ATLAS-M and Batt-M: Development of Flight Hardware for MAPHEUS Sounding Rocket

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Abstract. Two modules ATLAS-M and Batt-M were especially developed for application in the MAPHEUS (MaterialPHysikalische Experimente Unter Schwerelosigkeit) sounding rocket campaign. They were manufactured and built at the Institute of Material Physics in Space at the German Aerospace Center (DLR). ATLAS-M is a furnace for short time diffusion measurements achieving heating rates of 7K/s and cooling rates of 6K/s. Atlas-M is well suited for investigation of interdiffusion coefficients on a time scale of <200s. Batt-M is a rechargeable battery module, supplying a peak power of 12.6kW with a nominal capacity of 4.6Ah for operation.

1. Introduction
The main challenge for building scientific flight hardware on sounding rockets is to find the best compromise between the constructional and environmental constraints. Compromises have to be made concerning installation space, power consumption, overall weight, environmental conditions and available hardware components. The scientific payload has to fulfill these demands required for fully automated and reliable operation aboard. For Cu self diffusion quasi neutron scattering (QNS) delivers reliable and accurate results [4]. For binary and multicomponent alloys also chemical diffusion occurs. For binary alloys, the measurement of interdiffusion coefficients with QNS is typically not possible. Binary alloys require capillary experiments. These capillary experiments are affected by a number of problems. These problems may be overcome by x-ray tomography [5]. Microgravity is used to suppress buoyancy driven convective flow. For these μg experiments, the development of a furnace module for the sounding rocket MAPHEUS [1] was required. The MAPHEUS project aims to research material properties under microgravity using a two-staged sounding rocket. Therefore, the ATLAS-M (Atomic Transport in Liquid Alloys and Semiconductors on MAPHEUS) module was developed, processing a large number of samples simultaneously. For this purpose the Batt-M module was built, allowing a high power consumption.

2. Flight hardware
2.1. ATLAS-M
The ATLAS-M experiment is build to perform short-time annealing of metallic alloy diffusion couples in the liquid state during micro gravity.
The main component of ATLAS-M is the furnace housing. It contains 8 graphite crucibles. A single crucible contains 4 diffusion samples. With this setup it is possible to handle 8 crucibles and 32 samples in total. The crucible (Fig. 1) consists of graphite, milled and machined for this purpose.

Figure 1. Exploded view of crucible assembly with molybdenum heater.

Figure 2. Exploded view of furnace assembly with 8 crucibles

The used heaters, made of molybdenum wire $\varnothing 0.5\text{ mm}$ and embedded in $\mathrm{Al}_2\mathrm{O}_3$ tubes of $\varnothing_o 1.3\text{ mm}$ and an inner diameter of $\varnothing_i 0.7\text{ mm}$, are winded in a meandering shape. The whole crucible is wrapped in $\mathrm{Al}_2\mathrm{O}_3$ felt for thermal insulation. The heaters are attached to copper feed-troughs, located in the eight top covers, to obtain electric connectivity. A single heater delivers a heating power of 450 W at 30 V. The temperature measurement is accomplished by $\varnothing 0.5\text{ mm}$ thermocouples (TC) Type K, two for each crucible. The whole furnace is connected to a vacuum umbilical prior to launch for evacuating the eight (Fig. 2) sample chambers. For redundancy the eight crucibles are divided into two separate measurement units, achieved by discrete construction of the furnace complex. This helps to enhance the reliability in case the pressure increases unexpectedly or electrical problems occur. Before the vacuum umbilical is disconnected during lift-off, vacuum valves close the furnace complex to maintain the vacuum. During flight, the pressure inside the two independent units is measured with piezo pressure transducers. Automated processing of the entire control for the experiments is obtained via National Instruments cRio 9014 FPGA real-time controller using the programmable LabView User-interface (Fig. 3). The cRio-device is capable of handling several different types of data sources and is easily upgradeable through variable expansion cards such as analog and digital I/O devices and for thermocouple measurement. Additionally it records all the measured data and I/O-signals on an internal 2GB solid state flash memory. The operation during flight is stand-alone because $\mu g$-time is short and manipulation errors through experimenters would be
fatal. To keep the crucibles in a isothermal state (Fig.5), the temperature regulation is realized by pulse width modulation (PWM). Switching of the heating power, inert gas pressure- and vacuum-valve operation is managed by 12 solid state relays, located at a round shaped circuit board underneath the furnace.

The experiment work flow of ATLAS-M is as follows:

- Preheating prior to launch
- Lift-Off
- Heating close to the target temperature
- Melting of diffusion couples in $\mu$g-time
- Isothermal annealing at target temperature
- Rapid cooling to solidify the samples before end of $\mu$g-phase

To preserve the samples and ideally freezing in of the liquid diffusion profile before re-entry of the payload, cooling is supported by flooding the furnace with helium gas, provided by small gas pressure reservoirs. This enhances heat transfer into the aluminum furnace which serves as a heat sink. After recovery and disassembly of the payload, the crucibles are removed from the furnace for transportation and laboratory analysis.

**Figure 3.** ATLAS-M module cutout illustration. On the lower side of the assembly is the furnace housing, surrounded by two helium pressure reservoirs and gas valves. On the upper platform is the National Instruments cRio 9014 controller with up to eight measurement and/or digital/analog I/O controller boards.

**Figure 4.** Interior assembly (without outer hull) of Batt-M with six rechargeable battery packs and umbilical connector cable.
The ATLAS-M module was first launched on MAPHEUS-01 (lift-off 22.05.2009) with 8 graphite crucibles containing 16 diffusion couples. For MAPHEUS-02 (lift-off 27.10.2010) the crucible design was further enhanced. It enabled to process 8 crucibles with 32 diffusion samples in total. Additionally the existing circuit board was altered to achieve better heating performance at the expense of energy reserves in the batteries.

![Typical heating curve for ATLAS-M experiment. Target temperature 1373K.](image)

**Figure 5.** Typical heating curve for ATLAS-M experiment. Target temperature 1373K.

2.2. Batt-M

The rechargeable battery module Batt-M (Fig. 4) provided electrical power for the experiments accomplished on the sounding rocket campaigns MAPHEUS-01 and -02. Especially built as a power supply for high temperature furnace experiments, the Batt-M module provides sufficient capacity and ample power reserves for the accomplished experiments. The main battery system of the so called Service System of MAPHEUS is capable of providing about 30W (30 V, 1 A permanent, depending on battery charge status) for each experiment, and therefore is not suitable for experiments with high power consumptions [2]. Therefore a rechargeable battery was designed, housed in a separate module to supply the needed power to the experiments for MAPHEUS. The term battery is normally used for primary cells, these are non rechargeable and for single time use only. For flight hardware and laboratory use, primary cells offer only restricted possibilities due to their high costs and maintenance (exchange and disposal of used/empty cells). Secondary cells on the other hand are rechargeable and offer the same or even better performance as primary cells and require less frequent mechanical module maintenance. Secondary cells can be mainly distinguished by their technical relevance
Table 1. Secondary cell types and classification

| Description                          | Abbreviation | Single cell nominal voltage |
|--------------------------------------|--------------|-----------------------------|
| Lead acid                            | Pb           | 2.0V                        |
| Nickel cadmium                       | NiCd         | 1.2V                        |
| Nickel metal hydride                 | NiMh         | 1.2V                        |
| Lithium ion                          | LiIo         | 3.7V                        |
| Lithium polymer                      | LiPo         | 3.7V                        |
| Lithium iron phosphate               | LiFePO$_4$   | 3.3V                        |

and single cell nominal voltage (see Tab. 1).

To evaluate different representatives of cell types, laboratory tests were conducted. These tests demonstrated relatively poor discharge results and the lowest energy density for the tested lead (Pb) cells. For consumer application nickel metal hydride (NiMh) cells almost completely displaced nickel cadmium (NiCd) cells due to their heavy metal electrode material. However the main problem of NiMh cells is the comparatively low discharge current. Lithium Ion- (LiIon) and Lithium Polymer-cells (LiPo), up to now, are the most advanced secondary cells on the consumer market. They offer a low self discharge rate, very good performance to weight ratio and a high energy density for a reasonable price. This type is widely-used in notebooks, mobile phones and other portable devices. Problematic, especially for LiPo-cells, is their affinity to incinerate during recharging or misuse (short circuit) and their behavior to decrease in performance at low temperature conditions. As a subspecies of the LiPo-technique, lithium iron phosphate (LiFePO$_4$) cells evolved. Strictly, it is a LiIon-cell using lithium iron phosphate as a cathode material. In contrast to the LiPo-technique these cells offer a better thermal stability and uncomplicated handling during charging or in case of a misuse / faulty conditions. The major benefit is the high continuous discharge current.

Moreover for MAPHEUS the vacuum capability of the used cells is vital for safety and operation because the Batt-M module is not pressurized and exposed to ambient pressure during flight. For Batt-M the cells of A123-Systems offered good mechanical and thermal stability [3]. A123 single cells are housed in an electron beam welded aluminum enclosure. Tests in a vacuum chamber ($p_{ambient} \approx 10^{-4}$ mbar) showed no influence on the cells, the thermal stability was tested cooling the cell to a core temperature of $\approx -40^\circ$C. Afterwards the cell was discharged with a test-current showing the nominal capacity of 2.3 Ah. The mechanical strength of the cells was tested during shaker tests reaching g-levels of 12.7 $g_{RMS}$ and primary succeeded in the MAPHEUS-01 and -02 campaigns.

The Batt-M module consists of 108 single LiFePO$_4$ cells, assembled in six separate cell packs containing 18 cells each. The battery arrangement is called 9S2P, reaching a capacity of 4.6 Ah with a nominal voltage of 29.7 V. The six cell packs are connected to solid state relays with a switching current of 100 A. Prior to lift off, the battery module is connected to a stationary power supply to feed the experiments (without draining the internal power) via a umbilical connector, located at the outer hull of the module. Because charging of the cells is complicated and needs special equipment, it has to be done before assembly of the payload. Correct charging of LiFePO$_4$-cells is crucial. For proper operation, charging is done with a balancer, serving each single cell separately. The critical point is the maximum end-of-charge voltage for a single cell. It is not allowed to exceed this end-of-charge-voltage by any means. To accomplish this, the so called constant current / constant voltage (CC/CV) principle is used for recharging [3]. When the cell is empty, a constant current is applied to charge the cells. If the end-of-charge voltage
is reached (3.6 V for single LiFePO₄-cells) the charger continues with a constant voltage and the charging current is reduced (due to reaching the final single cell end-of-charge voltage). The charging process ends when the current reaches nearly zero, this indicates the complete charging process. This charging process results in expanded lifetime, consistent capacity and more charging cycles over lifetime. Six independent 29.7 V-cell packs are housed in aluminum cases which are framed to a baseplate. The weight of the assembled module including the outer hull is 28 kg including all peripheral components.

3. Conclusion
The ATLAS-M module processed 32 short time diffusion samples based on Al and Ge alloys during the MAPHEUS-02 flight. ATLAS-M reached a heating rate of 7 K/s with a maximum temperature of 1373 K and cooled down the furnaces, prior to end of μg-phase, achieving a cooling rate of 6K/s. The analysis and examination is done at the Institute of Material Physics in Space. The Batt-M module supplied sufficient power to the operated high temperature furnace experiments.

4. Outlook
ATLAS-M and Batt-M are designated for the MAPHEUS-03 campaign, scheduled for fall 2011. To achieve improved performance, minor technical modifications with respect to temperature control and reprogramming of the LabView interface is done. Both modules are being refurbished for summer 2011. Both modules can be used on future MAPHEUS flights but might also be used, with minor modifications, on other sounding rocket platforms.

5. References
[1] Stamminger A MAPHEUS - The Maiden Flight of a New Vehicle for Microgravity Experiments, IAC Proceedings, 2009
[2] DLR / SSC.REXUS User manual ver. 7.0. Euro Launch, 2009
[3] Retzbach L Akkus und Ladetechniken, Franzis, 2008
[4] Meyer A 2010 Phys. Rev. B 81 012102
[5] Zhang B, Griesche A, Meyer A 2010 Phys. Rev. Lett. 104 035902
[6] A123 Systems, www.a123systems.com, Datasheet High Power Lithium Ion ANR26650M1, A123, 2009