Chapter

Experiment Preparation and Performance for the Electromagnetic Levitator (EML) Onboard the International Space Station

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Abstract

The electromagnetic levitation (EML) facility on board the ISS is a powerful tool for investigation of solidification phenomena of metallic melts and precise measurement of thermophysical properties of the liquid. Containerless processing enables deep undercoolings prior to solidification and the analysis of crystal nucleation and growth phenomena. The microgravity environment allows studying these processes under reduced fluid flow and moreover under different levels of melt convection by systematic variation of electromagnetic stirring. Material properties like density, specific heat, surface tension, viscosity, thermal and electrical conductivity of liquid metals and semiconductors are determined in the absence of disturbances caused by container walls and gravity forces. Scientists are supported by facility and mission specialists for preparation and performance, which is decisive for successful operation on orbit. User support comprises the determination of material data, development of experiment procedure, parameter sets and their validation in the ground model as well as the conduction of space experiments by real-time monitoring and control. The comprehensive support program for the entire life cycle of science project from experiment definition to its operation ensures high-quality data and an optimum of scientific results.

Keywords: electromagnetic levitation, containerless processing, International Space Station, undercooled melts, ground support program

1. Introduction

Since more than three decades, electromagnetic levitation in ground-based research is an established technique for thermal experiment processing (heating, melting, and solidification) of electrically conductive material samples, without any contact of the sample to a containment. The samples are free-floating in an ultraclean environment, typically high-purity noble gases, in order to preserve intrinsic behavior during heating up, melting, in liquid state, and during solidification behavior. This unique feature enables the scientific investigation and measurement of material properties and characteristics that are otherwise not possible due to the interaction of the liquid samples with the container walls and any undesired contamination adhering to it. For example, liquid metallic materials are typically highly reactive with even smallest amounts of oxygen. 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 material behavior. In particular it enables the possibility to reach an undercooled state, in which the material stays liquid even below the equilibrium freezing temperature. This is achieved by levitating and heating the material sample through high-frequency electromagnetic fields generated by alternating currents in a coil. The field induces eddy currents in the sample, which is heated by Ohm's losses of the currents, while their interaction with the electromagnetic field leads to forces toward the center 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 electromagnetically and an unwanted heating bias. Furthermore, the liquid sample is getting deformed by the strong electromagnetic force needed to compensate gravity. In zero-g the sample floats by itself and requires only very small positioning forces to stay in the center of the coil system with a perfectly spherical shape, which is beneficial for a variety of techniques to measure thermophysical properties of melts. The heating can be controlled almost independently of the positioning, allowing processing of, e.g., highly reactive material, thermophysical measurements with much higher accuracy, and solidification experiments, with varying stirring conditions. Therefore, electromagnetic levitation under microgravity provides unique opportunities for the investigation of liquid metals, alloys, and semiconductors, both above and below their melting temperatures, i.e., also including the undercooled regime. Besides fundamental scientific interests, the research is also oriented to industrial applications where reliable data for accurate modeling of industrial processes are difficult or impossible to be obtained on ground.

The payload "electromagnetic levitator" (EML) is the realization of that concept for the International Space Station (ISS) and was jointly developed by the European Space Agency (ESA) and the *Deutsches Zentrum für Luft- und Raumfahrt* (DLR) space administration [1]. It was built by Airbus DS and installed in the European research lab COLUMBUS on the ISS by the ESA astronaut Alexander Gerst during the Blue Dot Mission in fall 2014. Containerless processing of metallic alloys and semiconductors with the electromagnetic levitator has been performed since April 2015. Using sophisticated methods of initiating and analyzing temperature modulations and liquid surface oscillations and their decay, thermophysical properties can be investigated. Measurements include the specific heat capacity, the surface tension and viscosity, as well as the electrical conductivity in the stable liquid and undercooled metastable liquid states. Entire sets of high precision data of thermophysical properties in the liquid and undercooled liquid regime have thus been obtained over extended periods of time using the ISS-EML device.

The scientific experiments in EML are grouped into batches. One batch is related to a specific sample chamber with 18 dedicated samples. Each sample can be melted many times; hence one batch consists in the range of about thousand individual melt cycles. Since its successful on-orbit commissioning onboard the ISS beginning of 2015, EML has been under quasi-continuous operation, and two complete batches of experiments have been conducted since, processing 36 samples with a total of more than 2000 individual melt cycles [2].

Before the realization of the EML facility for the ISS, the scientific community had gained substantial experience with ground-based research by means of electromagnetic levitation technique since the late 1980s. Driven by its shortcomings under terrestrial conditions, a first approach for a levitator to be used under reduced gravity conditions was developed in the Spacelab era in the 1990s. The technology development for the positioning and heating technique as well as the selection of suitable noninvasive diagnostics has been closely supported by the research teams of the former DLR Institute of Space Simulation (today "*Institut für Materialphysik im Weltraum*") which had established ground-based levitation facilities in their labs. When it was decided to adapt the levitation technique for application under reduced gravity, the DLR technical and scientific expertise was used in the proof of concept during early parabolic and sounding rocket flights of a precursor model of EML, which in the end led to the development of a Spacelab payload TEMPUS which was flown on three missions in the 1990s.

The authors are convinced that the success of the current EML payload onboard the ISS in its fifth year of on-orbit operation with currently approximately 2000 individual melt cycles performed on 36 pure metals, alloys, and semiconductors is the result of a longstanding facility and experiment development phase where a substantial built-up in technical, operational, and scientific expertise could be achieved. This will be substantiated by zooming in on preparatory work and performance of EML experiments. We will detail the evolution of the "EML type" payloads for use under microgravity and describe the user support provided for the preparation and conduct of the EML experiments for the ISS. Moreover, an outlook to near-term EML program activities and further future enhancements is given increasing the facility's capabilities for the coming years and sound scientific experiment batches.

2. Motivation and scientific background

It is well established that modern technologies can work properly only if suitable materials with tailor-made properties are utilized. Metallic materials play an important role in nearly all fields of daily human life and are used for many applications, e.g., in automobile or aerospace industries. The material properties (strength, hardness, corrosion behavior, and magnetic and electrical properties) are not only determined by the chemical composition but also sensitively depend on the microstructure. Nearly all metallic alloys are produced from the liquid state by solidification processes. The conditions during solidification of a metallic melt control the evolution of the microstructure and therefore the properties of the as-solidified material. Therefore, efforts of researchers are directed to a detailed understanding of the physical mechanism involved in the transition from the liquid to the solid state, which is mandatory for computer-assisted modeling of solidification processes and the formation of the microstructure. Computer simulations are increasingly demanded in industry since it enables the optimization of production routes in order to save costs and energy during manufacturing. The production of metallic materials belongs to the largest industrial sectors worldwide. For instance, in the European Union, there were more than 400,000 enterprises with more than 5 million employees in 2006 [3]. Therefore, large economic gains can be achieved even by small progresses in metal processing.

Solidification of melts is a very complex process. It is initiated by the formation of tiny crystals on an atomic scale (the so-called crystal nucleation process) and their subsequent growth into macroscopic dimensions. For the formation of the microstructure, the morphology of the moving solid-liquid interface plays a decisive role. Among a broad variety of pattern formation, the major growth mode in metallic systems is dendritic growth (see, e.g., review articles [4, 5]). In many cases an initially planar interface between the growing solid and liquid is not stable. Local fluctuations in growth rate lead to the formation of protrusions, and finally a tree-like dendritic structure with a primary stem and secondary branches is established as illustrated in **Figure 1**. Branches or dendrite arms are growing preferentially in certain directions with respect to the crystallographic structure of the solid. The cubic crystal structure of the solid phase in $Fe_{99}B_1$ alloys is reflected by the fourfold symmetry of the dendritic grain where growth directions of the primary dendrite and secondary arms are perpendicular to each other (**Figure 1**).

However, the microstructure is then composed of many dendritic grains originating from different crystal nuclei. Key parameters such as size of grains and their orientation to each other (texture), thickness and spacing between dendrite arms, and the distribution of solute atoms across the sample determine the material properties of the final product. These parameters can be controlled externally by the cooling rate or the temperature gradient during solidification, but they also sensitively depend on the liquid phase properties for the transport of heat and mass. As illustrated in **Figure 2**, solidification is accompanied with the release of latent heat of fusion, which needs to be removed from the solid-liquid interface. Generally, in alloys the solid phase and the melt exhibit different chemical compositions so that growth of the crystal requires a rejection of solute atoms ahead the interface. Transport of heat and solute atoms is not only ruled by thermal conduction and atomic diffusion, respectively, but also by fluid flow (see, e.g., [4]). Therefore, melt convection is considered as an additional process parameter controlling the evolution of the microstructure. Under the conditions of microgravity, a major source of natural convection, i.e., buoyancy-driven flow, is completely avoided, thus enabling the study of solidification processes under near-diffusive conditions. Moreover, external triggering of fluid flow, e.g., by applying electromagnetic fields, allows analyzing the influence of fluid flow systematically without superposition by gravity-driven effects.

Another important process parameter is the level of undercooling of the melt prior to solidification. When a melt is cooled down, the phenomenon of undercooling below the equilibrium freezing temperature always occurs. At the melting point, nucleation does not set in and the sample remains in the liquid state. Any level of undercooling, defined by $\Delta T = T_m - T$ (T_m: melting temperature, T: temperature of

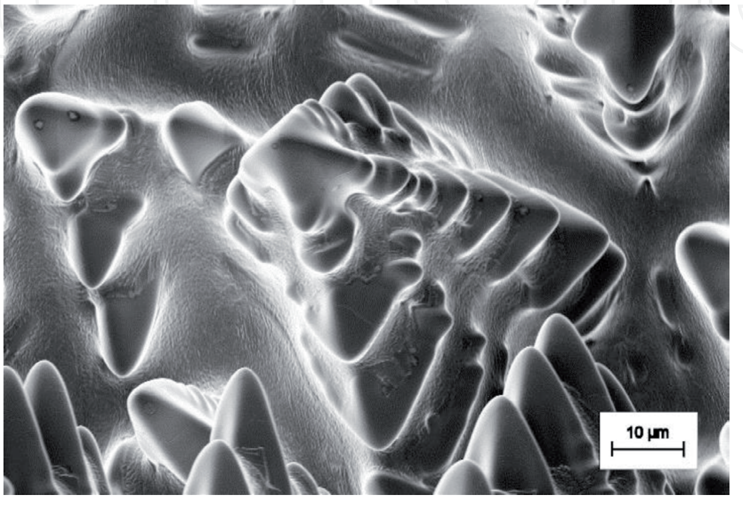

Figure 1.
Scanning electron micrograph of the surface of an as-cast $Fe_{99}B_1$ alloy showing the morphology of metallic dendrites. The length scale is indicated by the horizontal bar (M. Kolbe, T. Volkmann, DLR Cologne).

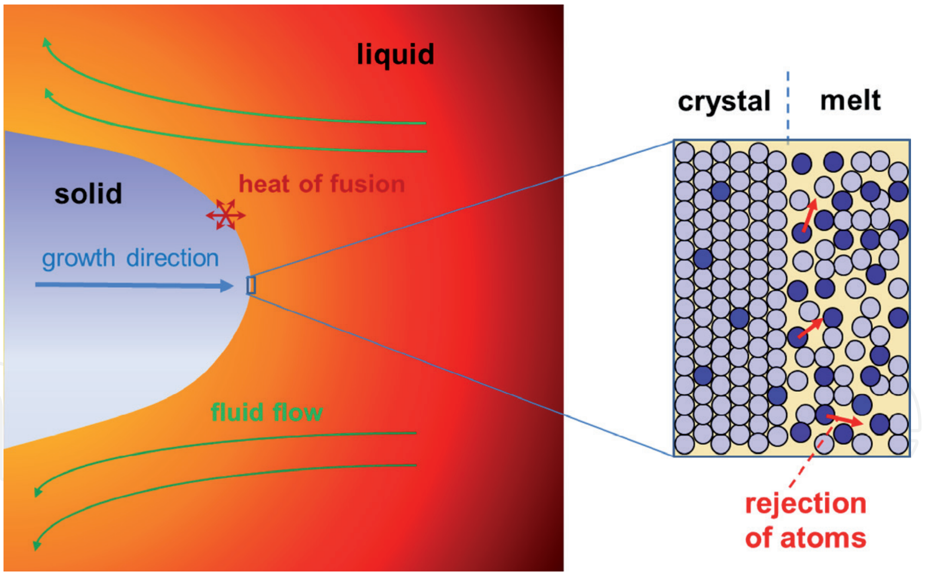

Figure 2.
Left: Illustration of a dendrite tip of the solid phase growing into the liquid. The heat of fusion is released at the solid-liquid interface. Right: The concentration of solute atoms (marked in dark blue) in alloys is different for the solid and the liquid (see text for details).

the melt prior to solidification), is necessary to generate a thermodynamic driving force in order to create nuclei of the solid phase. However, undercooling of melts is of special interest because it gives access to the formation of metastable solid phases and microstructures far from equilibrium [6, 7]. A large variety of metastable materials with new physical properties can be prepared comprising metastable crystalline phases, quasicrystals, metallic glasses, supersaturated solids, and grain-refined materials. In industrial applications, deep levels of undercooling are mainly achieved by rapid quenching of melts such as melt spinning and inert gas atomization of melts into fine droplets (powder fabrication) in order to produce metastable materials.

However, methods of rapid quenching are not suitable for a direct diagnostic of the physical mechanism involved in the selection of alternative solidification pathways into metastable phases. Deep undercoolings that typically amount to about 20% of the melting temperature can also be achieved by the avoidance or reduction of heterogeneous nucleation sites such as solid metal oxides on the sample and container walls. Thus, large undercooling levels can be realized even at slow cooling rates of the order of a few K/s of bulk samples. Containerless processing of melts such as electromagnetic levitation is a powerful technique since heterogeneous nucleation on containers is completely avoided. Moreover, the freely suspended droplet is accessible for a direct monitoring by pyrometers and high-speed video cameras, thus enabling the analysis of solidification processes and the measurement of various thermophysical properties of the liquid.

In electromagnetic levitation technique, the sample is inductively heated and levitated by a radiofrequency (RF) electromagnetic field. The sample is placed in a coil that is connected to a high-frequency generator, which is operated at frequencies of about 400 kHz. An example for a coil design that is used for levitation on ground is shown in **Figure 3**. The conical-shaped coil consists of seven water-cooled copper windings and four counter windings at its top. Such coil geometry produces an inhomogeneous electromagnetic field with a strong field gradient against the gravity vector. The levitation coil together with the sample of 6–7 mm in diameter (about 1 g in mass) is integrated in a vacuum chamber made of stainless steel. In order to avoid oxidation of the sample, the chamber is evacuated to pressures of about 10^{-7} mbar and then backfilled with inert gases like purified He up to about

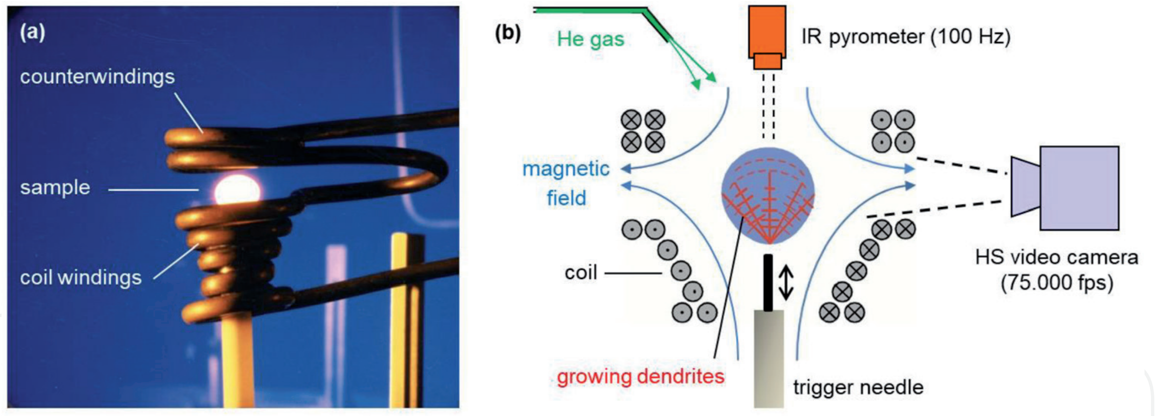

Figure 3.
(a) Coil design used in ground-based electromagnetic levitation facility at DLR Köln, Institut für Materialphysik im Weltraum. (b) Sketch of experimental setup showing a cross section of the levitation coil with an inhomogeneous magnetic field generated by the opposite directions of the RF current in lower coil winding and the upper counterwindings. The temperature is measured by an infrared pyrometer, and rapid solidification is monitored by a high-speed video camera. The nozzle at the top produces a He gas stream to undercool the sample convectively until spontaneous solidification set. Alternatively, nucleation can be triggered at a preselected undercooling by touching the sample with a ceramic needle.

500 mbar before the experiment. During the experiment the temperature is measured contactless by an infrared pyrometer at a rate of 100 Hz, and the sample is observed by a radial high-speed video camera. Changing the temperature of the levitating sample by variation of the electromagnetic field strength is possible only within a limited range because a strong field is needed for compensation of gravity. For many materials like Fe and Ni, the minimum temperature that can be reached by reducing the power is above the melting point. Therefore, for solidification experiments in ground-based levitator and to reach temperatures in the regime of the undercooled melt, the sample must be cooled by applying forced convection in a He gas stream to increase the heat flux to the gas environment. For that purpose, a nozzle system producing a He gas flow is installed in the facility on top of the levitation coil. In particular, the speed of the gas stream can be varied by a tunable valve in order to achieve different cooling rates or to establish a constant temperature. The levitated droplet can be cooled and undercooled below the equilibrium melting temperature until spontaneous nucleation and solidification set in. Alternatively, nucleation can be triggered externally at a preselected undercooling level by touching the sample with a ceramic needle, which acts as a heterogeneous nucleation site. Rapid solidification of the undercooled melt is recorded by the high-speed video camera at frame rates up to 75,000 fps.

An important aspect is that the huge field amplitudes required on Earth in order to generate a levitation force to compensate gravity lead to strong electromagnetically induced turbulent melt convection with fluid flow speeds up to about 0.5 m/s. For processing in microgravity, only slight positioning fields are needed being three orders of magnitude smaller than on the ground. Accordingly, fluid flow is significantly lowered to some centimeter per seconds [8]. After the melting process, the sample can be cooled and solidified without convective gas cooling by setting the electromagnetic field strength to a minimum. Alternatively, small field amplitudes can be applied, still allowing the sample to cool down but generating certain levels of electromagnetic stirring. Thus, the microgravity environment does not only allow the minimization of electromagnetic stirring but also the variation of the field strength in order to study solidification processes systematically under different levels of fluid flow. In parallel, a larger temperature regime is accessible for investigation. While convective gas cooling needed for processing on ground has only a limited efficiency, deeper temperatures can be achieved by reducing the electromagnetic field to a minimum, which is only possible under reduced gravity. This enables to cool and to solidify levitated samples with a low freezing temperature such as glass-forming alloys. Moreover, for many materials, thermal radiation is sufficient to cool the sample down so that it can be processed without a gas atmosphere. The benefit of vacuum conditions with a residual air pressure of typically 10^{-7} mbar in EML on the ISS is the high purity. For comparison, in a He gas atmosphere at 1 bar and with the highest purity of 99.9999%, the residual pressure of impurities (air) equals to 10^{-3} mbar being four orders of magnitude larger than in vacuum. Hence, under vacuum oxidation of extremely reactive materials such as liquid titanium or aluminum based alloys can be reduced to a large extend, which is mandatory to suppress heterogeneous crystal nucleation by solid metal oxides and to achieve deep undercoolings of the melt.

The schematics of a typical temperature-time profile during melting, undercooling, and rapid solidification are shown in **Figure 4**. The solidification process consists of two steps. The blue part of the temperature curve indicates when the sample is solid, while the yellow part shows the sample being liquid. In the undercooled regime, where the sample temperature has fallen below the melting temperature T_m, the rapid growth of dendrites into the undercooled melt leads to a steep temperature rise (recalescence) up to the melting point. The residual liquid in the interdendritic region solidifies subsequently under equilibrium conditions during the plateau at T_m. The rapid solidification process can be visualized by high-speed video records taken during recalescence as shown by the example in **Figure 5**. Due to the released heat of fusion at the solid-liquid interface, a steep temperature gradient is established ahead of the solidification front. The sharp contrast in brightness is due to the distinct temperature difference, which makes the solidification front visible when it intersects the surface of the droplet. Monitoring the propagation of the front enables the determination of the growth velocity. Measuring growth velocity as a function of undercooling is an effective method for testing and improving of models for crystal growth in undercooled melts by comparing model predictions of growth kinetics with experimental data.

It must be noted that the solidification front shown in **Figure 5** is macroscopic in dimension and is composed of many microscopic dendrites. The morphology of the front contains valuable information about the growing solid phases and the growth process. In case of deeply undercooled $Fe_{50}Co_{50}$ alloys (**Figure 5**), the recalescence event proceeds in two steps, which originate from the primary formation of a

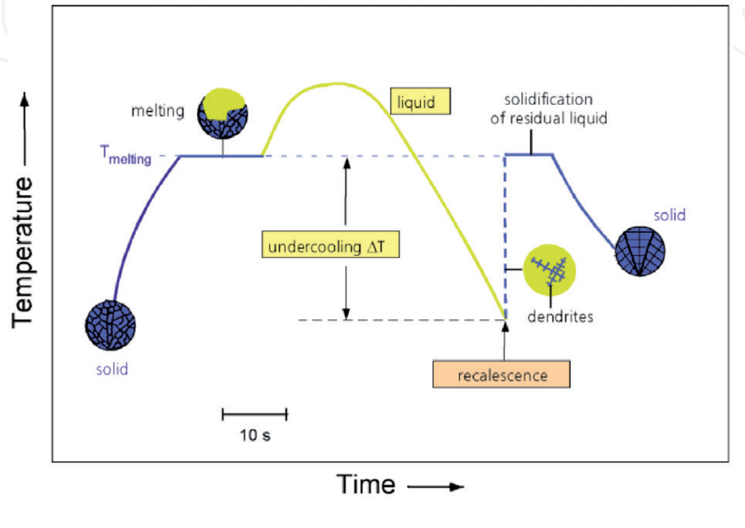

Figure 4.
Schematic temperature-time profile during heating, melting, undercooling, and rapid solidification (recalescence).

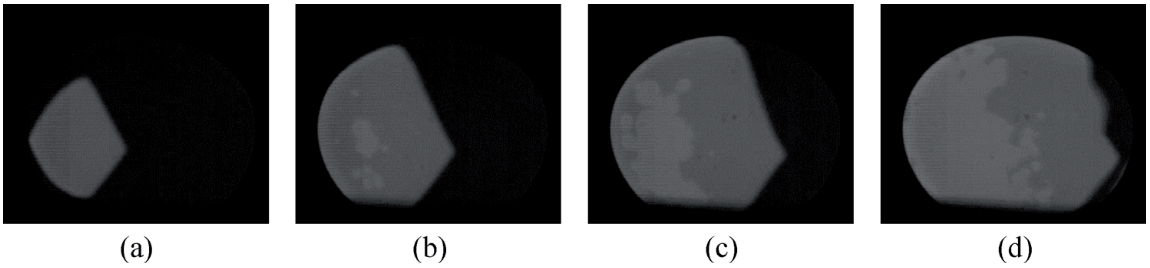

Figure 5.
High-speed video images during rapid solidification of $Fe_{50}Co_{50}$ showing a double recalescence at an undercooling of 245 K. The sample (diameter ~6.5 mm) was processed in a ground-based electromagnetic levitation facility at DLR Cologne. The camera was operated at 75,000 fps, and the figure shows each fifth frame, i.e., the time interval between the frames (a)-(d) is about 0.066 ms (images provided by C. Kreischer, T. Volkmann, DLR).

metastable solid with body-centered cubic crystal structure and subsequent transformation into the stable phase with face-centered cubic structure. The contour of the primary front reveals special features such as a fourfold symmetry and sharp edges and faces. The symmetry is due to dendrite branches originating from a single nucleation point and growing perpendicular to each other, which forms a dendritic grain with a pyramidal-shaped envelope. In that way, containerless processing is a powerful tool for the in situ analysis of rapid solidification processes.

The second research area, which is investigated using electromagnetic levitation techniques under microgravity (TEMPUS, EML), is the thermophysical property of liquid metals and metallic alloys [9]. For the simulation of casting and solidification processes including electromagnetic stirring in the melt and the effect of fluid flow on phase formation, the knowledge of thermophysical parameters of the liquid state, such as density, specific heat, thermal conductivity, and viscosity, are crucial. Contactless processing allows to obtain thermophysical data of highly reactive materials and to extend the temperature range of the liquid into the undercooled metastable state. A broad range of contactless measurement techniques on electromagnetically levitated samples was developed over the years. Many of these properties are difficult to measure in ground-based facilities due to the presence of stronger electromagnetic fields to counter gravitation. The microgravity environment provides optimal conditions for measurements with high precision since fluid flow is minimized and the levitating droplet is nearly free of external forces and exhibits an ideal spherical shape.

Several thermophysical parameters of the liquid state can be obtained from video records of the levitated droplet. By image analysis the volume of a spherical sample can be determined with a high precision and finally the density. Measurement of the density at different temperatures yields the thermal expansion coefficient. Viscosity and surface tension are analyzed using the oscillating drop technique [10–12]. As surface tension acts as the force driving a deformed liquid droplet to its equilibrium shape (sphere), surface tension determines the frequency of surface oscillations. The viscosity originates from the internal friction of liquid motion during oscillation and is therefore related to the damping of droplet vibrations. In microgravity experiments, surface oscillations of the molten sample are induced by short pulses with high amplitudes of the electromagnetic field, while droplet oscillations are recorded by the video camera as shown in **Figure 6** (left). A plot of the sample's radius as function of time reveals a damped oscillation (**Figure 6**, right). A fast Fourier transformation is applied to the radii data to obtain a frequency spectrum from which the oscillation frequencies and thus the surface tension are derived. The viscosity is proportional to the damping constant of the oscillation, which is determined from the decaying oscillation amplitude as shown in the right diagram in **Figure 6**. Under terrestrial conditions the oscillation spectrum is more complicated, and frequencies are shifted due to external forces and the aspherical shape of the droplet, which complicates the quantitative analysis with respect to surface tension. Improved evaluation procedures have to be applied in order to obtain surface tension data with the same precision than in microgravity experiments [12, 13]. However, measurements of viscosity in ground-based experiments could not be performed so far since the electromagnetically induced strong fluid flow is turbulent and the huge magnetic field causes an additional damping.

A contactless method for the measurement of specific heat is the modulation calorimetry [15, 16]. In this method the electromagnetic field is set to a certain level to establish a constant temperature of the sample. Then, the field strength and thus the heating power input are modulated, which lead to a periodical temperature response of the sample (see **Figure 7**). A precise determination of specific heat from the power input and the measured temperature response require a suitable choice of the modulation frequency, which is typically below 1 Hz. Determination of the effective power input requires the knowledge of the heat balance of the sample with the environment. Ideal conditions for calculation of the heat loss are provided under microgravity and by processing in vacuum. Under vacuum (at pressure of typically 10^{-7} mbar), heat flux by conduction to the residual gas atmosphere is negligible; heat loss is thus solely due to thermal radiation. The heat flux is proportional

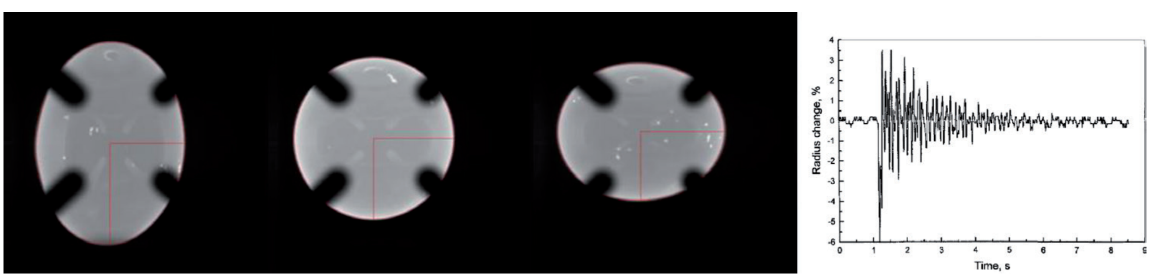

Figure 6.
Oscillating sample at three different times where the radii are marked by red lines (left). The time dependence of the sample diameter reveals a damped oscillation (right) [13].

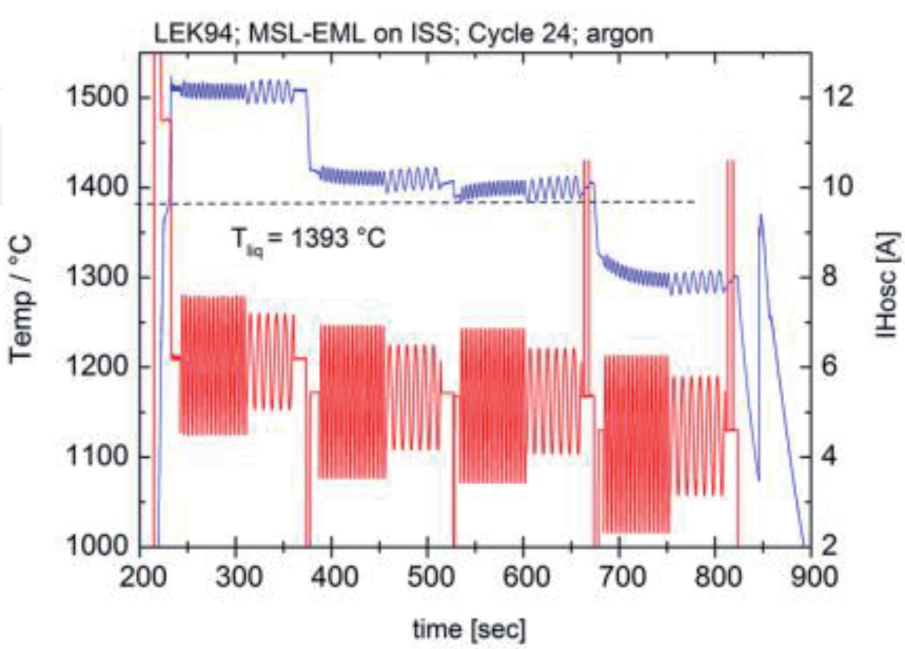

Figure 7.
Specific heat measurement at LEK94—Ni-base superalloy [14].

to the total surface area of the droplet, which has to be obtained from video records of the levitating sample. The highest accuracy is achieved if the sample is an ideal sphere. The modulation calorimetry also allows extracting the thermal conductivity if appropriate values for power input and modulation frequency are chosen.

The electrical conductivity is another important parameter, which can be deduced from electromagnetic levitation experiments by contactless methods. In particular, for liquid metals the electrical and thermal conductivity are based on nearly the same conduction mechanism (transport of free electrons) and are related according to the Wiedemann-Franz law. Hence, thermal conductivity can be derived from measurement of the electrical conductivity, which is less influenced by effects of melt convection. The principle is based on the analysis of the frequency-dependent resistance (impedance) of the electronic circuit consisting of coil including the sample [17]. The impedance is determined by measuring alternating current, voltage, and their phase shift and depends on the electrical resistivity (which is the inverse conductivity) as well as the size and the shape of the droplet. However, precise determination of resistivity from the measured impedance data requires a sophisticated coil design and evaluation methods of the radiofrequency data. A suitable coil system for utilization in microgravity providing measurements with high accuracy is presented in more detail in Section 3.5.

A broad variety of technically important materials such as steels; Ni-, Ti-, Al-, Zr-based alloys; and semiconductors are investigated by an international community using electromagnetic levitation on ground and the ISS-EML facility onboard the International Space Station [18]. The scientific program comprises crystal nucleation, growth kinetics, multiphase solidification (eutectic, peritectic systems), metastable phase formation, liquid-liquid phase separation, and solidification shrinkage phenomena including the measurement of thermophysical properties. The experimental investigations are supported by computer-aided modeling of solidification and the effect of fluid flow.

3. The payloads for use under microgravity and their respective purposes

3.1 Heritage: the spacelab facility TEMPUS

The idea to develop such a facility for the Space Shuttle stems from the Institute of Space Simulation at the German Aerospace Center (DLR) in the 1980s. This facility was built under the acronym *Tiegelfreies elektromagnetisches Prozessieren unter Schwerelosigkeit* (TEMPUS) and means containerless electromagnetic processing under weightlessness. The concept for the TEMPUS facility was tested in several parabolic flights with the KC-135 of NASA from 1988 onwards and one sounding rocket flight in 1989. After this successful proof of concept, it was decided to build a Spacelab facility. This TEMPUS facility was first flown on the Spacelab Mission IML-2 in July 1994. As a bilateral project, TEMPUS was co-funded by DLR Space Agency and NASA. The technical concept of electromagnetic levitation and the specification of the main components were again developed by the DLR Institute of Space Simulation. The scientific program for this mission consisted of 18 samples shared by 8 research teams from Germany and the USA. The scientific resources were equally shared between the US and German scientists. In total, approximately 1000 thermal individual experiment runs were performed within 14 days. The investigated materials comprised pure metals such as Au, Cu, Ni, and Zr but also alloys, such as steels, glass formers, or quasicrystals. During a reflight of TEMPUS on the MSL-1 and MSL-1R Missions, a second set of 18 samples was successfully processed under microgravity conditions, complementing the results of the IML-2 experiments [19].

3.2 Parabolic flights with the TEMPUS spacelab model

In the course of the experiment development for the Spacelab Missions, it became obvious that one major obstacle could not be overcome by ground-based activities alone: the positioning behavior in the electromagnetic fields under reduced gravity was *per se* inaccessible, as well as the coupling efficiency in the molten state. The need for submitting each of the selected samples to a testing during parabolic flights was acknowledged. In the early summer of 1994, shortly before the IML-2 launch on STS-65, the TEMPUS ground model was shipped to Houston for its first parabolic flight campaign. It was operated by a joint team of DLR and Airbus (former Dornier) personnel. All IML-2 science teams had representatives on-site at Ellington Airfield who joined the flight days as observers. With three operators and up to four members from the science community, the TEMPUS team was by far the largest group onboard the aircraft. Only a few minutes after takeoff and still in steep ascent, the teams were allowed to change their seats against positions in front of their respective hardware for setting up the experiments. For our experiments, preparation included running up the facility, selecting the first sample, and establishing vacuum conditions (**Figure 8**).

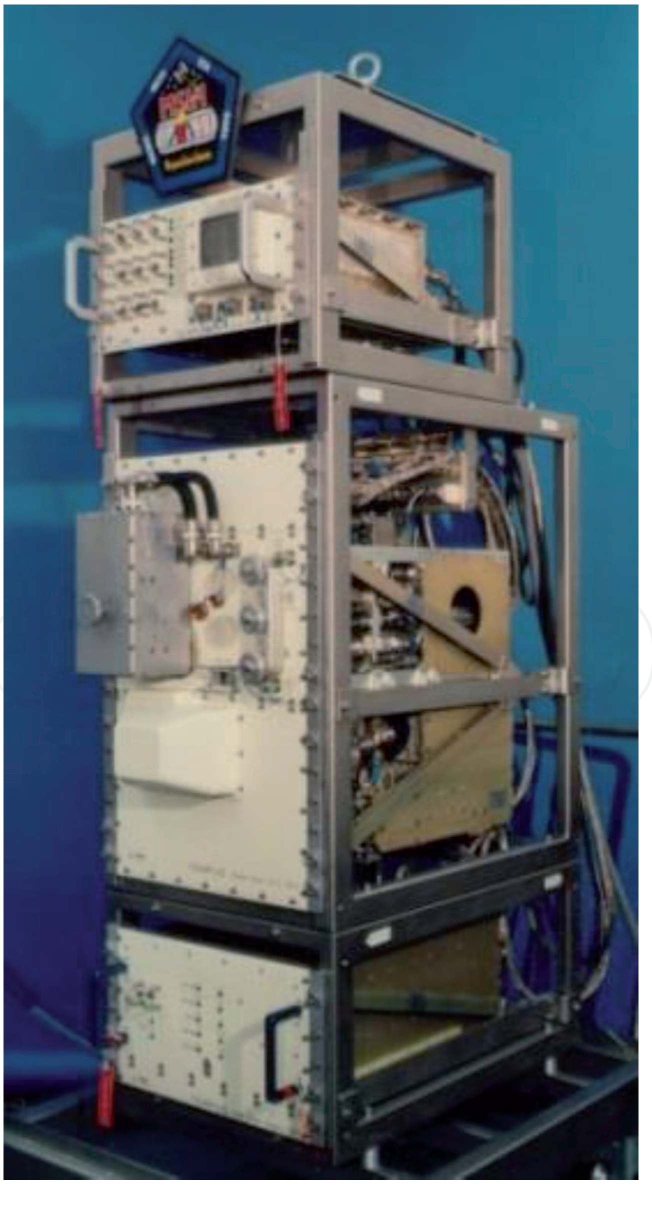

Figure 8.
Engineering model of the TEMPUS facility used during the shuttle missions (Photo Airbus).

The science program had been adjusted to the standard NASA flight profile which, back then, consisted of 48 parabolas per flight day, divided in 6 blocks of 8 parabolas. The eight parabolas in one block were performed back to back with a pause of 3–5 minutes in between the blocks. For TEMPUS flight days, one block was always dedicated to one sample, with several positioning and melting tests. The time between the blocks was spent on level flight and could be used to exchange samples. Apart from the dress rehearsal for the Spacelab experiments, the KC-135 campaign was also used for additional crew training sessions under the most realistic conditions for the Astronauts Rick Hieb, Chiaki Mukai, Don Thomas, and Leroy Chao who were all selected as IML-2 payload specialists. The most important finding from this first scientifically motivated parabolic flight was that all selected samples could be successfully positioned and subsequently melted in the TEMPUS coils system within the 20 seconds of microgravity and that the samples and the experiments were "Go" for launch. However, the learning curve was steep. To maximize the number of successful science runs for future campaigns, there were still some operational challenges to be worked. For example, samples needed to be handed over to the quadrupole field for a stable positioning before heating them by the dipole field well above their respective liquidus temperatures of between 800 and 1850°C. Then, the samples also needed time to cool down and solidify again, all of that in less than 20 seconds. It was planned to preheat the respective sample during the pull-up phase by having it sitting on the sample holder and to hand it over to the field at elevated temperatures at the onset of microgravity, by pulling the holder back. Unfortunately, there is a risk of the sample sticking to the holder at high temperatures, either due to reactions with the holder material or due to a thin layer of evaporated sample material condensing on the holder over the course of repeated melting cycles. It was found that in this case, a smooth transition is difficult and the started experiment has to be aborted and retried in the next parabola, ideally with changed heater parameters.

Usually, the pilots entered the low-gravity phase by slightly "overshooting," i.e., applying negative g levels and then oscillating around the zero line. It was found that due to the coil geometry, the TEMPUS facility was especially susceptible to microgravity disturbances in negative z-direction. In some cases, a free-floating sample was catapulted out of the coil center due to an overshoot or due to weather conditions and was thus lost for further science runs. Interactions with the flight personnel helped to minimize these events. With the parabolas being executed back to back, the time between the reduced gravity periods was in the order of 1 minute only. In case of a sample loss, the sample holder needed to be withdrawn and exchanged which took more time than that. In that case, one or two parabolas would pass unused.

During the first TEMPUS parabolic flight, the ground model of the spacelab facility was used, being identical in form, fit, and function, featuring the original flight software. This model was obviously not conceived for easy mechanical access to subsystems for, e.g., sample exchange, or for flexibility in experiment performance. With the benefits from that campaign, NASA and DLR decided to fund the development of a TEMPUS lab facility, dedicated to parabolic flight campaigns in the future. Between 1996 and 2019, this model and its updates have been used in 17 campaigns. The successful performance of experiments on a parabolic flight campaign today is the precondition for the selection of a sample material for operation in the EML facility onboard Columbus.

3.3 The dedicated parabolic flight facility: testing on a yearly basis

After the shuttle era, the dedicated parabolic flight facility was flown in the two Airbuses operated in Europe during 17 campaigns from 2001 onwards (**Figures 9** and **10**). A typical parabolic flight campaign provides 3 flight days with 31 parabolas each.

The duration of the weightlessness in each parabola is about 20s, and a small break between each parabola enables the operators to optimize the experiment conduction.

Usually, special requirements for the timing of the flight day can be negotiated with the support crew. In total, 2056 parabolas were flown and roughly 200 alloys were measured over the last 18 years. The facility itself consists of a vacuum chamber, which can be evacuated to high vacuum. For optimal cooling conditions, the facility is equipped with He and Ar gas. Typically, the sample is heated in (less cooling) Ar gas and then He is filled in for increased cooling when the maximum temperature is reached, and the sample must be cooled as fast possible, to solidify within the 20s of weightlessness. For temperature measurement, the facility is equipped with a pyrometer and the experiment is recorded with digital video cameras from two sides. One camera can be operated with frequencies up to 40 kHz, allowing the measurement of the fast solidification processes.

The TEMPUS parabolic flights have three aspects. New techniques can be tested under microgravity, scientific projects can measure thermophysical or solidification data under microgravity, and alloys planned for EML can be tested for their levitation behavior.

Figure 9.
Sample magazine of the parabolic flight facility with eight samples in cups and cages.

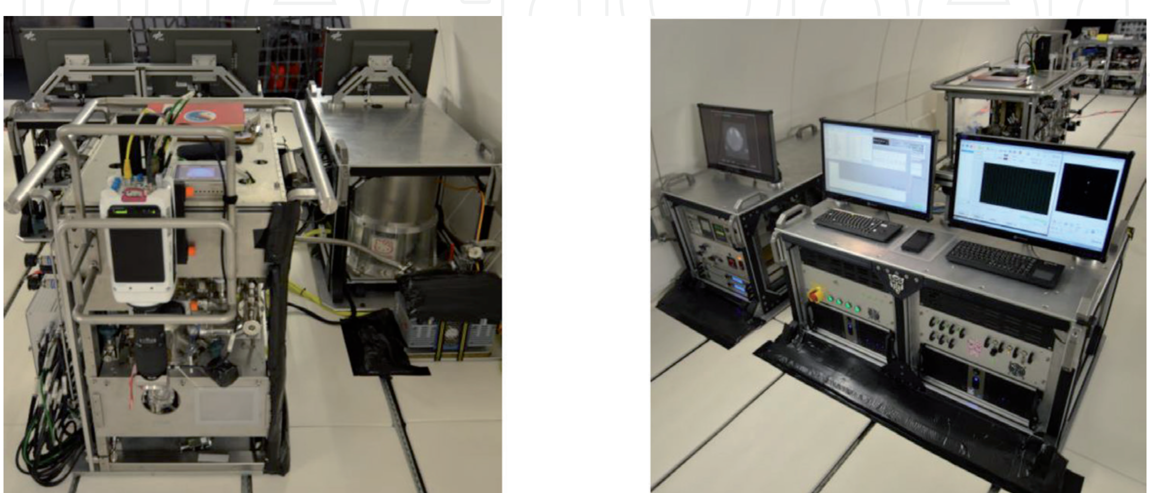

Figure 10.
TEMPUS facility for parabolic flight. The authors share the experience of more than 3000 parabolas both in the NASA KC-135 and in the ESA-CNES-DLR Airbus A300s.

3.4 The TEXUS facility: advanced testing capabilities in preparation for ISS

In addition to the parabolic flight campaigns, five sounding rocket missions between 2005 and 2013 were performed. The TEXUS rockets are launched at Esrange Space Center near Kiruna in northern Sweden (**Figure 11**). One launch provides about 6 minutes of microgravity and two samples can be processed. The TEXUS EML radiofrequency generator and coil system are comparable to the parabolic flight and EML facilities. The TEXUS EML experiments are completely remotely controlled and the housekeeping data and process control video images are downlinked to ground. Commands to optimize the heating or positioning can be uplinked, as necessary. Due to the longer microgravity duration, it is possible to run experiments, which are not possible in the limited time of the parabolic flights. For instance, modulation experiments need a long temperature hold, and also samples with a long solidification interval can be completely solidified in the available microgravity time of a sounding rocket flight. As the facility is available for refurbishment after the experiment, also strongly evaporating samples can be processed.

3.5 EML onboard the ISS

Based on the precursor facilities, the EML for the ISS was developed. The sample chamber can again store 18 samples, which defines the so-called sample batch. The diagnostic is comparable to the parabolic flight facility, with a high-speed camera from the side (with up to 90,000 frames per second) and a second digital camera mounted on top of the sample chamber. The temperature measurement is contactless by a pyrometer integrated in the same housing as the top camera. The technique of the RF generator is the same, and for all current facilities the same SUPOS coil system is used (see **Figure 12**). This coil system was developed at the DLR [20] and is advancement from the TEMPUS coils in the shuttle era where two independent coils for heating and positioning were installed. The so-called SUPOS system consists of a single coil and superimposes a quadrupole field with a strong gradient (but low field strength) for positioning and a (nearly) homogeneous dipole field with high strength for heating the sample as illustrated in **Figure 13**. The benefit is that both fields can be varied independently, i.e., positioning and heating are decoupled in contrast to electromagnetic levitation on ground.

In particular, the dipole heating field serves as the measurement circuit to determine the impedance and finally the electrical resistivity of the sample (compared to Section 2). The measurements are performed during cooling the sample where the

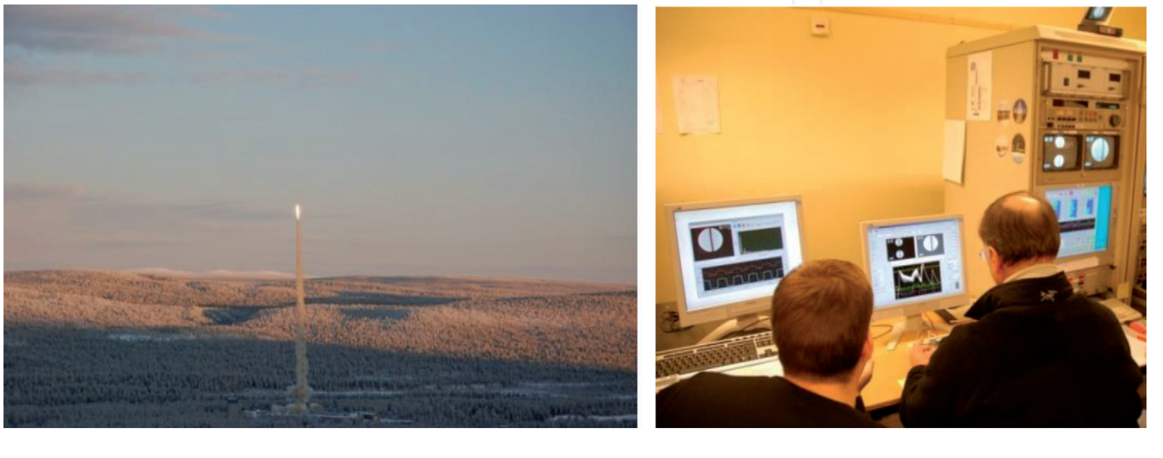

Figure 11.
Launch of the TEXUS sounding rocket at Esrange Space Center in Kiruna, Sweden, during the EML-2 mission (left) and real-time teleoperation of the experiment (right).

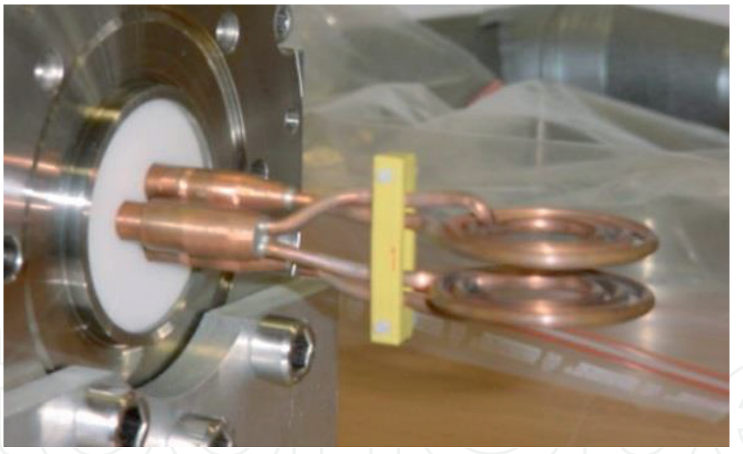

Figure 12.
Photo of the EML coil (Photo Airbus).

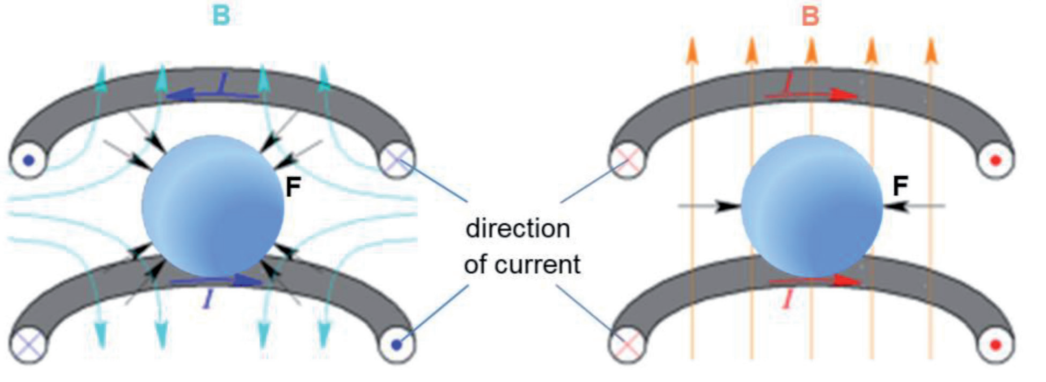

Figure 13.
Sketch of the superpositioning principle (reproduced from Ref. [21]). A current in the opposite direction for upper and lower coil winding creates a magnetic quadrupole field for positioning in the coil's center (left). A current in the same direction creates a magnetic dipole field for heating the sample (right).

heating field is set to a minimum so that the sample is not significantly deformed from its equilibrium shape by the residual weak forces. The homogeneity of the field and the spherical sample shape provide simple and well-defined conditions for evaluation of impedance data, thus enabling the determination of the resistivity with a high precision. For that purpose, the so-called Sample Coupling Electronics (SCE) has been developed [21]. The SCE is specially designed for the SUPOS coil system and measures the RF current and voltage of the heating circuit from which the electrical resistivity of the sample is derived.

EML was installed by the German ESA Astronaut A. Gerst in the European Drawer Rack (EDR) in October 2014, followed by a checkout of all subsystems. After that, two checkout experiments were performed in November 2014 and February 2015. The first scientific runs were successfully performed in spring 2015. The first two batches were already successfully performed in orbit; the third one is currently under preparation. The first sample chamber has already been downloaded, and the samples are being analyzed by the scientists.

4. The microgravity user support center of DLR

Being conceived as a fairly complex multiuser payload, the experiment development for TEMPUS and later EML was centralized at one focal point where the TEMPUS ground model was localized, and the scientific infrastructure to develop the experiments was available: the Microgravity User Support Center (MUSC) of DLR Cologne. Founded in 1986 by the DLR Institutes of Space Simulation and Space Medicine, MUSC has gained broad expertise in the scientific and operational preparation and conduction of space experiments. It started as the national point of contact for scientific users of microgravity facilities. In the first years, the focus was on bilateral scientific collaborations with NASA or Russia, who usually provided the launch vehicles for payloads developed in Germany. In these cases, the experiment resources were usually shared between the two collaborating countries. With the evolving ISS era, Europe has bundled its resources in order to provide a significant contribution to this large endeavor.

Today, MUSC is part of the network of European User Support and Operation Centers who, on behalf of ESA, are in charge of the operation of ESA developed payloads onboard the ISS (**Figure 14**). Over time, hundreds of microgravity experiments were developed in the ground models located at the DLR premises and supported from the control rooms at MUSC. Due to the broad range of scientific topics, payloads, and experiments, merely a small set of examples is listed here. In the 1980s–1990s, the MUSC activities were primarily focused on the preparation for and conduction of Spacelab experiments for the German Missions D-1 (1985) and D-2 (1993) mainly in the fields of materials and life sciences as well as technology development. In addition, experiments on unmanned carriers were supported. The retrievable European carrier EURECA was flown in 1992 and had six payloads onboard, including a protein crystal growth facility and different types of furnaces for solidification experiments. All of them were operated from the MUSC control room. From the early 1990s, first experiments on the Russian MIR Station were supported; the first time was for the Russian-German MIR92 Mission of astronauts Reinhold Ewald and Klaus-Dietrich Flade. During the EuroMIR 1994 and 1995 missions, a German furnace (TITUS) was operated by ESA astronauts Ulf Merbold and Thomas Reiter. Both had received training on the TITUS ground model located at MUSC. The Matroshka experiment from the DLR Institute of Space Medicine located on the outside of the Zvezda Module of the ISS in 2004–2005 marked the start of the new era of international collaboration. In the meantime, MUSC has operated the ISS payloads MSL, Biolab, DOSIS, EXPOSE, EDR, EML, and FASTER. There is a continuing close collaboration with the neighboring scientific institutes and the mutual exchange of staff and expertise, which puts MUSC in the position to support science teams in technical and science operational matters with respect to the optimization of their respective science runs onboard the ISS.

In general, MUSC tasks include the preparation and conduction of experiments in the payloads under its custodianship, including data dissemination and archiving. In order to fulfill these tasks, MUSC operates ground models of the experiment

Figure 14.
The microgravity user support center of DLR.

facilities and provides the ground infrastructure for the real-time on-orbit experiment performance in the control room located at DLR Cologne. For TEMPUS and later EML, even more customized services are provided (see next section).

5. Comprehensive experiment preparation for EML: transcription of scientific goals into facility settings

For TEMPUS and EML, a so-called ground support program was established. It accompanied the TEMPUS scientists during the entire life cycle of their experiments from the proposal to the delivery of the final experiment data. Activities comprised the measurement of sample properties needed for the development of experiment control parameters, their validation in the TEMPUS Ground Model, and the operation of the Spacelab and nowadays ISS experiments. All activities at DLR are performed in close coordination with the science teams and often performed in their respective presence. Preparation activities consist of three major parts.

First of all, the availability of certain physical sample properties, e.g., evaporation rates, coupling to the HF field, and spectral and hemispheric emissivity, is mandatory for the experiment preparation and execution. The knowledge of the amount of sample material evaporating from the sample surface during processing is essential. Therefore, the evaporation rate of each flight sample composition is measured in a dedicated facility on flight sample material provided by the science teams (**Figure 15**). The obtained data are later used in the experiment planning in order to design the temperature-time profiles such that the amount of evaporated material is minimized. Under vacuum conditions, the evaporated sample material condenses on the surfaces of the process chamber, while under gas atmosphere, the particles will agglomerate to fine aerosols or dust particles. It must be assured that the amount of dust remains in the nontoxic regime to protect the astronauts in case of a failure with the EML process chamber sealing.

In order to mitigate both aspects of sample evaporation, a software tool was developed at MUSC which calculates the mass loss of a sample during processing from the incoming temperature data and the known evaporation rates. In a next step, the layer thickness condensing on the coils is derived, and the element specific evaporation is calculated. This tool is used during the on-orbit experiment execution.

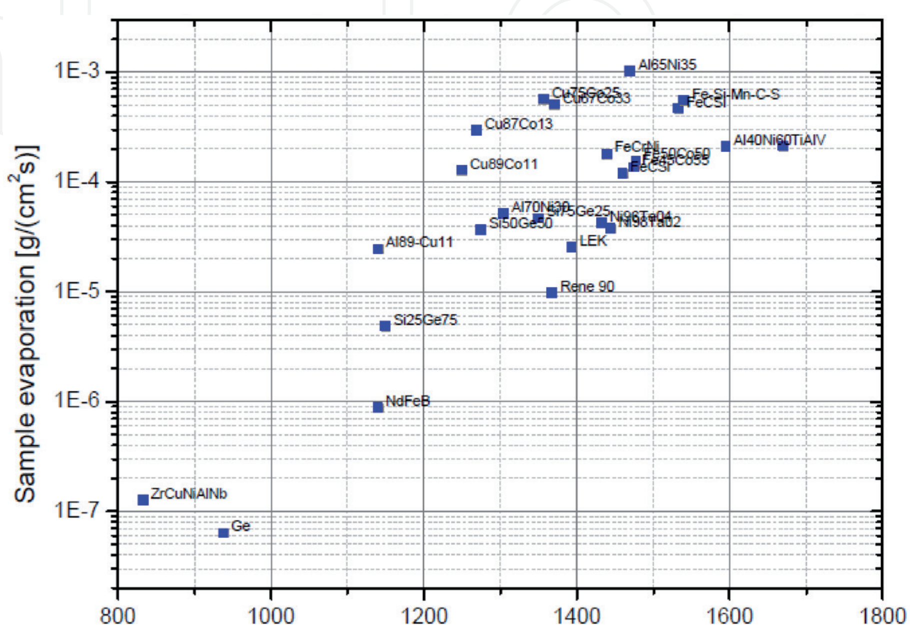

Figure 15.
Measured evaporation rates of batch 1 samples at the corresponding liquidus temperature in °C.

For the detailed planning of the experiments, the coupling of each sample to the RF field has to be known. The coupling describes the temperature reaction of the sample to applied field strength. Since TEMPUS and EML are not designed to levitate samples under terrestrial conditions, all ground-based measurements are limited to the solid state. They are performed on samples suspended in the coils on ceramic rods. In addition, due to the longstanding history of EML, a number of experimental data stemming from parabolic flight and sounding rocket campaigns are available today and will be used in support of future experiment developments. The obtained coupling data are needed to simulate the required temperature-time profile of the liquid sample with a TEMPUS/EML simulator software. This simulator tool is a MUSC development which has undergone refinements by systematic comparison of as-flown profiles with simulation results over the years of operation. For a correct temperature measurement with the pyrometer onboard, the sample emissivity at the melting temperature 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 flight facility.

Secondly, the individual operational flow for each experiment is developed, yielding the outline of all nominal and contingency operation. For that purpose, the so-called science protocols are prepared by MUSC on behalf of and in cooperation with the science teams. This document is kept in a narrative form, describing, e.g., key temperatures of the samples to be reached; facility settings for, e.g., camera recording and downlink; aimed pressure; or vacuum values. In addition, it contains a detailed experiment planning with respect to all aspects needed to fully describe the scientific and operational requirements of the respective experiment (**Figure 16**). The assembled information includes the following:

- The required EML configuration at the start of the experiment
- The applied process strategy, planned temperature-time profiles, maximum temperatures, and heating rates
- The planned sequence of cycles within experiments

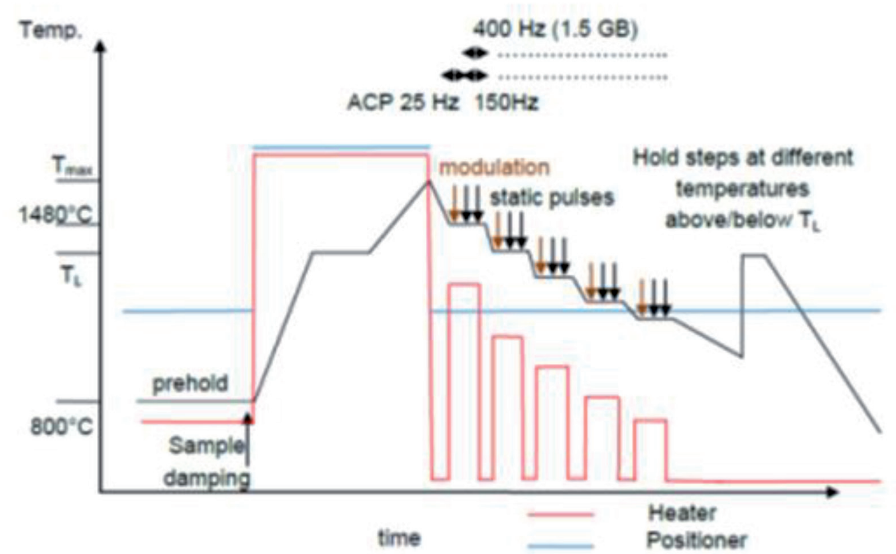

Figure 16.
Example of planned temperature-time profile (black) including the heating (red) and positioning control voltages (blue) as part of the science protocol showing specific heat measurements with the modulation calorimetry at five constant temperatures.

- Any planned modulation settings and heater stimuli settings
- The required diagnostics settings, e.g., camera settings (such as frequency, resolution, allocated memory)
- Strategies in case of unexpected sample behavior such as unsatisfactory sample stability or undercooling

With the determined sample material properties and the individual science protocols, the MUSC team can start the third part of the ground support program, which is the development of the so-called parameter sets. These parameter sets are interpreted by the EML process control software.

Experiments in EML are divided into individual thermal cycles which usually encompass one melting and solidification event. In the liquid phase, the scientific data are obtained either by high-speed video observation of the solidification front or by sample stimulation by modulation or applying pulses of the heater field and observing the effect on the temperature and sample shape. Each individual cycle is divided into several steps, which are described by two sets of parameters. The experiment parameters (EPs) define the experiment flow. With 38 parameters per step, the facility settings can be controlled. Up to 99 steps determine the time flow of one experiment thermal cycle. In addition to the experiment parameters, the so-called limit parameters (LPs) provide an independent guard rail envelope of RF values for each experiment that can never be exceeded. This safety measure was put in place in order to prevent any facility damage in case of a malfunction of the RF generator. Since the Spacelab era, MUSC has been developing and updating a TEMPUS/EML experiment simulator tool, which is used to derive the core experiment and limit parameters. This tool predicts temperature-time profiles from applied RF parameters. The calculation is based on the coupling behavior of the sample to the RF field and takes the planned process atmosphere into account. With this tool, the heater and positioner voltages for heating and melting of the sample and equilibrium temperatures for modulation measurements are determined. These voltages are then transformed into the final EP and LP sets for the facility (**Figure 17**).

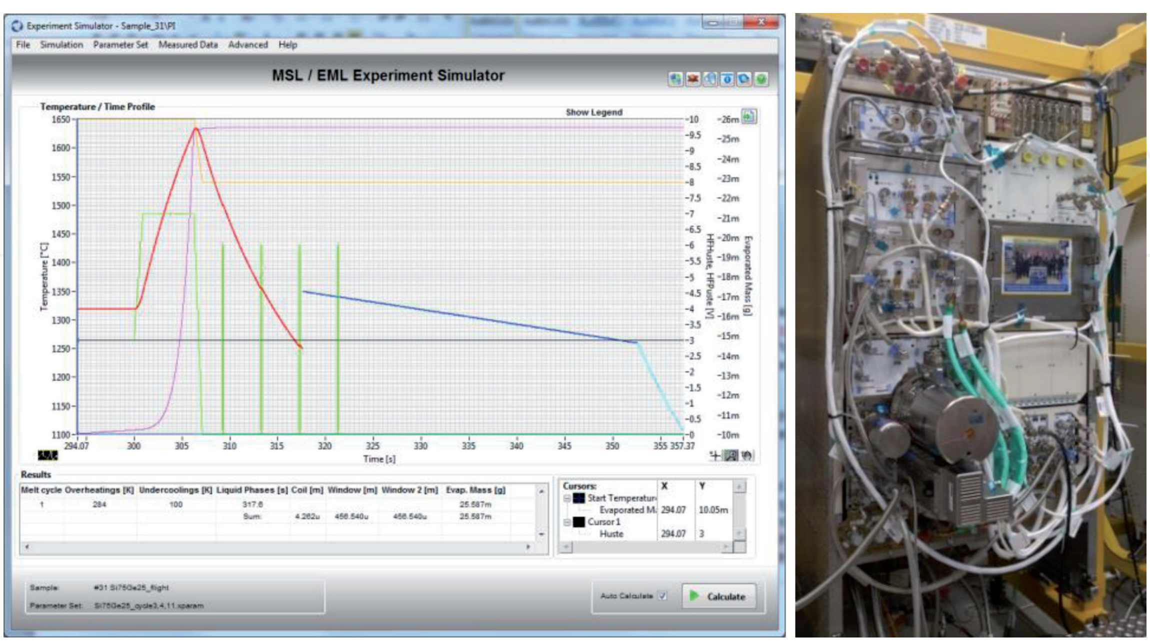

Figure 17.
Left: Thermal profile (red curve: liquid, blue curve: solid) simulated by using parameters developed for the space experiment, here an oscillating drop measurement where surface oscillations are induced by applying short pulses of the heating field (green curve) at different temperatures during cooling. Right: EML ground model used for validation of experiment parameter sets.

After the development of the flight parameter sets, they must be validated in a representative EML ground model. For this purpose, the Operational Model (OM), which also acts as flight spare, is used. During the validation the parameter sets are processed on a suspended high melting sample which remains solid during the validation run. With this approach, it is possible to test that all parameter sets are syntactically correct and that the experiment procedure follows the correct logic in all steps. A successful validation run in the EML OM is a precondition for the experiment performance onboard the ISS.

For the analysis of the video data, DLR MUSC developed a software, which displays the video and housekeeping data simultaneously [22, 23]. This enables the scientists to analyze both data together and investigate the sample behavior, observe the sample surface, etc. For the scientific analysis, image processing routines were developed, which measure the edge of the sample and calculate two perpendicular radii, area, center of mass, and half axes of an ellipsoid fit. On these data, a Fourier analysis can be performed, and the oscillation frequency of the sample surface can be measured. From the oscillation frequency, the surface tension can then be calculated. The decay of the surface oscillations is related to the viscosity. The development of this tool was started for the parabolic flight campaigns and later enhanced to be compatible with the EML data.

6. Operational preparation: how the experiments are implemented in the ISS context

The operational preparation is ongoing in parallel to the scientific preparation described above and is transparent to the scientific community. It consists of (a) resource allocation and coordination, (b) procedure development for ground and on-orbit operations, and (c) ground segment setup [24]. The most restricted resource is crew time. For EML, the experiment itself is performed via ground commanding without crew interaction; nevertheless, an astronaut is needed to change facility settings according to the requirements of the respective experiment, e.g., on the EML high-speed camera and hand gas valve settings regarding Ar or He as the gas atmosphere in the process chamber during the runs. These crew activities are relatively short and recurring with typical durations of 5–10 minutes and can usually be accommodated straightforward. More challenging is the planning of long crew activities like a swap between two EML sample chambers with a duration of 60 minutes or a hardware update of EML.

Further resources needed by the EML experiments are power, access to the Columbus vent line, high rate data bandwidth for the download of the science videos, medium rate telemetry of the payload, and commanding capability for active control of the experiment. During the science runs, the response time from ground needs to be minimized in order to react to any issue with the molten sample in due time. To ensure this, EML is granted a timeframe of exclusive telecommanding during "hot phases" of the experiments. A good microgravity level without disturbances during experiment phases is also mandatory. To achieve optimum microgravity conditions, experiments are deconflicted with all activities on the station that are known to induce microgravity disturbances such as planned thruster firings of the ISS or docking/undocking events. In addition, the experiments are always performed during crew sleep to minimize disturbances induced by crew presence in Columbus.

The experiment execution on the levitated sample is always observed with real-time video of both EML internal cameras. This ensures the proper experiment performance by visually monitoring the sample behavior and by sending safing commands if required. Periods when the onboard crew is not sleeping are used to download the stored science videos obtained during the night. It is coordinated with the flight control team that the maximum available bandwidth is made available for EML data download in order to cope with the high amount of data generated by EML. For operating EML from the MUSC control room located at DLR Cologne, MUSC is connected to the ESA Interconnecting Ground Segment. The EML Ground Segment is based on the commonly used monitoring and control architecture CD-MCS provided by the Columbus Control Center. MUSC receives telemetry (low and medium rate facility status data and video) and has telecommand capabilities to control the payload behavior and experiment performance in real time. In addition, dedicated ground support equipment is available, which transforms the incoming high-rate data streams into readable video data for process control purposes and off-line scientific evaluation.

7. Successful experiment performance on orbit

The EML experiments of a sub-batch are typically grouped into weeks of operation with "24/5" operations. This means that on Monday morning, the facility is switched on, and process conditions are established. The experiments only start late in the evening, when the crew sleep period begins, and finish prior crew wake-up. This yields a period of 8 hours and 30 minutes of science operations four times a week. Right after the last experiment cycle of the night, the conditioning process as described above is started again to optimize processing conditions for the upcoming experiments. In parallel, the download of the stored science video data is initiated. During the download, the operator on console needs to check the completeness of the incoming data, and in case of packet losses, the download has to be restarted. Afterwards the raw video data is processed into CINE file format. This complex task consists of many steps performed in the ground segment utilizing a dedicated software tool. Rundown of EML is usually performed on Friday evening, after the data download is completed.

Figure 18 shows the flow chart of a typical science campaign showing the schedule of samples with allocated number of melting cycles, gas atmosphere, and high-speed camera settings. In the frame of the ground support program, the experiment flows have been defined in detail. For some experiments, it is required to implement

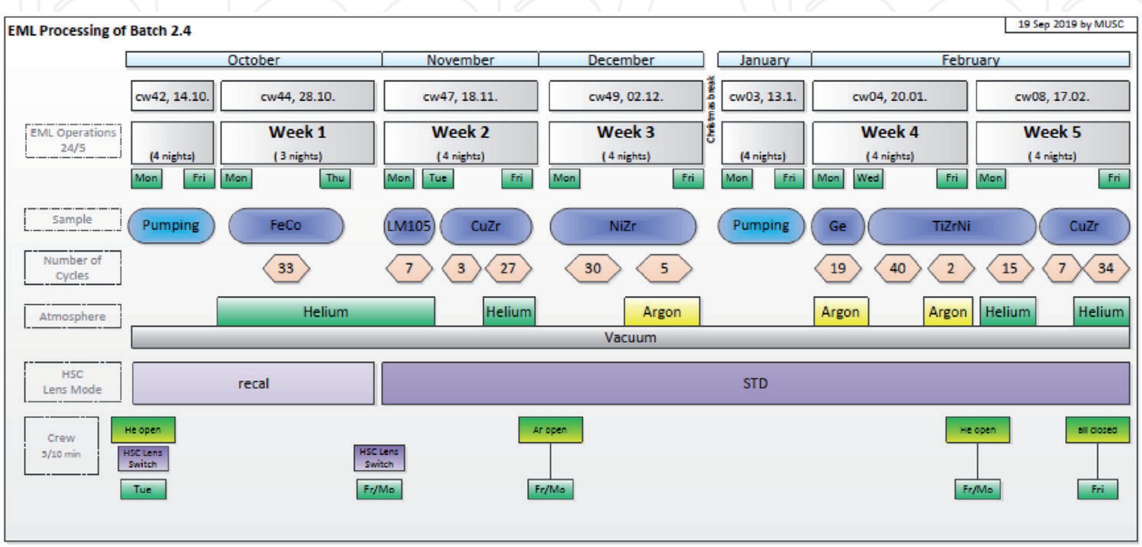

Figure 18.
Flow chart of a typical EML science campaign, in this case sub-batch 2.4 performed in autumn 2019. The Fe-Co sample processed in week 1 is investigated by a science team including the author T. Volkmann.

an intermediate break for a quick look analysis of the science data obtained before continuing. The provided flow chart depicts one specific experiment which requires such a break. During this time experiments on other samples are not excluded.

Once crew sleep has started, the operations team on console initiates the science operations. Prior to the start of cycle 1, EML is commanded to operational mode by selecting and calling a cycle. The cycle starts with the option to reprogram the experiment parameters by telecommand. It must be noted that the limit parameter sets are not accessible via commanding. They can only be changed by ground via file transfer (and only from ground) if the dedicated EML reprogramming cable is mounted by crew. Prior to starting science operations, it is ensured that telemetry and real-time video are available and that MUSC is enabled for commanding. The operators also check that the duration of the signal connection to the Space Station is long enough to perform the thermal cycle. The positioner is switched to ON. Then, the sample is mechanically stabilized in the field center by contact of the sample with the sample holder bottom and preheated according to the parameters in the EP set.

After verification that all prerequisites required to perform the thermal cycle are met, the semiautomated performance of the experiment parameter set is started. At this point in time, the EP Set is synchronized with the Limit Parameter Set (LP) which is independently controlled in the so-called Hazard Control Electronics (HCE). The sample is then heated, molten, and subsequently overheated. Upon reaching the maximum temperature, the heater is switched off or reduced. During cooling, the scientific measurements are performed. This may be any of the following or combinations thereof: (a) heater modulation, (b) heater pulses, (c) external triggering of recalescence, and (d) capturing of the recalescence event with high-speed camera. The cycle is finished once the sample has solidified and subsequently reached thermal equilibrium at a low temperature.

While performing the EP set, the HCE is monitoring the voltages in the oscillating circuits, ready to automatically switch off the heater and positioner in case of a limit violation. For safety reasons, any HCE cycle, that has been partially performed, may not be reused for a later experiment.

The automated cycle performance is closely monitored by the ground operators. One console position is dedicated to the telemetry supervision, and a different console position is responsible for telecommand generation if required. Commanding may be required, e.g., to rapidly cool down a sample in case of unexpected sample movement, if the sample temperature does not reach the expected value or if mechanical damping of sample oscillations is required. Additional reprogramming may be required in order to optimize EP values for an upcoming cycle.

The science operation is highly interactive and often requires ad hoc decisions on how to proceed. Therefore, experiments are always performed with the respective scientist on console (see **Figure 19**) to monitor the experiment on a dedicated console and to advise during scientifically motivated reprogramming. The science representative has also access to the EML video GSE to observe the process control video and to the voice loops for situational awareness. The science representative is assisted by two MUSC operators who actively monitor and control the experiment and who interface with the Columbus Control Center. They support the science team in any activity related to optimum experiment performance and perform the necessary parameter reprogramming for upcoming experiment cycles. This EML console team is assisted by operators in charge of the hosting EDR rack and a ground controller responsible for the data systems at MUSC. Directly after a melt cycle, the scientist is provided with the sample temperature data that allows fine-tuning of experiment parameters for the upcoming run (**Figure 20**). For this task, the EML simulator tool already used in the experiment preparation is available to the console team. It is not uncommon to send as many as 500 single commands to EML during one night.

Figure 19.
Operation of ISS-EML by telecommanding at the console in the control room at MUSC on 30 October 2019. The authors T. Volkmann and S. Schneider performing experiments with a Fe-Co sample as part of batch 2.4.

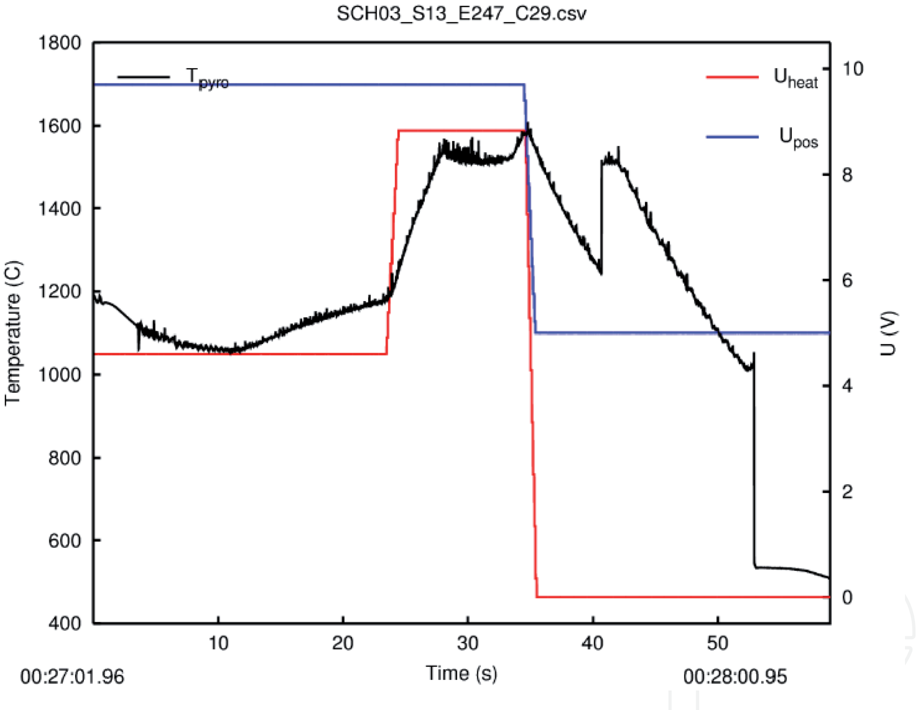

Figure 20.
Temperature-time profile (black), heater (red), and positioner control voltage (blue) during heating, undercooling, and solidification of $Fe_{60}Co_{40}$ processed on October 30, 2019.

After the performance of the first thermal cycle on a given sample, the as-flown sample temperature profile is analyzed by the EML telemetry/telecommand console position with the toxicity tracker software tool. From the temperature profile and the known evaporation rate of the material, the occurred mass loss is determined and compared to the respective limit for this cycle. The analysis is presented to ESA safety in a later stage, if needed, to prove that the result remained below the allowed limit values. This is required as under gas conditions; the evaporated material forms an aerosol, which, depending on its concentration, is considered toxic. The EML experiments are planned in such a way that they always remain in a nontoxic concentration (EP set performance controlled by HCE limit parameter set). In case of a violation of the limit for a specific cycle/experiment, processing of the specific sample would not be continued until a solution has been found. This toxicity tracker additionally keeps track of the evolution of dust the process chamber.

In parallel, it must be ensured that the overall facility degradation by evaporated material at any point within EML remains below a predefined limit value in order to preserve, e.g., the coil and surfaces of the optical components over the planned EML lifetime. Each experiment is provided with predefined maximum values for these layer thicknesses.

The video data of the high-speed camera are stored during a cycle in a ring memory. After performing the cycle, the video data are transferred to the hard disk of the computer controlling the high-speed camera system. The transfer of this video files must be completed before the HSC is reconfigured for recording (series of videos) with different settings for the next science run. Subsequent cycles are then performed according to this operational flow, starting over with the mechanical stabilization of the sample in the coil, if needed. After a night of science operations, the video data are transferred to ground where they are post-processed for later scientific evaluation. For that purpose, the science teams can use the MUSC developed tool, by which video and payload data can be displayed synchronously.

Last step in the experiment support chain is the archiving and distribution of the EML data in a data archive. Already during the parabolic flight era, a data archive basing on the web-based data management platform Hypertest was developed. All TEMPUS/EML data with associated metadata are stored in this archive and can be accessed by the respective data owners. This enables the user to search for metadata such as sample material, responsible scientists, campaign, date of performance, etc. The archive is accessible via the Internet, and thus all involved scientists can easily download their experiment data.

8. Evolution of the EML facility

Since its arrival on the ISS in 2014, two EML subsystems were upgraded. The operating system of the radial high-speed camera was exchanged with a faster one, reducing the waiting time between the cycles for video storage on orbit and thus allowing processing more cycles per night. The upgrade involved the exchange of an electronics board within a submodule of the experiment controller module. The pictures below show the EML operations team supporting the onboard activities performed by NASA Astronaut Andrew Feustel (**Figure 21**).

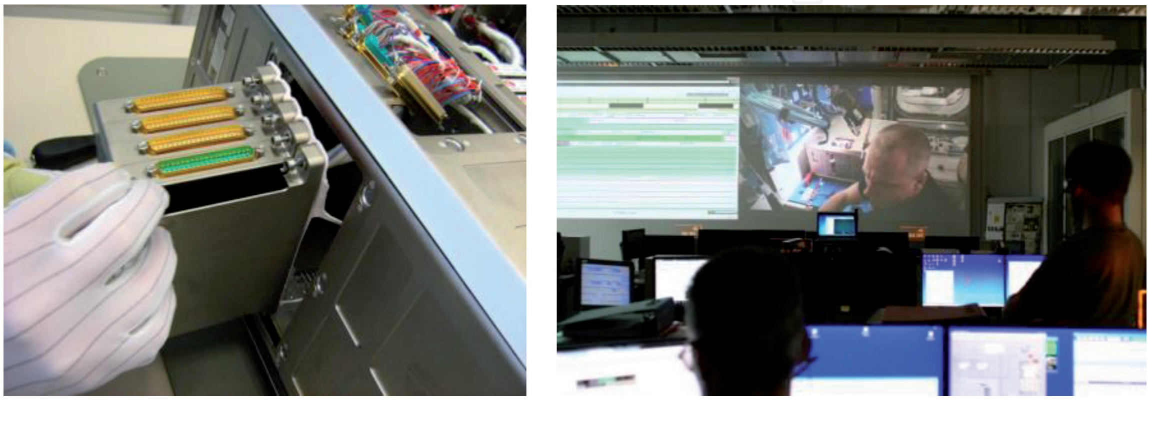

Figure 21.
Upgrade of the high-speed video camera operating system: location of board (left photo: Airbus) and operation team in the control room supporting Andrew Feustel (right).

The second upgrade applied to EML is the Sample Coupling Electronic (SCE) for the measurement of electrical conductivities. For the parabolic flight facility, a comparable SCE is available, which provides a higher measurement rate and can be used for the analysis of surface oscillations. Since its successful installation and on-orbit commissioning beginning of 2017, it has been used by the majority of EML science teams. This system is also a development of the DLR *Institut für Materialphysik im Weltraum*.

In the meantime, the community has opted for a third upgrade, the possibility to monitor and control the oxygen content in the samples. In order to keep the facility up to date on scientific level, Airbus is working on an "oxygen sensing and control system" (OCS), which is an insert that will provide adjustable and defined oxygen partial pressure of the EML processing atmosphere [25]. Oxygen represents a serious and potentially harmful contaminant to many materials at elevated temperatures due to its high chemical reactivity. Especially in containerless materials science experiments in which the processed sample is directly exposed to the process atmosphere and not contained in a cartridge, the presence of oxygen in the atmosphere might lead to a contamination of the sample leading to the formation of an oxide layer on the surface or to dissolution of oxygen into the liquid sample. These occurrences could significantly alter the experimental results and influence the nucleation of the solid phase in the undercooled liquid sample. The technology used for the OCS is founded on ceramic-based oxygen sensors and oxygen pumps and provides adjustable oxygen partial pressure of the processing atmosphere in the range from nominal down to the "parts per billion" range. The Phase B study of EML OCS has established a preliminary design that is compatible with the scientific-, technical-, and safety related requirements and interfaces for the future use in space environment. The functionality and performance were demonstrated with a dedicated prototype. According to present planning, the OCS shall be ready for launch in 2023.

9. Conclusions

The electromagnetic levitator EML onboard the ISS is a multiuser facility for containerless processing and undercooling of melts of metallic systems and semiconductors. The level of undercooling prior to solidification is an important process parameter controlling the evolution of the microstructure during solidification as well as the selection of alternative solidification pathways with metastable phases and therefore the properties of the solidified material. Processing in microgravity in combination with advanced diagnostic devices and evaluation methods enable the investigation of solidification phenomena in undercooled melts as well as the precise measurement of a variety of thermophysical properties of the liquid state as function of temperature including the undercooled regime. While strong levitation fields are needed for electromagnetic processing under normal gravity positioning: heating is decoupled in the ISS-EML. This allows minimizing electromagnetic stirring in the melt, thus enabling to study nucleation, solidification, and phase formation phenomena under (nearly) diffusive conditions. Moreover, under microgravity, electromagnetic stirring can be varied so that these processes can be investigated systematically under different levels of melt convection. Such experimental results provide the basis for verification and refinement of physical models for crystal nucleation and growth kinetics including the influence of fluid flow. Thermophysical properties like density, specific heat, viscosity, and thermal and electrical conductivity are not only fundamental quantities in physics and materials sciences but also serve as input parameters for numerical modeling of casting and solidification processes. Only with a detailed understanding of the physical mechanism involved and reliable input data the simulation of microstructural evolution is a powerful tool for fine-tuning of material properties and optimization of production routes.

Experimentation with the EML in space is very complex and needs a careful planning and preparation. Many tasks cannot be accomplished by the scientists who need a comprehensive support from facility and mission specialists for experiment preparation and performance. In particular, the infrastructure with hardware and software for preparation, conduction of the space experiment, and analysis of flight data is provided in the frame of the ground support program. Moreover, the ISS-EML facility must be constantly monitored and kept ready for operation. The support program is performed in close cooperation with the scientists and comprises the measurement of material properties relevant for processing in EML (evaporation rate, coupling parameters, and emissivity), the development of experiment procedure and parameter sets, and their validation in the EML ground model. Experiment planning also includes scheduling of all samples in a batch or sub-batch, which must be coordinated with the ISS activities concerning allocation of crew time, settings of the high-speed camera, change of gas atmosphere, energy consumption, and data transfer to ground. During space experiments, the operators in the control room actively run the EML facility by telecommanding in attendance of the scientists. Reprogramming of experiment parameters ensures the optimization of experiment cycles. A full support program for the entire science project from experiment definition to its operation on orbit and the management of flight data is decisive in order to obtain high-quality data and an optimum of scientific results.

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