EML - An Electromagnetic Levitator for the International Space Station

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Abstract. Based on a long and successful evolution of electromagnetic levitators for microgravity applications, including facilities for parabolic flights, sounding rocket missions and Spacelab missions, the Electromagnetic Levitator EML provides unique experiment opportunities onboard ISS. With the application of the electromagnetic levitation principle under microgravity conditions the undercooled regime of electrically conductive materials becomes accessible for an extended time which allows the performance of unique studies of nucleation phenomena or phase formation as well as the measurement of a range of thermophysical properties both above the melting temperature and in the undercooled regime. The EML payload is presently being developed by Astrium Space Transportation under contracts to ESA and DLR. The design of the payload allows flexible experiment scenarios individually targeted towards specific experimental needs and samples including live video control of the running experiments and automatic or interactive process control.

1. Motivation
Electromagnetic levitation is a powerful technique for containerless processing of electrically conducting samples such as metals and semiconductors. Eddy currents are induced in the sample by the electromagnetic field generated by the levitation coils. The sample is heated by ohmic losses of the induced eddy currents, whereas the interaction of these eddy currents with the electromagnetic field leads to a displacement force on the sample towards the center of the coil system which is used to control the position of the sample inside the coil.

The prospect of processing metallic samples without contact to a container wall represents the striking advantage of electromagnetic levitation. This means that experimental investigations can be performed with a free floating liquid droplet in a wide range of temperatures above and below the melting temperature of the material.

In particular, it is possible to undercool the sample significantly. Undercooling describes a non-equilibrium state where the sample is liquid at temperatures below its equilibrium melting temperature. In order to achieve significant undercooling nucleation has to be reduced as much as possible. This is achieved mainly by the absence of any container walls in contact with the liquid sample, a feature inherent in the electromagnetic levitation technique, in combination with an ultraclean process environment, e.g. ultra-high vacuum or high-purity noble gases.

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Patented by Muck in 1923 [1], electromagnetic levitation is one of the oldest levitation techniques used for containerless processing experiments and has been applied in material science investigations for decades. Other techniques comprise aerodynamic and acoustic levitation [2], as well as electrostatic levitation [3]. In this technique levitation forces arise from electrodes located above and below the sample that contains a surface charge, whereas heating is performed e.g. via lasers. Electromagnetic levitation is the most mature of all containerless processing techniques and has been applied both in ground-based experiments as well as in microgravity experiments with a wide range of alloys for decades [4]...[9].

In order to levitate a sample in a ground-based experiment strong levitation fields are needed in order to counteract gravity. This leads to a number of drawbacks and limitations for the experiments to be performed. Due to the strong levitation fields required for positioning against gravity positioning and heating are strongly coupled, the achievable minimum temperature is high which excludes samples with low melting points, the samples are deformed by the electromagnetic pressure, and strong convection is induced.

These drawbacks can be eliminated if levitation is performed under microgravity conditions where only small levitation forces are required to compensate for the residual accelerations. With a coil system optimized for microgravity conditions heating and positioning can be performed almost independently. Since the required positioning forces are very low the low temperature regime becomes accessible, convection is reduced and deformation of samples eliminated. As a result, many more sample materials can be processed and their thermophysical properties can be determined with higher accuracy.

There is a wide range of opportunities to perform electromagnetic levitation experiments under microgravity each with its unique advantages and disadvantages. One factor to consider is the microgravity quality: Since the coils are optimized for low positioner forces the sample is only weakly mechanically coupled to the electromagnetic field. This mechanical system can be described as an almost ideal harmonic oscillator with resonance frequency in the order of 1-3 Hertz and almost no damping. Hence mechanical disturbances in this frequency range must be minimized to achieve a stable sample positioning.

Other factors are the duration of the microgravity periods, and the possibilities for the experimenter to interactively control the experiment process during the runs. Electromagnetic levitators have been developed for a wide range of carriers and missions, as follows:

- Parabolic flights provide several periods of reduced gravity in the range of several milli-g for about 20 seconds each providing the experimenter direct access to the experiments during the
flight. The environment is suitable to perform individual melt cycles of dedicated samples for which such a cycle can be performed in the limited available time [10], [11]

- Sounding rocket flights provide a very quiet microgravity environment (about $10^{-5}$ g) for about 6 minutes which allows performing multiple melt cycles. Experiments are controlled remotely via telemetry [12].
- Spacelab flights as performed in the 1990s provided a mostly quiet microgravity environment, sometimes interrupted by crew exercise activities ($10^{-4}$-$10^{-5}$ g). Due to the mission duration which was in the order of 1-2 weeks, several experiments with durations of several hours each could be performed, where each experiment with a given sample included several melt cycles with that sample. Experiments were pre-programmed; interactive access via telemetry was possible. [13].
- ISS missions are essentially an extension of the former Spacelab missions and provide long-term access to a good microgravity environment. Several batches of samples can be uploaded to the facility, processed, and returned to ground. Experiments are pre-programmed; interactive access via telemetry is possible. An exhaustive discussion of experiments that can be performed with EML on ISS is given in [14].

2. Heritage of Electromagnetic Levitators

Electromagnetic levitation under microgravity has been successfully applied on a number of hardware carriers for more than 25 years. [4] … [8]. Starting with a laboratory model developed by Astrium in the mid-1980’s, a long-term development program was established which provided electromagnetic levitation facilities with increasing performance and versatility. These electromagnetic levitation facilities were collectively known under the name TEMPUS which is a German acronym (*Tiegelfreies Elektromagnetisches Prozessieren unter Schwerelosigkeit*). A TEMPUS parabolic flight facility and a TEMPUS version for the TEXUS sounding rocket targeted towards longer microgravity periods and reduced microgravity disturbances offered by sounding rocket missions were developed and had their maiden flights in the late 1980s. The next big step forward was the development of a TEMPUS version for Spacelab which offered mission durations of 1-2 weeks and thus allows processing numerous samples for an extended time during one mission. TEMPUS was operated on three Spacelab missions (IML-2 in 1994, MSL-1 and MSL-1R in 1997) and provided a wealth of scientific data.

Since the first parabolic flight and sounding rocket missions these facilities have been continuously upgraded. Numerous parabolic flights and sounding rocket missions have been performed with a dual focus on both implementing and testing of improvements and new functions of the system and on conducting scientific experiments. Meanwhile these missions are routinely performed, the last TEXUS mission was completed in April 2011, and the parabolic flight facility is currently being upgraded in preparation of future missions.

With the advent of the ISS new opportunities for electromagnetic levitation are now available, in particular much longer mission durations compared to a Spacelab mission (years instead of days). In order to exploit these opportunities ESA and DLR have decided to join forces and to develop an ISS version of TEMPUS, now called EML or *Electromagnetic Levitator*. The EML facility is currently under development and will be described in detail in the following chapters.

Funded and contracted by DLR Space Administration Astrium has been responsible for the industrial implementation of the electromagnetic levitators from the beginning of the development program [5] … [8]. The technology of all major elements such as the RF generator, the oscillating circuit and coil system, the ultrahigh vacuum chamber and associated mechanisms, the scientific diagnostic elements and so forth has been developed by Astrium in a long-term cooperation with a number of key partners such as the DLR Institute of Materials Physics in Space, and Pink GmbH. As Prime Contractor responsible for the overall system Astrium has manufactured, tested, and delivered, upgraded and refurbished all above mentioned electromagnetic levitators and is involved the mission operations of these facilities in cooperation with the DLR Microgravity User Support Center. The
development of the EML facility for ISS is carried out by Astrium and the established industrial consortium under joint funding of DLR and ESA.

During this long-term development program Astrium has acquired unique expertise in the field of electromagnetic levitation facilities which is underlined by the long-term continuity of the project staff.

3. EML on ISS: Payload and Mission

3.1. Overview
In order to accommodate the ISS version of EML inside the European Drawer Rack (EDR) of the International Space Station ISS Columbus module the facility is composed of four modules designed to fit into drawers and lockers of EDR, as shown in figure 2. The main functions of the 4 modules are given in table 1. The EML is designed as class 2 payload meaning that EML will use the resources provided by EDR, i.e. power (120 & 28 VDC), cooling (water and air), data and video interfaces, pre-vacuum and vent line as well as dry nitrogen. On the other hand EML will also provide dedicated resources as e.g. high-purity noble gases (Ar, He), ultra-high vacuum generated by a turbo-molecular pump, mass memory for data and video as well as its own data management & control system.

| EML Module                     | Main Function                                                                 |
|--------------------------------|-------------------------------------------------------------------------------|
| Gas Supply Module (GAS)        | Storage and distribution of the noble gases                                   |
| Levitation Power Supply/ Water| Provision of RF voltage to the RF coil generating the electromagnetic fields.  |
| Pump Module (LPS/WAT)          | Secondary cooling loop to subsystems                                          |
| Experiment Module (EXM)        | Core experiment: comprising e.g. vacuum chamber, RF coil, diagnostics,        |
|                                | mechanisms, samples                                                           |
| Experiment Controller Module   | Data management & control, power distribution                                 |
| (ECM)                          |                                                                                |

The modular design of EML allows not only the exchange of the above mentioned complete modules but also supports exchange of subsystems such as the optical diagnostic systems, video control & compression units, mass memory, and electronic units controlling motors or pumps, and filter cartridges in the gas system. The concept of in-orbit replaceable units (ORU) allows both, maintenance of modules or subsystems by the crew if needed (e.g. replacement of empty Gas Module) as well as future upgrade of optical diagnostic systems (cameras and/or pyrometer) with specific diagnostic tools developed for achieving dedicated experiment goals.

Crew involvement in facility operation is limited and only needed for facility installation into EDR, exchange of sample chambers and transfer of samples from the sample chamber into the Sample Download Container. The experiment operation itself is fully automated and does not require crew involvement. Instead, the experiment control concept is based on pre-defined parameter sets which are developed and validated on ground. In addition the control concept foresees re-programming capabilities for the change of the pre-defined parameters due to lessons learned from previous experiment runs.

According to the experiment scenario the facility will be configured by ground commanding prior to an experiment run. However, intervention from ground is also possible during automated experiment processing. The need for such ground interventions may arise in case of positional instabilities of the sample. The facility design and operational concept allows such ground intervention with short reactions times. Hence the experiment operation can be described as near real-time operation requiring live video transmission for ground monitoring as well as near real-time interactive capabilities for ground commanding to interrupt or alter the pre-defined automated process. This
automated process is sub-divided into short time intervals in which facility parameters are set according to the loaded parameter set to define the temperature-time profile of the sample as well as the settings of the diagnostics and stimuli observing and affecting the sample.

![Image of EML Modules located inside the EDR rack, shown with interconnecting harness and lines](image)

**Figure 2.** EML Modules located inside the EDR rack, shown with interconnecting harness and lines

3.2. EML Payload Design
The Experiment Module (EXM) houses the core experiment with all diagnostics, vacuum chamber, RF coil system, mechanisms and samples and defines the payloads capabilities with respect to the experiment. Figure 3 gives a functional overview of the various subsystems which are implemented in the EXM as described hereafter.

3.2.1. Process Environment. Central part of the EXM is a stainless steel ultra-high vacuum chamber with all-metal gaskets. The exchangeable sample chamber will be flanged to it, whereas the vacuum interface is secured by two vacuum locks. The process atmosphere is either ultra-high vacuum or high-purity (99.9999%) noble gas Ar or He or a mixture of these. The pressure inside the 2 chambers can be varied between 10⁻⁸ mbar and 400 mbar during experiment runs. To establish the ultra-high vacuum conditions a turbo-molecular pump is used interfacing the ISS vacuum line. The noble gases are provided by the EML GAS module which stores up to 500 Nl of He and 1000 Nl of Ar. The module can be exchanged if necessary. The EML gas distribution system also offers the possibility of a closed loop gas circulation by a specially designed UHV-tight gas pump. This feature can be used to either introduce a smooth gas flow onto the sample for scientific purposes or to flush sample particles or condensates into dedicated filters. The EML also possesses an interface to the ISS nitrogen supply, which might be used for flushing purposes or during storage times when EML is not operated.
The vacuum chamber also houses two double mirror systems which protect the optical viewports from evaporated sample material. Both mirror systems allow exchanging one of the mirrors by its respective sophisticated mechanics, if the reflection due to accumulated material is too low.

3.2.2. **RF Heating and Positioning System.** The RF heating and positioning system consists of the Levitation Power Supply providing the RF power and the Coil System Module (network of coil and capacitors, mounted to the vacuum chamber) generating the electromagnetic fields. Both, positioning and heating are done at the resonance frequencies of the positioning and the heating circuit, respectively. Thus the LPS only needs to compensate for the power losses within the self-oscillatory circuits with easy-to-handle currents in the order of 10 A. The design of the coil is such that the RF currents generating the positioning and heating fields are superimposed within the same copper coil which leads to a very high concentricity of both fields and therefore to an optimized positioning stability. 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 sample material and process environment heating rates of about 100 K/s can be applied such that sample temperatures of up to 2100°C can be reached within less than 1 minute. To meet scientific requirements heater and positioner voltages can be varied as linear functions of time. In addition, the heater circuit allows a harmonic voltage or power modulation as well as short pulses (0.1 s) as stimuli for the sample.
Figure 4. Superimposed electromagnetic fields in EML (note the diagram shows the two fields separately whereas just one coil is physically integrated in EML).
- Top: dipole heating field (red field lines)
- Bottom: quadrupole positioning heating field (blue field lines)

3.2.3. Sample Holders and handling: EML can accommodate 18 samples (5-8 mm diameter) per sample chamber. The samples are housed within individual sample holders (inner diameter 14 mm) mounted to a carousel within the sample chamber. By this mechanism, a selected sample can be transferred from the storage position to process position within the r.f. coil. The sample holder design provides a containerless environment for the sample during nominal processing while a contact of the levitated sample with the RF coil is prevented in case of any crew or station induced excessive accelerations, and also sample containment during launch is assured.

Two generic types of holders will be available; cage and cup with slit openings for observation from axial and radial direction by the EML diagnostic instruments. Common to both types is a ceramic foot on top of which the sample confinement is mounted. Depending on the scientific goal and/or the expected sample behavior (e.g. evaporation) one or the other type will be chosen. In order to prevent undesired coupling to the electromagnetic fields the sample holders are made mainly from ceramics. The selected silicon nitride is thermo-shock resistant and compatible with highly reactive melts. The cage design uses tungsten-rhenium wires with a geometry that minimizes coupling to the r.f. fields. The samples will be integrated into the sample holders in a glove box on ground and will then be transferred to the sample chamber under noble gas atmosphere until launch and mounting to the EML facility in orbit.

Figure 5. Proposed Sample Holder types under development.

3.2.4. Sample Stimuli. EML offers various methods for sample stimulation such that the sample's reaction on the stimulus can be observed by the diagnostics to derive the scientific goal. The various stimuli are:
- Short pulse of r.f. heater field: the force on the sample's surface created by the dipole field squeezes the sample and thus excites shape oscillations from which the surface tension and viscosity can be derived
- Modulation of r.f. heater field: the sinusoidal varied input power leads to a respective sample temperature response from which e.g. the thermal capacity can be derived.
- Trigger needle: a coated Rhenium needle integrated into the sample holder lid is used to touch the sample (by moving the sample holder relative to the free floating sample) and acts as nucleation trigger. Hence nucleation can be induced at defined undercooling temperatures and the solidification direction is defined and can be imaged by the orthogonally arranged video systems.
- Chill Cool Plate: ceramic plate integrated as top lid to the cup-type sample holder acting as heat sink for increasing the cooling rate at the sample surface when being touched with the chill cooling plate. The plate offers a small drilling (1.0 mm) to observe the temperature of the interface plate/sample.
- Gas flow: a gas circulation system allows generating an adjustable gas flow around the sample to impose dedicated cooling or convection conditions.
- Sample damping: the cone shape of the sample holder bottom can be used to mechanically dampen translational oscillations of the sample by moving the sample holder relative to the levitated sample.

3.2.5. Diagnostics - Pyrometry. EML offers a highly sensitive digital pyrometer integrated together with the axial camera in one instrument. Both instruments are using the same optical path where the NIR spectrum is separated from visible light by a beam splitter. The instrument called ACP (axial camera & pyrometer) observes the sample in axial direction of the coil system. Key pyrometer performance data are listed in table 2 below.

| Measurement rate: | 100 Hz |
|-------------------|--------|
| Measurement range: | 300-2100°C |
| Emissivity $\varepsilon$: | 0.05 ...1.00 |
| Integration time: | 5 ms |
| Measurement spot diameter: | 0.8 mm |
| Wavelength: | 1.45 - 1.80 µm |

Temperature resolution (for $\varepsilon = 0.05$):
- $\leq 0.1$ K @ $T > 600$°C
- $< 0.5$ K @ $500^\circ$C $< T < 600^\circ$C
- $< 1.5$ K @ $400^\circ$C $< T < 500^\circ$C
- $< 3.0$ K @ $300^\circ$C $< T < 400^\circ$C

3.2.6. Diagnostics - Axial Video System. For visual observation a digital high resolution video camera is integrated in the above mentioned instrument ACP together with the pyrometer. The camera is able to observe fast sample oscillations for measurement of surface tension and viscosity. The optics is also capable to detect relative sample size changes of $2 \times 10^{-4}$ supporting thermal expansion measurements. By its telecentric property the lens supports the mentioned measurements even for samples slightly moving +/- 1 mm back and forth along the optical axis. Key performance data of the ACP camera are given in table 3 below.

| Sensor: CMOS, resolution 1280x1024 pixel | Various fields of view, resolutions & max. frame rates, e.g.: |
|------------------------------------------|--------------------------------------------------|
| Digitalization: 10 bit/pixel             | - 10x10 mm: 704x704 pixel, 50 Hz                |
| Global shutter, fixed or auto exposure   | - 10x10 mm: 352x352 pixel, 150 Hz               |
| Frame rate enhancing by sub-sampling 2x2 (i.e. pixel reduction by factor 4) | - 8x8 mm: 280x280 pixel, 200 Hz |
| Focal point of optics: 1.7 mm above sample equator towards the pole | - 18x14 mm: 1280x1024 pixel, 15 Hz (for inspections) |
3.2.7. *Diagnostics - Radial Video System.* EML offers a second video camera, called HSC (high-speed camera) observing the sample through a 8 mm wide gap in the RF coil windings from the radial direction with respect to the coil. Hence the camera orientation is perpendicular to the one in the ACP such that EML cameras are observing the sample in two orthogonal views. The HSC provides two modes of observation called "oscillating drop mode" and "recalescence mode" which are achieved by a bifocal lens system allowing imaging the constant field of view on two different chip areas. This feature enables the HSC to acquire up to 30,000 frames per second in the high-speed "recalescence mode" at reduced spatial resolution still imaging the entire sample to visualize the solidification front growth. The "oscillating drop mode" achieves a higher spatial resolution at the expense of a reduced time resolution to support measurements on the surface shape oscillations and thermal expansion as described for the ACP camera. Key performance data of the HSC are given in the table below. The video captured by the high-speed camera is stored first in a camera internal ring memory in order to comply with high-speed requirements and in a later step transferred to dedicated mass memory. In order to capture the recalescence event on video the recording is stopped by an automated recalescence detection algorithm based on the temperature reading.

The HSC provides also the possibility of thermal radiation mapping due to the high digitalization which can be used to display temperature distribution across the sample in false colors by offline ground video processing. Minimum temperatures for which samples can be visibly observed are between 500 -1000°C depending on sample emissivity and exposure time.

| Table 4 | Key Performance Data of EML Camera HSC |
|------------------|-----------------------------------|
| **Sensor:** CMOS, resolution 800x600 pixel | **Various fields of view, resolutions & max. frame rates, e.g.:** |
| **Digitalization:** 14 bit/pixel | • 10x10 mm: 600x600 pixel, 8.5 kHz |
| **Global shutter, fixed or auto exposure** | • 10x10 mm: 250x250 pixel, 30 kHz |
| **Frame rate enhancing by pixel reduction** | • 13x10 mm: 800x600 pixel, (for inspections) |
| **Real time analog NTSC video output for process control** | **Recording duration of 2 GB ring memory partition (examples), for entire 8 GB ring memory a factor 4 applies.** |
| **Internal 8 GB ring memory for high-speed video acquisition, download to EML mass memory after experiment** | • 600x600 pixel, 200 Hz: 16.6 sec |
| **Triggering of recording by event through experiment controller, e.g. by recalescence detection algorithm** | • 600x600 pixel, 8500 Hz: 0.39 sec |
| | • 256x256 pixel, 10 KHz: 1.854 sec |
| | • 256x256 pixel, 30 KHz: 0.615 sec |

3.2.8. *Diagnostics - Coil System.* The coil system module (CSM) not only heats and positions the sample it also delivers significant housekeeping data such as frequency, voltage and current of the oscillating circuit from which the electrical conductivity and inductivity of the sample can be derived. This is possible because the metallic sample inside the r.f. coil act together as a transformer with the sample as a damping element. Thus with changing electrical sample properties the oscillating circuit changes its electrical properties. EML offers the possibility to measure these small changes on comparable big scale r.f. power signals provided by the Levitation Power Supply.

3.2.9. *Data Processing and Downlink.* Process control and data acquisition is performed by the ECM module which contains a dedicated computer system (ECE) with associated interface and power supply electronics. The ECE acquires standard scientific and housekeeping data at rates between 1 and 100 Hz (i.e. pyrometric data). Data downlink is performed in real time by transferring the data to EDR via Express Rack protocol.
Digital video data are acquired separately by two dedicated systems one for each camera. Both video systems interface the EDR Video Management Unit (VMU) via HSSL link for downlinking of the acquired video data.

- In case of the ACP camera the captured video is acquired and processed in real-time by the Digital Video System (DVS). It allows to split the incoming video stream in two simultaneous streams with different image processing applied for the two purposes below. Control of DVS is possible per experiment parameter set to allow synchronization to events determined by the timeline of the melt cycle or per ground commanding.
  - real-time video: highly compressed video to comply with downlink constraints, used for process control purposes by ground operators
  - scientific video: low or uncompressed video stored on DVS own hard disk for later non-realtime downlink
- In order to clear the HSC internal ring-memory the captured video will be transmitted to the dedicated video management unit called HSC-OS (operating system). The HSC-OS is able to compress, store and downlink the recorded video files on request by ground command. For process control purposes the HSC delivers besides high-speed digital recording also a live video stream as analogue NTSC standard which is transmitted to ground via the analogue video interface of EDR VMU.

3.3. Mission Scenario
The EML facility will be launched and transported to the International Space Station ISS, where it will be installed in the European Drawer Rack (EDR). During its service lifetime of 5 years EML will be operated in the EDR. In order to be able to process a large number of scientific samples during the service lifetime, samples can be uploaded and downloaded between ground and EML on ISS according to the following scenario (see also figure 6):

- The flight samples which include pure metals, alloys and semiconductors, are spherical in shape with diameters ranging from 5 to 8 millimeters and are manufactured by the participating scientists in their labs.
- These samples are then integrated into dedicated sample holders and subsequently into a Sample Chamber (SCH) under very strictly controlled environmental conditions since the scientific results of the levitation experiments depend critically on the purity of the samples. Each Sample Chamber has a capacity of 18 samples which are stored in individual sample holders mounted on a magazine wheel in order to manipulate and select each sample individually for processing.
- The fully loaded Sample Chamber is uploaded to the ISS where it is attached to the EML facility.
- Sample processing is performed according to a sophisticated procedure which not only involves the settings of the levitator but also of diagnostics elements. The data delivered by the diagnostic elements, mainly high-speed and high-resolution video cameras and pyrometers are the main scientific raw data gathered during the mission. Since the duration of a typical melt cycle of an EML sample is in the order of seconds or minutes and the processing procedure is very complex with hundreds of individual settings, the procedure is developed before the mission in a ground based experiment development program, converted into a parameter set for the facility, and is then automatically executed by the facility. Interactive control of running experiments can be performed e.g. to optimize parameters based on the results of the previous runs by tele-commanding from the user center on ground which is permanently monitoring and controlling the running experiments.
- After all samples in a Sample Chamber have been processed, they are transferred to a Sample Download Container (SDC) by the flight crew for download to ground. The design of SDC has been optimized for the tight constraints of the download in terms of mass and size.
After landing the processed flight samples are removed from the SDC and returned to the scientists for further analysis.

According to the mission scenario up to two Sample Chambers per year will be uploaded to the EML facility, which translates to a total of 36 samples that can be uploaded, processed, and downloaded per year. Therefore, a maximum of 180 samples can be processed during the 5 year service lifetime of EML.

**Figure 6.** EML Mission Scenario, showing the complete life-cycle of the experiments from experiment preparation to post-flight evaluation.

Limitations of the EML on-orbit lifetime arise mainly from three factors which are all related to the usage of the facility by the experiments: The first limitation comes from the fact that melted samples under ultra-high vacuum conditions will evaporate, which leads to deposition of evaporated sample material on the inner surfaces of the process chamber. While measures have been implemented to protect sensitive elements of the chamber from deposition (e.g. the optical viewports) the deposited layer thickness is limited; if the limit is exceeded the layer may peel off and contaminate the process chamber with flakes which would not be compatible with the ultraclean environment needed by most experiments. The second limitation comes from a similar phenomenon: if samples are processed under a gas atmosphere, the evaporated material forms microscopic dust particles. The amount of the thus produced dust is limited by safety considerations; on the other hand a dust removal system has been implemented in EML which reduces the problem of dust accumulation. The third limitation is related
to the consumption of noble gases stored in EML by those experiments that are running in a gas atmosphere versus the storage capacity of the EML gas supply system.

4. EML Program Overview

EML for ISS is a project jointly funded by ESA and DLR [15]. After going through some pre-development phases the development and manufacturing of the flight model was launched in 2008 as part of a comprehensive program that not only covers the development of the flight facility but also various aspects related to the preparation of the ISS mission, as follows:

- The flight facility is based on the TEMPUS concept but includes several upgrades in particular with respect to diagnostics, and is currently being manufactured by the industrial team under the leadership of Astrium. Delivery is planned for 2012.
- A second model called "Operational Model" OM which is essentially a copy of the flight model is manufactured and will be used for experiment preparation and verification, for sustaining engineering during the mission, and will serve as spare pool for the flight facility.
- A Science Reference Simulator SRS, which is a software based tool designed to support the ground preparation of experiments
- A Training Model TRM, which will be used by the European Astronaut Center to prepare crew operations
- A Ground Support Program GSP with the objective to prepare the flight experiments on ground by performing tests with representative samples in a ground levitation facility and by developing the parameter sets that will control the flight parameter sets
- An Experiment Infrastructure EXI project, which will provide custom-made sample holders for each flight sample and the ground infrastructure needed for integration of the flight samples into the Sample Chambers in a controlled environment
- Development of a Sample Coupling Electronics SCE which is a potential future upgrade of the EML facility which would enhance the diagnostic capabilities of EML to allow a precise determination of the sample's electrical conductivity (see Chapter 5).
- Development of an Oxygen Sensing and Control System OSC which is another potential future upgrade of the EML facility which would allow precisely determining and controlling the oxygen partial pressure in the process atmosphere and would therefore allow improving and characterizing the process atmosphere (see Chapter 5).
- Upgrade of TEMPUS parabolic flight facility PFF in preparation of future parabolic flight missions. Experiments in the PFF are planned as precursors for ISS experiments for samples that have not been previously processed in TEMPUS and for samples which can not be processed on ISS due to safety constraints.

5. Evolution potential

The modular character of the EML facility allows the upgrade of existing instruments and stimuli elements and the implementation of additional systems or the exchange of used ones. Consequently, there are two major classes of possible evolutions:

1. Short-term: Broadening of experimental capabilities by implementation of new diagnostic and stimuli elements

   The modular character of the facility allows for an easy implementation of further diagnostics or stimuli elements like
   - Fast pyrometer (order of MHz)
   - Different video cameras
   - Sample coupling electronics (SCE)
   - Oxygen control system

2. Long-term: Life time extension

   In order to extend the total operation time of the facility a replacement of the experiment
chamber after a certain number of experiments can be envisaged, since the life time is limited by the contamination of the coils. This, however, would indeed impose a large effort on logistics and crew time.

A number of highly peer-ranked scientific proposals require the implementation of two diagnostic/stimuli systems out of the mentioned short-term options. These will be introduced shortly in the following sections.

5.1. Oxygen control system
For the measurement of surface tension and viscosity the control of the partial pressure of oxygen in the ppm region is necessary [16]. This feature is not yet realized in the basic version of the EML facility, but is regarded as an add-on diagnostic system having a high priority.

A space-compatible technology demonstrator of an oxygen sensing and control system has been developed and tested in the frame of an ESTEC technology study [17]. An oxygen measuring and loading system including a control loop to adjust a dedicated oxygen partial pressure in a gas circulation has been developed and tested which consists of a combination of a potentiometric sensor based on Yttrium-stabilized zirconia with an oxygen titration. This system is suited to measure and to adjust the oxygen partial pressure in the sub-ppm range and can be operated in wide range of oxygen partial pressures ($10^{-3}$-$10^{-19}$ bar). In a laboratory setup a standard deviation of $\log(pO_2/1\text{bar}) < 0.003$ orders of magnitude could be verified for a period of 30 h. Furthermore, field tests of this system performed in the levitation facility of DLR in Cologne have verified the feasibility for operating this system in the harsh environment of a levitation facility.

This concept is also capable to be implemented into the EML facility as an add-on diagnostics. The complete system consisting of sensor, pump, and electronics would be completely accommodated in an additional single locker. The corresponding supplies and control lines are already foreseen by EML.

A further attractive feature which could enhance the technical potential of the EML facility is the capability of the titration pump to remove oxygen from the atmosphere without being limited by any saturation effect. Hence, contamination of the process atmosphere caused by samples or small leaks can be compensated by this pump reducing the risk of a facility shut-down tremendously.

As a next logical step the development of a prototype demonstrator of such an oxygen control system has been proposed to ESA/DLR. This demonstrator shall be compatible with utilization in the TEMPUS parabolic flight facility, terrestrial levitation facilities, and the EML-OM.

**Figure 7.** Titration pump for adjusting the partial pressure of oxygen in the sub-ppm region as developed under ESA contract.
5.2. Sample Coupling Electronics

In a DLR funded development a laboratory model of a sample coupling electronic (SCE) device has been developed. This unit is connected to the RF oscillating circuit and allows for measuring of thermophysical properties such as electrical conductivity, surface tension and viscosity via the inductive method. Whereas resistivity measurements per induction is relatively straightforward, the instruments high sensitivity and fast response time is such that even sample shape oscillations can be detected from which viscosity and surface tension can be derived. Thus the SCE is a perfect complement to the optical diagnostic tools [18]. The EML facility already foresees the interfaces to accommodate the SCE mechanically, electrically and in terms of data management.

The device is already miniaturized, implements the interfaces to EML and needs a power supply of less than 10 W. During ground tests in the TEMBUS parabolic flight facility a calibration procedure has been developed and first tests with a solid tungsten sample have been successfully conducted showing excellent results.

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