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THE ELECTRO-MAGNETIC LEVITATOR (EML) ON BOARD THE ISS – AN OVERVIEW AND OUTLOOK

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Abstract

The Electro-Magnetic Levitator is a multi-user research facility for materials sciences experiments on board the ISS. It provides for container-less melting and solidification of electrically conductive, spherical samples, under ultra-high vacuum and/or ultra-clean gas conditions. EML is a successor of the German TEMPUS facility that was flown on three Spacelab missions in the 1990s, and is based also on the corresponding TEMPUS Parabolic Flight Facility and the EML TEXUS sounding rocket payload. The three facilities together form a unique portfolio of equipment, offering flight opportunities with increasing levels of experiment duration and zero gravity quality to a large international scientific community. This research is also oriented to industrial applications where reliable data for accurate modelling of industrial processes are difficult or impossible to be obtained on ground.

The EML for ISS has been developed in a joint undertaking of ESA and DLR Space Administration. It was designed, assembled and tested by German and Italian industry under the lead of Airbus Defence and Space, and launched to the ISS in 2014 with ATV-5. Installation in the Columbus module was performed by the German astronaut Alexander Gerst, and the operations of the facility are now being conducted from the Microgravity User Support Center (MUSC) in Cologne.

This paper provides an overview of the technical development of the EML, including its heritage from TEMPUS facilities, the installation and commissioning on board the ISS, the mission scenario for the coming years including the operations concept by MUSC, and an outlook to some envisaged facility upgrades.

1. ELECTROMAGNETIC LEVITATION

Electromagnetic levitation is a technique for thermal experiment processing (heating, melting, solidification) of electrically conductive materials samples, without any contact of the sample to a crucible (so-called “containerless processing”). The samples are free-floating in an ultraclean environment, typically vacuum or high-purity noble gases, without touching anything that could influence its own intrinsic behaviour during heating up, melting, liquid state variations, and solidification. This unique feature enables the scientific investigation and measurement of materials properties and characteristics that are otherwise not possible due to the interaction of the liquid samples with the container walls. For example, liquid metallic materials are typically highly reactive with even smallest amounts of oxygen, and contact with any solid particle or element can trigger the immediate nucleation and forming of crystal structures while cooling down through the solidification point. The absence of any such disturbance on the other hand allows observation of the “pure” materials behaviour, and in particular enables the possibility to reach an “undercooled” state, in which the material stays liquid even below the solidification point.

This is achieved by levitating and heating the material sample through high frequency electro-magnetic fields generated by alternating currents in a coil. The field induces eddy currents in the sample, which is heated by ohmic losses of the currents, while their interaction with the electromagnetic field leads to forces towards the centre of the coil system. The technique can be applied both on ground and in reduced or zero-gravity, but the latter provide much better experiment conditions. To levitate a sample under normal gravity requires strong levitation fields, which induces convection and an unwanted heating-bias. Furthermore the liquid sample is deformed by the strong electromagnetic force pressure against gravity. In zero-g however only very small positioning forces are needed to compensate residual accelerations and keep the sample in the centre of the experiment set-up, thereby enabling a perfectly spherical shape. The heating then can be controlled almost independently of the levitation, allowing processing of materials with lower melting temperatures and measurements with much higher accuracy. Both options have been implemented with electromagnetic levitators on ground, in parabolic flight airplanes, sounding rockets, and orbital laboratories.

Alternative techniques providing similar experiment conditions include electrostatic levitation and acoustic levitation. In these cases the levitation is achieved by electrostatic forces or acoustic pressure, while heating is performed mostly with lasers. None of them is however as mature as the electromagnetic levitation, which has been applied to a wide range of alloys for decades.

Conventional “furnace” type facilities on the other hand enclose the material sample in a crucible or container, which is inserted into the furnace. Then the entire furnace is heated up to the processing temperature, whereas in the containerless techniques only the sample itself is heated. The furnace type facilities, such as the MSL (Materials Science Lab), also on board the ISS, have therefore typically much longer processing cycles, and are used to investigate other properties and phenomena than those targeted by the EML.

History and heritage of EML

Electromagnetic levitation was invented and patented already in the 1920s. Its application under reduced or zero gravity was started in the 1980s, when a long-term development program was initiated in Germany under the name TEMPUS, which is an acronym for containerless electromagnetic processing under zero gravity (Tiegelfreies Elektromagnetisches Prozessieren unter Schwerelosigkeit). The company Dornier (now part of Airbus Defence & Space) together with the DLR Institute for Materials Physics in Space, funded by the German Federal Ministry for Research and Technology (later continued by the Ministry of Economic Affairs and Energy), and commissioned by the DLR Space Administration developed a series of facilities with increasing performance and versatility. Starting with a laboratory model and progressing with facilities for parabolic flights and the TEXUS sounding rocket, the goal was to perform experiments for increasingly long periods, from seconds to minutes, under micro-gravity conditions.

The next big step forward was the development of a TEMPUS facility for operation in the Spacelab on board the US Space Shuttle, offering mission durations of 1 to 2 weeks and allowing the processing of numerous samples for an extended time. It had its first successful flight in orbit in 1994 as part of a multinational cooperation with NASA, the International Microgravity Laboratory (IML-2) Spacelab mission. Together with two more flights in 1997 (MSL-1 and MSL-1R) it provided a wealth of scientific data. The TEMPUS Spacelab facility is now on display in the Dornier museum Friedrichshafen.

The parabolic flight facility has been continuously upgraded and is still flown on a yearly basis with Novespace’s Zero-G airplane from Bordeaux-Merignac airport. The objective is twofold, to conduct scientific experiments as precursor and “dry-run” to the corresponding experiments on the ISS, and to implement and test new functions and equipment that could potentially be used also on orbit.

2. THE DEVELOPMENT OF EML FOR THE ISS

Meanwhile the International Space Station (ISS) provides a permanent laboratory in orbit, thereby enabling extended and complementary series of experiments, rather than single data points. Based on the experience gained with the TEMPUS programme, and with a number of highly rated experiment proposals available from an international Announcement of Opportunity by the European Space Agency (ESA), it was therefore decided to develop an Electromagnetic Levitator (EML) for the ISS. In a cooperative effort of ESA (within its ELIPS programme) and DLR’s Space Administration (within its national ‘research under micro-gravity’ program), DLR brings in their long experience gained with the TEMPUS and TEXUS-EML facilities, while ESA contributes the expertise on the ISS and Columbus environment and operations. Furthermore the joint undertaking allows the involvement of both German and other European industry under the lead of Airbus Defence & Space.

The EML was originally intended as a “class 1” payload, with its own full-size rack destined for a location in the Columbus lab. With the development of the other large European research facilities like Biolab etc. already much advanced, one of the last remaining standard flight racks of ESA was therefore earmarked for EML. The early development phases were performed on this basis, when suddenly an important boundary condition changed: Triggered by the tragic accident of the Columbia Space Shuttle in 2003, the US Administration decided to stop flying the Shuttles by the end of 2010. This had severe consequences for the transport of crew and material to and from the station, and for a number of years it would be impossible to bring complete racks to the ISS. The smaller size of the hatches on the Russian side of the station does not allow transfer of full size racks from one module to another, and for a while there was no type of vehicle docking at the US/international side of the station.

As a consequence the DLR and ESA management requested a re-direction of the EML design towards a modular “sub-rack” approach that would allow transportation on either ATV, HTV, or Progress, followed by integration on orbit into an existing rack. The host rack selected for this purpose is the European Drawer Rack (EDR), which was however conceived to accommodate several smaller “class-2” payloads that can be exchanged and replaced within months, and was not originally intended to host a large facility as EML over many years. But the industrial team succeeded in devising a concept that would allow to distribute EML over 4 large modules and an exchangeable sample container, all connected by a multitude of cables and hoses in front of the rack. This concept was found feasible and was subsequently developed further into a successful design of a “distributed” facility that fulfils all original scientific requirements.

EML now occupies 5 out of 7 available experiment accommodation spaces in EDR, and makes use of most of the resources provided through the host rack, i.e. power (120 and 28 Vdc), cooling (water and air), data and video interfaces, pre-vacuum and venting line. In addition to this, EML brings some of the needed resources by itself, such as the high purity noble gases (Argon, Helium), a turbo-molecular pump to generate ultra-high vacuum, mass memory for data and video as well as its own data management & control system.
Figure 1 gives an overview of the EML configuration inside EDR.

EML elements

The EML payload consists of 4 major modules and an exchangeable sample chamber. These are the

- Experiment Module
- Levitation Power Supply and Water Pump Module
- Gas Supply Module (Argon and Helium)
- Experiment Controller Module

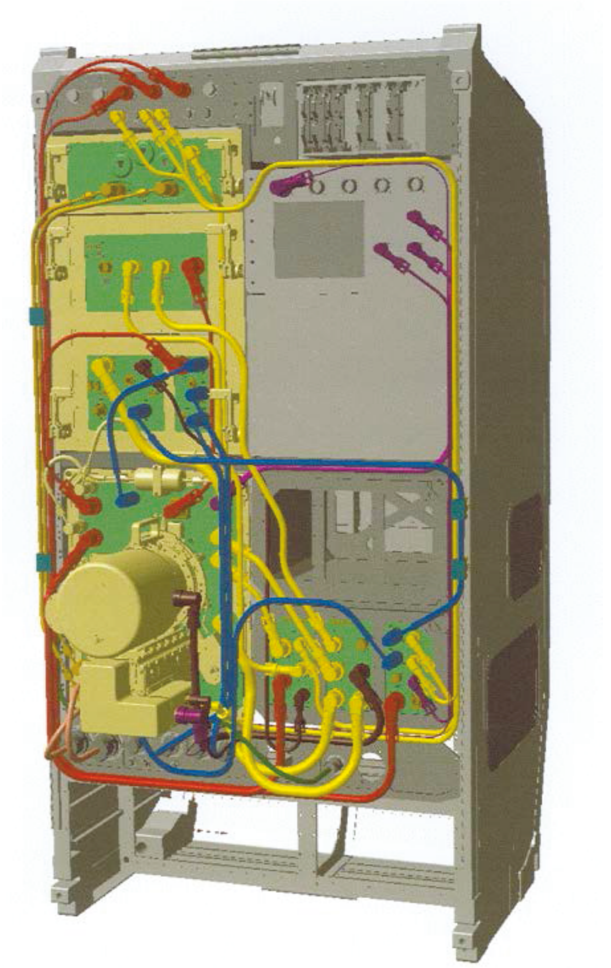

FIG. 1. Illustration of EML inside the EDR rack

The Experiment Module (EXM) houses the core experiment chamber with all diagnostics, RF coil system, mechanisms and samples, and defines the payloads capabilities with respect to the experiment. It is the biggest and most complex module of the four. Central part of it is a stainless steel ultra-high vacuum chamber, to which the exchangeable sample chamber is being flanged upon upload to the ISS. The process atmosphere is either ultra-high vacuum or high-purity (99.9999%) noble gas, Argon or Helium or a mixture of these. The pressure inside the 2 chambers can be varied between 10^{-8} and 400 mbar during the experiment runs. Furthermore the EML gas distribution system offers the possibility of a closed loop gas circulation, in order to either apply a smooth gas flow onto the sample during the experiment, or to flush particles and dust into a filter afterwards.

The coils generating the electromagnetic fields are made from oxygen-free copper and are water cooled from inside. Both the levitation power and the cooling water are supplied from the second large module, the Levitation Power Supply and Water Pump Module (LPS/WAT), through cables and hoses. The design of the coil is such that the RF currents generating the positioning and heating fields are superimposed within the same coil, thereby achieving a high concentricity of both fields and hence an optimized positioning of the sample. The positioning field is of quadrupole type with low heating efficiency and operates at about 140 kHz, whereas the heating field is of dipole type with low forces on the sample and operates at about 380 kHz. Depending on the sample material and process environment heating rates of about 100 K/s can be applied, allowing sample temperatures of up to 2100°C to be reached within 1 minute. Both heater and positioner voltages can be varied as linear functions of time.

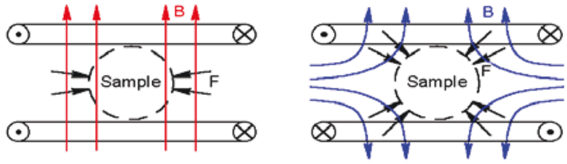

FIG. 2. Heating and levitation/positioning field

The 18 samples are housed in individual sample holders that are large enough to allow contactless free floating during the experiment run, but provide the necessary containment and handling interface during storage and transfer into the chamber. Furthermore they prevent inadvertent contact of the samples with the coil; important especially during the liquid phase. In the same time however they need to enable visual observation of the samples by the two cameras and the optical pyrometer. This is achieved through two basic types of holders: a ‘cage’ type made of rhenium wires on top of a ceramic foot, and a ‘cup’ type that is entirely from silicon nitride ceramics and has observation cut-outs at the top and at one side of the cylinder. These materials are selected to withstand the temperatures and the thermal shock in case of inadvertent contact with a molten sample, and to prevent undesired coupling of the holder to the electromagnetic fields.

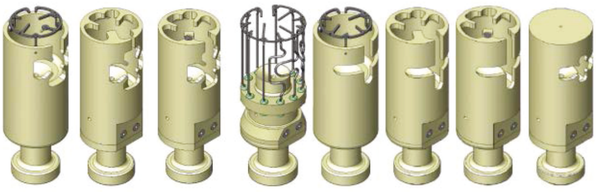

FIG. 3. Variations of EML Sample Holders

The sample holders are mounted on a turnable carousel, allowing selection of any sample to be processed, without pre-defined order. Motorized mechanisms rotate and transfer the holder with the sample into the centre of the coil, in an automated sequence commanded from ground.

The scientific measurements and observations need to be contactless as well. EML offers three main instruments:

- a pyrometer
- a video camera in the axial direction of the coil
- a high-speed camera in the radial direction.

The digital pyrometer allows temperature measurements in the range of 300 to 2100°C with a resolution of ≤ 0.1 K above 600°C.

The cameras are able to observe fast sample surface oscillations, to determine surface tension and viscosity. Also the measurement of thermal expansion is supported with a capability to detect relative size changes down to 2*10-4. The high-speed camera allows frame rates up to 30.000 fps to visualize solidification events. Both cameras provide also the possibility of a thermal radiation mapping, allowing to display the temperature distribution across the sample in false colours by offline ground video processing.

A fourth instrument measuring the electrical properties of the sample is currently being developed and will be launched and installed in the near future, see Chapter 5.

For the manipulation and stimulation of samples during the experiment run the following techniques are available:

- RF stimulation: the electromagnetic field can be programmed to include either short pulses of heater power peaks or harmonic modulations, thereby inducing surface or temperature oscillations of the liquid sample to determine thermo-physical properties of the melt.

- Nucleation triggering: both sample holder types can be equipped with a trigger needle. By slowly moving the holder until the needle touches the liquid sample, the nucleation process of an undercooled melt can be triggered at a desired temperature.

- Convection cooling: a small nozzle integrated with the coil system allows to apply an adjustable gas flow onto the sample, introducing desired gas convection or enhancing the cooling rate in a limited range.

- Chill plate cooling: the ‘cup’ type holders allow integration of a chill plate, which increases the cooling rate instantly upon contact with the sample. This can be used to freeze the microstructure at the solid/liquid interface close to the sample surface.

The Experiment Controller Module (ECM) is used for the data acquisition and commanding/control of all facility functions. Furthermore it contains the power supply electronics for all sensors, actuators and elements other than the levitation & heater fields, and a dedicated computer unit with hard-disk for the high-speed camera system. It interfaces with EDR data and power provisions on one side and most of the EML subsystems on the other side, therefore comprising a multitude of connections arranged on a very limited front panel size.

Standard scientific and housekeeping data are acquired at rates between 1 and 100 Hz, which are downlinked in real time through EDR and Columbus. The high-speed camera (HSC) generates large amounts of data within short periods, which are then transferred from the camera internal ring memory to the HSC operating system for lossless compression and intermediate storage. Download to ground occurs offline between experiments, using the HSSL video interface of EDR. To allow real time monitoring of the experiment a lower quality NTSC signal is provided to the EDR analogue video interface, and further to the operators on ground.

The axial camera system however has its own computer unit, integrated directly in the Experiment Module, which includes a hardware data compression and storage capability.

The process control is performed in a semi-automated way: ground operators select the sample to be processed, with matching experiment parameters and settings for the process environment. These are uplinked by telecommand, and the ECM initiates all necessary steps to bring the facility into the desired status. Pre-defined routines for all actions related to facility preparation and experiment runs are stored in the on-board software, and can be started either by telecommand from ground or by an automatic ‘experiment handler’ software. The ISS crew is usually not involved, with the exception of a few manual operations like opening a (safety) gas valve before starting a series of experiment runs.

During an experiment the parameters can be modified – within safety imposed limitations – by ground command, thereby giving the scientists the flexibility to influence the process according to near-real time observations or knowledge gained from previous runs. A separate, dedicated ‘hazard control electronics’ unit monitors the actual heater profile and ensures that it never exceeds the envelope approved by the ESA and NASA safety experts.

One of the special challenges during the development and operation of EML is the toxic characteristic of metal dust particles. Each time an alloy sample is heated up and molten it evaporates small amounts of material. Since these are potentially toxic for the crew, it has to be assured that the resulting dust particles are captured within the hermetically sealed process chamber, with 2 levels of containment (1-failure tolerant). In addition the Safety Panel requires that the total amount of generated dust is limited and stays below critical values. Therefore both the pre-programmed parameters and the real time variations need to be compared against the allowable envelope.

If the experiment is performed in vacuum, the evaporated material will plate on all cold surfaces directly exposed to the sample. This includes especially the coil, being in closest vicinity of the hot sample. The resulting growth of condensed material on the coil windings constitutes an operational limit and is monitored during the experiments. As a precondition, the temperature dependent evaporation rate of each sample material processed in EML is determined in the course of the ground support programme.

Furthermore the plating would also affect the observation windows for the optical diagnostics, if they were in a direct line of sight to the sample. Since this would however quickly lead to a dramatic loss of transparency, and hence dark video images with insufficient contrast, a double mirror concept is used to protect the optical windows from direct exposure. Instead, the front mirror is exposed, which can be exchanged against a new one when the reflectivity has degraded too much. By means of two small, compact mechanisms inside the vacuum chamber it is possible to rotate from a stock of 5 and 48 mirrors for the radial and axial camera direction, respectively, into the optical path.

The development of these mechanisms, that are driven from stepper motors outside of the vacuum chambers, and has to work flawlessly over several years without maintenance, was just one of various special challenges during the development of EML.

3. EML LAUNCH, INSTALLATION AND COMMISSIONING

The overall mission concept foresees the facility to be launched and installed in the ISS, remaining there for at least 5 years. Distributed over this period a number of experiment batches (currently assumed 6) will be uploaded and, after completion of the experiments, returned to ground for further investigation of the samples in the scientists' labs. The first batch was launched together with the facility, so that scientific operations could start without delay as soon as the commissioning was completed. The processing of one batch will take several months, and is preceded by an extensive ground support/ preparation program. Likewise, it will be followed by coordinated ground investigations and analyses of the samples and data after their return. This leads to a continuous flow of parallel activities covering the preparation of the next batch, on-orbit processing of the current batch, and post-flight analyses of the previous batch of experiments in an approximate 1-year cycle.

To enable all necessary activities the EML programme has produced three hardware models:

- the Flight Model, launched to the ISS and installed in the Columbus lab;
- the flight-identical Operational Model, installed in the EDR Ground Model at MUSC;
- a simplified Training Model, available at the European Astronaut Centre in Cologne for crew training.

In addition a lab model, largely inherited from the TEMPUS programme, is used for experiment preparation measurements, and a software simulator was made available to the scientists for development and iteration of temperature-time profiles and various equipment settings.

Launch and Installation

The EML Flight Model was transported to the ISS on board the Automated Transport Vehicle ATV-5 which docked at the ISS on August 12, 2014.

FIG. 4. German Astronaut Alexander Gerst working on the installation of the EML Experiment Module into the EDR Rack on board the ISS

Due to the extent of the hardware consisting of a large number of items, a complex transfer and installation procedure had to be applied before EML was ready for operation. The two largest modules had to be unpacked inside ATV in order to fit through all hatches and passageways in between ATV and the Columbus module.

In the course of August and September the EML components were successfully assembled and installed by the German astronaut Alexander Gerst, followed by the first EML switch-on.

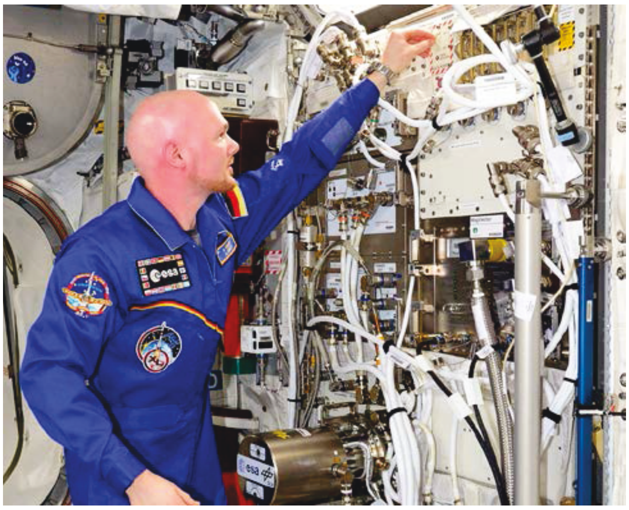

FIG. 5. First EML Power-up by Astronaut Alexander Gerst

On-Orbit Commissioning

The on-orbit commissioning was then executed from ground. As a first step, a thorough checkout of all EML subsystems was successfully performed, proving that the facility has survived the launch and that all its subsystems and diagnostics work as expected. This functional test was followed by a first Facility Checkout Experiment (FCE) in November. This was the first time a sample was levitated and positioned in EML, since levitation on ground, under 1g-conditions, is not possible with the EML coil system.

The FCE was designed to apply all available diagnostic systems and stimuli, and to test settings for positioner field control voltages under different experiment conditions on a solid sample. It turned out that the positioning behaviour was slightly different than expected, showing lateral sample movements when heater and positioner values were changed. A modified version of the related control profiles was developed and tested in a repetition of the FCE in February 2015. During this second checkout experiment, a Zr and a FeCrNi sample were stably positioned and subsequently molten and undercooled. This marked the successful end of EML Commissioning. Lessons learned from the commissioning were then implemented in the parameter sets for the scientific experiments.

4. EXPERIMENTS AND OPERATIONS

The planned experiments cover two major scientific topics: a) Measurement of thermo-physical properties (viscosity, surface tension, density, thermal expansion, etc.) and solidification; b) investigation of the sample solidification behaviour.

In order to investigate the undercooling and solidification velocities, the temperature of the onset of nucleation is measured with the pyrometer and the solidification velocity is determined from the high-speed video images. Solidification can either occur spontaneously or be triggered by touching the undercooled sample with a nucleation trigger needle which is part of sample holder.

Heat capacity, effective thermal conductivity, enthalpies, solid fraction are determined e.g. by the modulation of the heating input power into the sample and measuring the temperature response.

By pulsing the heating field to induce surface oscillations in the molten sample surface tension and viscosity can be determined by observation of the surface oscillation frequencies and the decay of the oscillation amplitude by video cameras.

Thermal expansion data can be obtained by measuring the sample size with video cameras using sub-pixel resolution techniques.

Changes in the coupling of the sample to the RF magnetic fields can be used to determine the temperature dependent electrical conductivity.

EML Operations Scenario

EML is planned for an in-orbit lifetime of 6 batches with 18 samples each, shared between a broad international scientific community. For the first batch of experiments, ten research teams and industrial co-workers are planning for 36 individual investigations, typically requiring multiple melt and solidification cycles for each sample.

EML integrated in EDR is operated by the German Microgravity User Support and Operation Center DLR MUSC as part of the established ESA Ground Segment for ISS operations. Data services to and from EML (commanding, telemetry and file up- and downlink) are based on the utilization of the standardised systems available to all European USOCs - customised for EML requirements. In that scenario, MUSC is not only responsible for the scientific preparation of the experiments but also for the operation preparation for the experiments in EML, e.g. the development of crew and ground command procedures and all additional operational products (e.g. ground displays) needed to conduct the experiments on-board the ISS from ground.

The EML Ground Segment at MUSC is embedded in the ESA Ground Segment for Columbus operations. Console positions at MUSC (Fig. 6) connect to the standard ground segment architecture using the Payload Data Center client software.

FIG. 6. MUSC Control Room for ISS payload operations

For EML, four consoles are available covering the following functions:

- EML Operations Lead
- EML Operations Coordinator
- PI console for real-time experiment monitoring
- Simulation / Payload Development support.

Each console provides monitoring and control functionality via the PDC client software, as well as access to the Col-CC and NASA Ops Support tools.

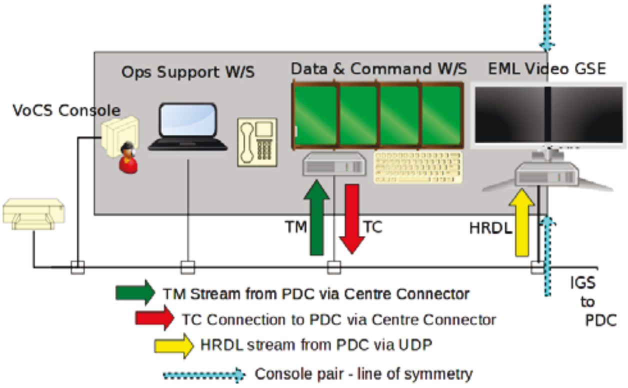

FIG. 7. Console set-up for EML operations

For the display of the live video and the generation of the scientific video data from the on-board recorded data, a dedicated video ground support equipment was developed. This tool allows the synchronous visualization of the four video channels generated by EML.

The EML data, i.e. scientific and facility housekeeping data are archived in a data archive based on the Hypertest platform. The data can be distributed easily and fast to the scientific community via this archive. In addition, Hypertest serves as long term data archive fulfilling ESA and DLR data holding policies.

Experiment Preparation: Ground Support Program

The EML offers a high degree of flexibility to the user, with several hundred freely adjustable experiment parameters, e.g. heating power and time, modulation frequencies, camera settings, etc. These parameter sets are defined, tested and validated in the frame of a preparatory Ground

Support Programme (GSP). The experiment preparation is embedded in the overall operations preparation at DLR MUSC and the DLR Institute of Materials Physics in Space. GSP covers all the activities needed to transcribe the individual scientific ideas into verified experiment and facility control parameters and files. It provides the scientific users with technical and scientific services in the preparation, performance and evaluation of the experiments.

The ground support program consists of three major parts with respect to operations preparation.

Sample Characterization

The determination of certain physical sample properties is mandatory for the experiment preparation and execution, e.g. evaporation rates, resistivity and emissivity.

The knowledge of the amount of sample material evaporating from the sample surface during processing is essential because the evaporated metal dust is a resource in the EML. The deposited metal layer growing stably on the coil is limited and the evaporated metal must not exceed certain limits, due to the toxicity of metallic dusts. Therefore the evaporation rate of the each flight sample composition is measured in a dedicated ground model on flight sample material provided by the respective science teams. The obtained data are later used in the experiment planning. During the real-time experiment operation, the evaporation rate is used to observe that the element specific limit values are not exceeded and to monitor the layer-thickness growing on the coil.

For the detailed planning of the experiments also the coupling of each sample to the RF field has to be known. Since EML is not designed to levitate samples under terrestrial conditions, all ground based measurements are performed on solid samples suspended in the coils. The obtained coupling data are later used in order to simulate the required temperature time profile of the sample with an EML simulator software.

For a correct temperature measurement with the pyrometer on-board, the sample emissivity is measured in the EML ground model. The sample is heated until melting sets in and by a comparison of the measured and literature melting point the emissivity can be derived. The optical setup and used pyrometer of the ground model is comparable to the EML facility.

Experiment development

The first step in the experiment development is the definition of the individual operational flow for each experiment, yielding the outline of all nominal and contingency operation For that purpose, so called ‘science protocols’ are prepared by MUSC on behalf of and in cooperation with the science teams, describing key temperatures of the samples to be reached, facility settings (camera, pressure, etc.) and a detailed experiment planning with respect to e.g. facility configuration, sequence of planned science runs, diagnostic settings, what-if scenarios etc. These science protocols are the base for the further development of the parameter sets.

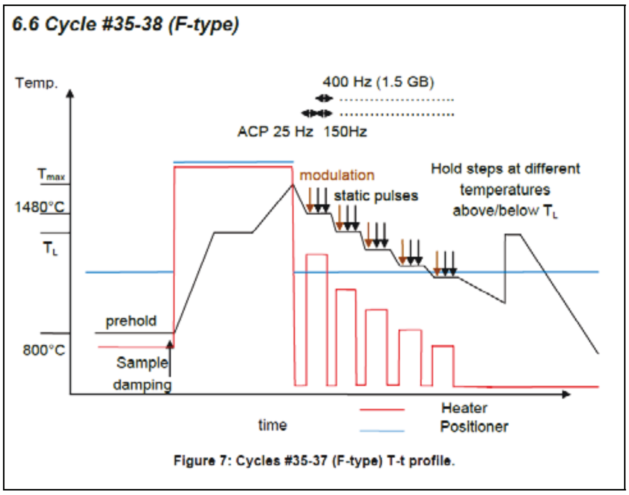

FIG. 8. Example of a Science Protocol

EML experiments require two sets of parameters: The experiment parameters (EPs) define the experiment as planned. Each thermal cycle consists of numerous (typically more than 20) individual steps, which are described by 40 parameters each. A typical experiment consists of a multitude of melt cycles, 35 in average.
The so called limit parameters (LPs) provide an independent envelope of RF values for each experiment that must never be exceeded. This feature was implemented in order to assure that the vapour generated by each experiment remains below the allowable toxicity level under all circumstances, even in case of a malfunction of the facility.

The core parameters for both EP sets are developed with the EML experiment simulator (Fig. 9), which currently predicts temperature time profiles from applied RF parameters and the coupling behaviour of the sample to the RF field.

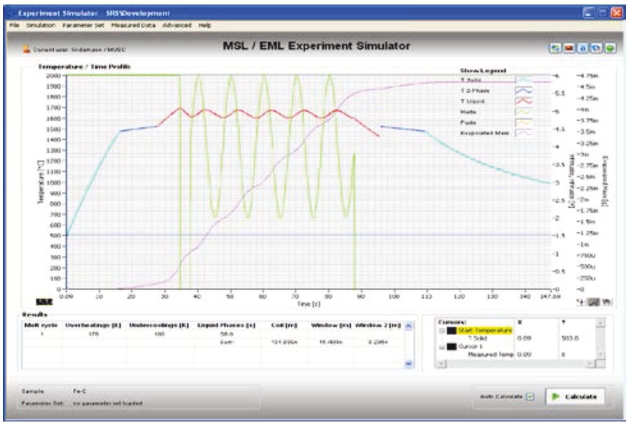

FIG. 9. Example for development of temperature/time profile in EML simulator

Experiment verification

After development of the complex parameter sets by means of simulation, they must be validated in a representative EML model. For this purpose the Operational Model (OM) located at MUSC is used. During the validation the parameter sets are processed on a suspended high melting sample and thus the parameter sets and the experiment performance can be validated. Especially the timing and interaction of the two independent sets of parameters is checked.

First Experiments: Batch 1

The EML Batch 1 consists of approximately 600 individual melting and solidification runs on the 18 sample on board.

The first sub-batch, 20 thermal cycles on 4 different sample materials was performed in April 2015. From an operational perspective, all thermal cycles could be performed successfully according to the adapted Experiment Parameter sets. The EML house keeping data were provided to the scientific community for scientific evaluation. Data deliverables consist of a subset of the EML telemetry and the experiment related live video feeds of both cameras.

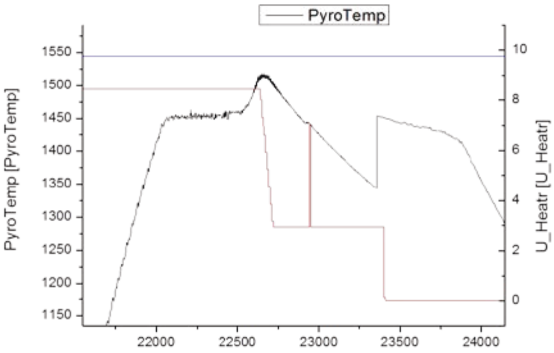

FIG. 10. Temperature (black line) vs. time profile of FeCrNi melt cycle, performed during Batch 1.1, with heater (red line) pulse to investigate surface tension and viscosity at low level of undercooling and subsequent recalescence event

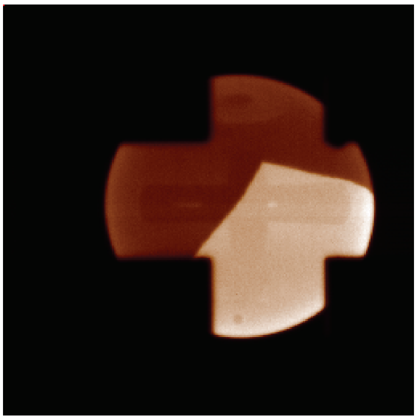

FIG. 11. Solidification front moving through a sample

Another 550 science runs on 16 samples are foreseen in three sub-batches (1.2 a, b, and c) between November 2015 and summer 2016. After completion of the Batch 1 experiments the sample chamber will be removed from EML and returned to ground. Up- und download of SCHs and other EML equipment will make use of the SpaceX 'Dragon' cargoship and possibly other vehicles.

Operations Planning and Constraints

The EML experiments are designed to run semi-autonomously with interaction and control from ground Due to the fast processes during heating, melting and cooling, a turn-around time of 5 seconds between telemetry and video reception at MUSC and a command reception by EML is required during experiments. Experiment parameter reprogramming between single experiments is foreseen to maximize the science output. To optimise microgravity conditions, experiments are performed during the crew sleep periods. However, EML relies on occasional crew support for the handling of the gas supply valves and for the change of the radial camera optics between the science runs. Between batches, the SCHs are exchanged and LP sets loaded with crew support.

Experiments with other COLUMBUS vent line users (e.g. the PK-4 payload) are mutually exclusive. During thruster firings, experiments need to be interrupted. During downlink of the science video data, a bandwidth of 32 Mbps is requested.

These requirements are provided to the European Planning Team according to the respective need dates during tactical planning.

Based on the previous on-orbit experience, approximately six science runs can be accommodated per night. Figure 12 shows a flow chart of the Batch 1.2a planning, as an example for the sequence of experiments during a sub-batch campaign.

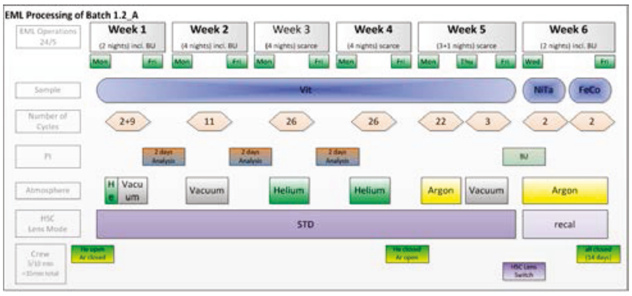

FIG. 12. Flowcharts of Batch 1.2a planning

5. OUTLOOK AND FUTURE ACTIVITIES

The EML is planned to be operated on the ISS for at least 5 years, and possibly longer. In this timeframe it is intended to process at least 6 batches of experiments.

In parallel to the execution of batch1 , the Ground Support Programme for the second batch is already under way. It has an expected duration of approximately one year, so that the operational products needed for its' on-orbit performance will be available when Batch 1 is completed.

The scientific programme for batch 2 features 980 thermal cycles on 18 sample compositions, including semi-conductors. On each of the specimen, a variety of measurements shall be performed, so that the samples are shared among the international research teams.

Also for batches 3 and 4 the scientific community has already identified a preliminary list of materials and experiments, and the corresponding 'Experiment Requirements Documents' are under preparation. Once they are finalized and agreed, the ground preparations can be started.

In general it is envisaged to always perform the on-orbit operations in parallel with the ground based preparation of the follow-on batch in order to enable continuous on-orbit operations, maximizing the throughput of experiments in a given timeframe.

The modular concept of EML allows exchange of defective or degraded subsystems, as well as re-supply of consumed resources, e.g. fresh filters or a new set of gas bottles. This will be needed to extend the operational lifetime and provide sufficient resources for a maximum of experiments.

Furthermore it enables the addition of new elements over the years, to enhance the facility's functionality or connect additional diagnostic instruments. Two such 'upgrades' are already under way:

The 'Sample Coupling Electronics' is a measurement device for electrical properties of the sample material. It makes use of the fact that the electrically conductive samples interact with the field around the coil. The feed currents to the EML resonance circuit react very sensitive to any changes in the total inductance of the coil system, including the levitated sample. Therefore an electronic device for measuring this current, the voltage and the phase shift between the two was developed by DLRs Institute for Materials Physics in Space. The coupling of the sample is a function of its material properties. From the data obtained the scientifically important electrical resistivity and thermal expansion can be derived. The flight model of this measurement device is currently in the test phase and will be delivered to the ISS in 2016. The needed interfaces on EML side are already implemented, allowing a straightforward installation of this additional electronics box.

Another potential enhancement for EML is an 'Oxygen Control System'. Due to its high reactivity with many materials, especially at higher temperatures, oxygen represents one of the most relevant "contaminants" for the melt cycle experiments. The presence even of smallest amounts of oxygen in the atmosphere can lead to the forming of an oxide layer on the surface of the sample, or to dissolution of oxygen into the liquid melt. These occurrences can significantly alter the experimental results. Therefore the exact knowledge of the residual oxygen traces in the process atmosphere, and a way to influence and control it, would be an essential add-on.

A prototype of such a system has been developed and tested in the frame of an ESTEC technology study. It includes a potentiometric sensor and an oxygen titration pump integrated in a gas circulation loop, enabling the exact measurement and adjustment of oxygen partial pressure in a range down to 10^{-15} Pa. The concept has been demonstrated to be compatible with the EML boundary conditions, and the development of a flight unit is planned to be started shortly. The EDR host rack would still allow the installation of an additional module next to the existing EML facility, so that the gas loop connection between the two can be kept as short as possible.

With these added capabilities the EML will further expand its range of diagnostic tools available to the scientists, and keep it at the forefront of containerless processing also in the coming years.

6. REFERENCES

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