not capture aspects that led to considerable overtime. Power cable non-conformance (wrong clocking connector) led to tension in the setup
10 Aug - 04 Sep 2019	Assessments of risks related to the power cable and identifying options. Qualification of the old harness available on-board and crew swap-out procedure development.	FSL was kept de-activated during this time.
05 Sep 2019	Power cable swap and FSL activation	
06 Sep 2019	EC checkout	Issue with automatic EC Internal Power Lines activation, manual activation needed

Dates	Activities	Notes and anomalies
07 Sep 2019	BC thermalisation tests and HSIR camera calibration	
08-18 Sep 2019	Science Commissioning (repetition of science runs from ground validation tests)	High Speed science data issues during transfer to VMU: - EC sometimes goes to SUSPENDED Mode or even reboots - sometimes the transfer does not stop by itself, need for manual intervention After a few full range movements of the MTC-R, increased mechanical resistance leading to the rack to get stuck in intermediate position
19-21 Sep 2019	Second campaign of BC thermalisation tests and HSIR camera calibration	Thermal run-away effect leading to FSL TEC power board trip on 20 Sep 2019
22-30 Sep 2019	Commissioning data analysis on ground, assessment of EC status and anomalies and change in science run strategy and schedule to minimise actuator movements	FSL was kept de-activated during this time Decision to keep the MTC-R in the Home Position for all first priority Pool Boiling and Shear Flow runs to make sure to still be able to perform the runs needing the electrode
01-12 Oct 2019	Science runs fine-tuning for Pool Boiling and Shear Flow runs	
13 Oct - 01 Nov 2019	Science runs for Pool Boiling and Shear Flow	FSL had to be de-activated for 6 days in this period due to ISS power system issues during high beta angle
02-10 Nov 2019	Science runs fine-tuning for Electric Field runs and combined Electric Field + Shear Flow runs	
12 Nov -15 Dec 2019	Science runs for Electric Field and combined Electric Field + Shear Flow	Issue that the HVE would not activate above 8.5mm from the SH, 9mm was planned but could not be used
16-18 Dec 2019	MVIS commissioning to characterise the system with the EC and harness	
19-31 Dec 2019	Science Runs with active MVIS microgravity isolation	After last runs needing the electrode a new attempt was made to move the MTC-R, reached 10mm above the SH and got stuck there. (Ops interruption on 25 Dec)
02-04 Jan 2020	Additional science runs for Shear Flow and Pool Boiling	On 04 Jan 2020 the communication to the HSIR camera was lost and could not be re-established
05-25 Jan 2020	HSIR camera troubleshooting, assessment and EP update installation for operations without the HSIR camera	During this period FSL had also to be de-activated for a Columbus software cycle and Columbus mass memory unit failure
26 Jan - 28 Feb 2020	Last set of additional science runs for Shear Flow and Pool Boiling, without the HSIR camera	
05 Mar 2020	Final attempts to get the MTC-R loose and put it in Home Position for future missions	Very last homing attempt successful with alternative approach in little steps and pressure variations in the BC

Dates	Activities	Notes and anomalies
06 Mar 2020	Crew removes the EC from FSL	
04-12 Mar 2020	Ground testing on the FSL EM and EC EM with working HSIR camera to assess the local heating due only to the laser pulse with SH off	Tests could not be performed with the Flight Model on-board ISS due to the HSIR camera anomaly
14 Oct 2020	Crew installs the EC back into FSL	
15 Oct 2020	EC Checkout	
16-26 Oct 2020	New set of science runs for Pool Boiling	Starting on 23 Oct 2020, start of sporadic corruption issues in recorded science data on the VMU hard disks
28-31 Oct 2020	Fine-tuning for Shear Flow runs with additional flow rate	
01-11 Nov 2020	New set of science runs for Shear Flow	
12-19 Nov 2020	New set of science runs for Electric Field	
20-22 Nov 2020	Fine tuning for runs with combined Electric Field and Shear Flow, for the additional flow rate	
23-30 Nov 2020	New set of science runs for combined Electric Field and Shear Flow	
02 Dec 2020 - 10 Jan 2021	Bonus runs for types of science runs	FSL had to be de-activated for 1 day on 21 Dec 2020 due to a Columbus Power-down (High ISS beta angle) Operations interruption for holiday period from 24 Dec 2020 till 03 Jan 2021.
26 Jan 2021	Crew removes the EC from FSL a final time	

4.1 Mission overview

The mission was kicked off with both software and hardware installation in the FSL facility on respectively 7 and 9 August 2019. The experiment scripts and libraries installation from ground went smooth, but several un-anticipated hardware-related issues happened during the crew activity which could be resolved with ground support in real time, leading to some substantial crew activity overtime. One issue however could not be solved: the power cable had a connector house that had a wrong orientation. The connector had been reworked late before launch and this happened after the successful fit-check, so the issue had not been caught. After an attempt to install the harness as is, the harness was deemed un-reliable and it was decided to instead re-qualify on paper an older harness that was available on-board and was compatible with the new setup.

After the problematic cable was swapped out successfully with the legacy one, the EC was checked out successfully, but soon it was noticed that the automatic power on routine of the internal power outlets was not always reliable. An operational work-around for this was successfully developed and integrated into the ground procedures, but required an increased need for monitoring and manual intervention from the operator team, hence less automation.

After the successful BC thermalisation tests and HSIR camera calibrations, the science commissioning started, during which more software-related issues sporadically occurred during the transfer of high-speed science data from the EC to the VMU after science runs. Regularly, the transfer would not stop by itself and occasionally, the EC would even go in Suspended Mode or even reboot. Also these issues were solved by operator monitoring and intervention when it happened, increasing the need for attention and responsiveness of the operator team during the rest of the mission. Workarounds for both issues could be identified, after a careful analysis of the telemetry by the operations team.

A more hardware-related issue also started occurring during the science commissioning, where the MTC-R would not appear to be in the expected position indicated by the stepper motor counts. This happened after only a few full range movements in and out of the BC and it appeared like the actuator was experiencing increasing mechanical resistance until getting stuck. Troubleshooting and attempts to move the actuator with higher current settings and different moving strategies had variable degrees of success, ultimately concluding that the actuator could be homed reliably, but the position into the BC that was intended for most Pool Boiling and Shear Flow science runs could not be reached any more. The decision was made to keep the MTC-R in the home position to allow for all science runs requiring the electrode to be positioned in the BC to be completed (the 2 devices are exclusive and when not in the home position one device would prevent the other device from moving).

During the second part of BC thermalisation tests and HSIR camera calibrations, at one occasion there has been a run-away effect of the thermalisation, leading to a short period of massive boiling during an un-monitored period called Loss Of Signal (LOS) and the TEC system of FSL to be shut down by an automatic protection mechanism. This runaway effect was made possible by the design choice of having a TEC channel of the FSL controlling a resistive element while it is designed to operate elements that can both cool or heat up according to the direction of the injected direct current. So in some rare cases, the control law would instruct the TEC controller to reverse the current in order to cool down the element, while the resistor could only heat up no matter the direction of the current. This feature was known in advance and trained for by the operator team, but the occurrence reminded of the need to be extra attentive and not to have thermalisation changes during unmonitored moments like LOSes.

During the analysis of the commissioning data, FSL was kept switched OFF. The ground procedures were re-worked to include all workarounds from aforementioned issues and also the whole planning and science run order was re-shuffled to include the findings of the MTC-R issue. It was decided to first run a series of pool boiling and shear flow experiments with the MTC-R in the homing position, then perform all the science runs requiring the use of the HVE, and finally make an attempt to bring the MTC-R into the boiling cell to a height of 0.5mm above the substrate heater and complete the pool boiling and shear flow experiments.

The FSL rack was then re-activated to perform science runs fine-tuning in order to prepare for the routine phase with the bulk of the foreseen science runs. The goal of the science fine-tuning was to determine working settings for thermalisation and bubble nucleation and this for well-chosen conditions throughout the science parameter space (subcooling, SH power, shear flow and or electric field) in the un-tested microgravity conditions. Specially developed event lists were used that would fire the laser at several consecutive timestamps after the SH activation and the operator would then together with a representative of the science team determine in near real-time which would be the first laser pulse that resulted in bubble nucleation. This would then define the shortest t_{wait} that had to be applied before a laser pulse could reliably initiate bubble nucleation.

With the setting obtained during the science runs fine-tuning, the routine science phase could start, going through all the intended incremental changes in science parameters. We noticed that successful thermalisation of the BC could not always be repeated using the settings from the fine-tuning, so those cases would again require manual intervention from the operator to reach the thermalisation criteria.

The routine science run phase has been interrupted by a few issues unrelated to FSL. In October 2019, the rack had to be kept de-activated during 6 consecutive days due to power issues at ISS level during a high beta angle period. Later, in January 2020, FSL also had to be kept de-activated for a few days for a Columbus software cycle maintenance and for a Columbus Mass Memory Unit failure. Those illustrate the kind of interruptions that can occur during a scientific payload mission on ISS and in Columbus due to external factors.

At the end of the Electric Field science runs, we were confronted with an unexpected limitation from the hardware, that would not allow the electrode to be producing a High Voltage (HV) electric field in positions higher than 8.5mm above the SH. The science team had foreseen some science runs with the electrode at 9mm above the SH, but due to this limitation they had to be performed at 8.5mm.

During the last 2 weeks of December 2019, a selected sub-set of science runs was repeated with the active microgravity isolation system MVIS instead of the standard passive isolation through the rubber AVM brackets, in order to provide means for comparison of science runs performed under different microgravity conditions.

Once all intended science runs involving the electrode were complete, more attempts were made to move the MTC-R to a position close to the SH for the rest of the Pool Boiling and Shear Flow runs, but the closest point that could be reached was at 10mm above the SH (instead of the target 0.5mm) and it got stuck in that intermediate position. As a result of this, the precise characterisation of the boundary layer above the SH surface was only possible for the very few first science commissioning runs instead of all the intended ones. Also on no occasion has a vapour bubble been pierced by the MTC-R. Those science objectives have not or only very partially been accomplished.

Shortly after, the communication was lost with HSIR camera on 4 January 2020. Troubleshooting activities were not successful in re-establishing the link with the camera and the EP had then to be adapted and re-validated to perform science runs without using the HSIR camera. It was only at the end of January 2020 that the execution of the remaining set of science runs could be resumed until completion of the mission at the end of February 2020.

Considerable effort was put into finally homing the MTC-R again at the end of the first mission to make sure that in future missions or campaigns it would still be possible to use the electrode. It was only shortly before the de-activation of FSL that we managed to get the MTC-R loose that had been stuck since December 2019, applying a new strategy using small steps of movement and using the pressurisation system to cycle the delta pressure between the inside of the BC and the EC housing at each step. The MTC-R was then successfully retracted into its home position, essentially clearing the EC for more science runs involving the electrode during potential future missions.

4.2 Mission extension

Three major hardware anomalies, namely 1) the failed HSIR, 2) the unreliable functioning of the MTC-R actuator, and 3) the impossibility to perform tests with the electric field when the electrode is positioned at distances higher that 8.5 mm with respect to the substrate heater, resulted in only a partial achievement of the scientific objectives. Nevertheless, the results of Multiscale Boiling were interesting and promising. ESA then also granted a mission extension of approximately 2 months duration, partly as a compensation for the missed science objectives. With the MTC-R successfully homed after the first part of the mission, additional science runs for all four experiment series were still possible with the limitation that the temperature of the vapour phase and the spatiotemporal evolution of the temperatures of the heated substrate could not be acquired (due to the MTC-R issue). A preliminary analysis of the science data of the first mission yielded insights in potential interesting alternative combinations of experiment parameters and revised strategy for the external forces. For pool boiling, combination of lower heat flux and longer t_{wait} were investigated; shear flow experiments at lower pressure and flow rate up to 700 ml min^{-1} were performed; and for the electric field a new strategy was applied with a temporal variation of the electrical field strength. In addition, the approach for the HSBW recording was modified, including more observations after the onset of nucleation. In total, 348 new science runs plus an additional 243 lower priority runs were identified. The operations were performed between 15 October and 23 December 2020 and from 04 to 13 January 2021, completing all the identified experiment runs. No major anomalies occurred during the mission extension, although the hard disks of the FSL VMU started to show signs of degradation. A corrupt sector on one of the four VMU hard disks resulted in incomplete science records. Luckily only few records were impacted and none of those data records were scientifically relevant. The replacement of the corrupted hard disk resolved the issue.

4.3 Mission performance summary

The original experiment science requirement document for Multiscale Boiling mentioned an amount of experiment runs to be performed of 631 runs (x3 repetitions per run) within a 5 months mission duration [7]. The resulting first Multiscale Boiling campaign ended up spanning 212 days, of which we should count 36 days of troubleshooting downtime and used to reassess the schedule after the major issues and 14 days of FSL downtime due to external factors. The remaining 162 days of nominally foreseen mission activities is close to the initial 5 months requirement.

In the second campaign, the requirement was set at 338 experiment runs (x3 repetitions) in 2 months [7]. The second Multiscale Boiling campaign ended up spanning 92 days, thanks to some flexibility in the schedule of the next FSL mission after Multiscale Boiling and the support of ESA management to allow for extended time to perform a good amount of bonus runs. A distribution of how time was attributed during each campaign can be found in Fig. 6. The exploded sectors of the pie charts represent unforeseen issues. It can be seen that for the second campaign, a much larger part of the time could be dedicated to science as would be expected for an extension of an already performed mission, in part also thanks to the fact that no major issues happened any more during the second campaign. The second campaign also allowed for a longer B.USOC closure time during holiday season. No more downtime was needed any more during the second campaign for the science teams to perform data analysis since there was no more need for a science commissioning and HSIR camera calibrations.

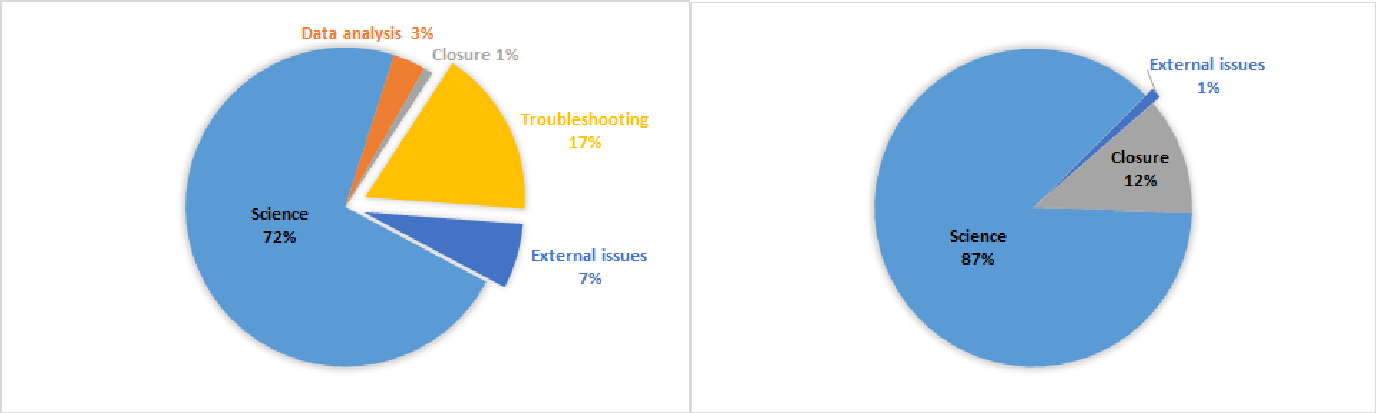

Fig. 6. Time attribution for the first Multiscale Boiling campaign (left) and the second one (right)

For the first Multiscale Boiling campaign, a total of 674 different experiment runs were ran through with an addition of 50 experiment runs with the use of MVIS for microgravity isolation. The second campaign resulted in 348 new experiment runs complemented by another 243 lower priority bonus runs. Both campaigns resulted in considerably more experiment runs than required. A distribution of the experiment runs over the mission phases is shown in Fig. 7.

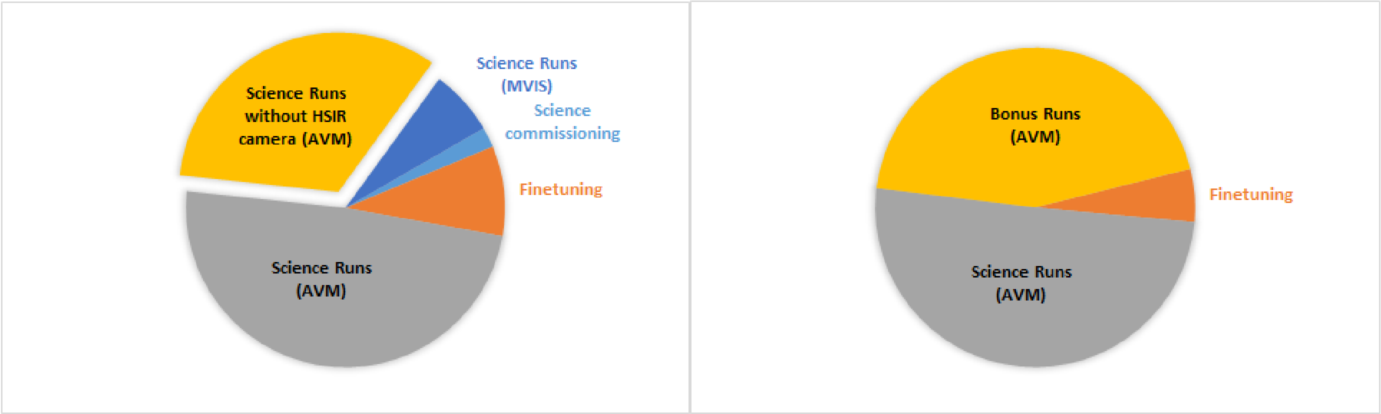

Fig. 7. Distribution of experiment runs per mission phase for the first Multiscale Boiling campaign (left) and the second one (right)

The exploded sector of the pie chart of the first campaign are the science runs from after the HSIR camera failure. Note that only 6 experiment runs for Pool Boiling and 2 experiment runs for Shear Flow could be performed with the MTC-R in a position close to the SH during the science commissioning, hence almost all experiment runs for Pool Boiling and Shear Flow were impacted by the MTC-R issue. During the second campaign, a smaller share of experiment runs were used for fine-tuning, thanks to the reuse of the fine-tuning information obtained during the first campaign.

5. Discussion and lessons learnt

- The change in design for the power cable was a consequence of lessons learnt from a previous FSL science mission. It imposed additional requirements on circuits to be attached to the FSL TEC system, to protect it upstream. This added complexity on the harness assembly and schedule. The fact that the legacy power cable was compatible and was cleared to be used with low enough risk could put forward lessons learnt about the initial assessment about the need for such a protection system.
- Specifically for the FSL EC, a lot of hardware is integrated in a small predetermined volume, which makes it difficult to access for repairs once integrated. The flight model EC being still close to a prototype, hardware failure is likely during mission.

- It is good to have flexibility built in the operational concept in order to minimise impact of failures and anomalies. Real enabling factors for the workarounds that were developed and manual operator interventions were the expertise acquired by the operator team in terms of EP functionality, the flexibility of the EP built-in after pre-launch testing and feedback and the implementation of direct command capability to the EC to perform single actions that would otherwise be performed either automatically by an EP function or by explicit EP commanding through a message to EP from operator console.
- The FSL engineering model is not collocated with the EC developer, so integrated testing of the EC within the FSL EM has to be carefully planned and last minute changes that require integrated testing should be avoided.
- FSL design is getting outdated (including computer power and software) and the as-built model is not always fully documented, making integrated testing very important.
- Any science mission on ISS with a timescale of months will be impacted by many microgravity disturbances like docking and reboosts, but also at times temporary resources limitations that could even require multiple day powerdown of the payload rack.
- Mission preparation with integrated team across payload developers, science teams, sponsoring agency and operations team is key to a successful completion of the flight mission. The team should remain in place all the way until the end of the mission, to ensure quick and effective response to anomalies or on-board events requiring re-planning. Early involvement of the operator team in preliminary/critical design review and assisting/supporting assembly, integration and testing/verification activities helped a lot to acquire the required expertise, develop the operational products for the mission and by providing feedback in the early design stages insure the design allows for efficient operations during the mission.

6. Conclusions

The Multiscale Boiling experiment was the first experiment in microgravity investigating both the undisturbed growth of bubbles in pool boiling conditions and the effect of external forces on the boiling process. The data were collected during two mission campaigns, running between 6 September 2019 and 13 January 2021. The full achievement of the science objectives could not be accomplished due to some hardware failures during the operations execution. This prevented measurements of the vapour temperature and analysis of the spatiotemporal changes in the heated surface. Despite this adversity, the experimental campaign was considered a success and the collected data allow for a detailed analysis of fundamental bubble dynamics, force and stress balances, bubble detachment mechanisms, and heat transfer rates.

Operationally the Multiscale Boiling experiment was challenging, as it required not only a careful monitoring of the experiment, but also a fundamental understanding of the experiment design and scientific requirements. The complexity of the experimental setup did not allow for an autonomous execution of the operations. Before the experiment protocol could be started, the Boiling Cell had to be conditioned at the desired temperature within the required level of temperature accuracy and homogeneity. This required experience from the operator to understand the impact of the different heaters on the liquid temperature. The eventual settings to use highly depended on the environmental conditions such as cooling loop liquid temperature, total on-time of the Experiment Container, experiment history. This makes that the entire thermalisation phase was more time consuming than assumed pre-mission. Also the various telemetry items related to the internal power lines and current draw had to be carefully monitored, in order to assure repeatability and correct execution of the experiments. Nevertheless, all the science runs requested could be performed within the allocated mission duration. This achievement is the result of the intense collaboration between the operations team, the engineering teams, and the science teams under ESA guidance. The involvement of the operations team in the different pre-mission test campaigns resulted in improvements in the experiment software, and allowed to gain the necessary experience for the mission execution. It also allowed to optimise the graphical users interface display design for real-time telemetry monitoring and commanding and other operational products. The close collaboration with the science team resulted in a well-prepared mission scenario. Weekly meetings during the mission execution contributed to a transparent communication between all the teams involved. This all contributed to a fluent mission execution despite the issues encountered. From an operational point of view, the Multiscale Boiling experiment was then also a truly rewarding mission.

Acknowledgements

The authors thank the European Space Agency (ESA) Directorate of Human and Robotic Exploration (HRE) and the Belgian Science Policy Office (BELSPO) for their funding. B.USOC is part of the Royal Belgian Institute for Space Aeronomy (BISA).

Furthermore the authors thank the ESA ISS Operations Management, the Columbus Control Centre Flight Control Team (Col-CC FCT), the FSL Payload Developers, the Multiscale Boiling Payload Developers and Science Teams, and the B.USOC Operator and ground controller team for the good collaboration and support.

References

[1] M.M. Mahmoud, T.G. Karayiannis, Pool boiling review: Part I – Fundamentals of boiling and relation to surface design, Thermal Science and Engineering Progress 25 (2021) 101024

[2] P. Di Marco, W. Grassi, Motivation and results of a long-term research on pool boiling heat transfer in low gravity, Int. J. Therm. Sci. 41 (2002) 567–585

[3] N. Sentse, ESA user guide to low gravity platforms, 2014, *https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Research/European_user_guide_to_low_gravity_platforms*, (accessed 29.12.2022).

[4] R. Raj, J. Kim, J. McQuillen, Pool boiling heat transfer on the international space station: Experimental results and model verification, J. Heat Transfer 134 (10) (2012)

[5] G.R. Warrier, V.K. Dhir, D.F. Chao, Nucleate pool boiling eXperiment (NPBX) in microgravity: International Space Station, Int. J. Heat Mass Transfer 83 (2015) 781–798

[6] K. Inoue, H. Ohta, Y. Toyoshima, H. Asano, O. Kawanami, R. Imai, et al., Heat loss analysis of flow boiling experiments onboard International Space Station with unclear thermal environmental conditions (1st report: Subcooled liquid flow conditions at test section inlet), Microgravity Sci. Technol. 33 (28) (2021)

[7] D. Mangini, Multiscale Boiling Experiment Scientific Requirements, ESA reference: SCI-ESA-HSO-ESR-MultiscaleBoiling, 2020

[8] A. Sielaff, D. Mangini, O. Kabov, M.Q. Raza, A.I. Garivalis, et al., The multiscale boiling investigation on-board the International Space Station: An overview, Applied Thermal Engineering 205 (2022) 117932

[9] M. Schmitt, S. Klaï, D. Van Hoof, ISS FSL Ground Software Interface – Unleashing the Yamcs Suite, IAC-16-B6.1.5.x35014, 67th International Astronautical Congress (IAC), Guadalajara, Mexico, 2016, 26-30 September

[10] *https://yamcs.org/*