EXPLORE: TECHNOLOGY AND PROCESS DEMONSTRATION FOR ORBITAL REFUELLING ON A SOUNDING ROCKET

Christine Hill(1), Juergen Schlutz(2), Andreas Fink(3), Johannes Weppler(4), Robert Schelling(5), Emil Nathanson(6), Daniel Stoerk(7), Thorben Heinrichs(8)

(1)University of Stuttgart, Thuermchenswall 15, 50668 Cologne, Germany, Christine@explore-rexus.de
(2)University of Stuttgart, Thuermchenswall 15, 50668 Cologne, Germany, Juergen@explore-rexus.de
(3)University of Stuttgart, Buesnauerstr. 30, 70563 Stuttgart, Germany, Andreas@explore-rexus.de
(4)University of Stuttgart, 59 Miller Street, Room 814, Glasgow, G1 1EB, United Kingdom, Johannes@explore-rexus.de
(5)University of Stuttgart, Hauptstr. 116, 70563 Stuttgart, Germany, Robert@explore-rexus.de
(6)University of Stuttgart, Wolfmahdenstraße 46, 70563 Stuttgart, Germany, Emil@explore-rexus.de
(7)University of Applied Sciences Offenburg, Bergstraße 17a, 77971 Kippenheim, Germany, Daniel@explore-rexus.de
(8)Aalen University, Marktplatz 22, 73430 Aalen, Germany, Thorben@explore-rexus.de

ABSTRACT

Space exploration missions, in particular human and large cargo flights, require considerable transportation efforts to future destinations such as Moon and Mars. One option to achieve this payload and crew capabilities is by refueling of orbital transportation stages. The "EXPeriment for Liquid On-orbit REfueling" (EXPLORE) aims at informing the investigation of technologies and processes for these orbital refueling activities through a microgravity experiment. EXPLORE launched on the REXUS 9 sounding rocket in February 2011 at the spaceport Kiruna in Sweden. Further the paper will present the final experiment setup and evaluated results.

1. INTRODUCTION

While storable propellants are already transferred in orbit (e.g. at ISS), the handling of more efficient cryogenic propellants pose specific challenges, as described in [1], [11] and [12]. A fuel tank is typically pressurized by a gas, which then remains in the tank after depletion. Refueling activities then have to ensure best filling of the tank without mixture of the liquid and gaseous phases, while keeping the imposed pressure to avoid propellant boil off, as in [2] and [7]. This refueling process is reproduced in the EXPLORE experiment to investigate the influence of the filling flow velocity on the propellant flow and final fill level.

2. EXPERIMENT SCIENCE AND GOALS

As already mentioned above the main intention of the EXPLORE experiment is the need of on-orbit and on the way refueling mechanisms for future exploration missions to distant targets, such as Moon, Mars or Near-Earth objects, as shown in Figure 1. By using refueling stations on-orbit the costs of exploration mission could be minimized, while astronaut and propellant safety could me maximized.

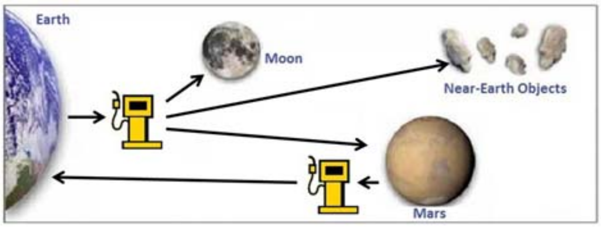

Figure 1. Future exploration missions to distant targets.

Up to now liquid propellant is stored in tanks with a membrane or vane separation between liquid and gaseous phase, as described in [3]. By emptying the liquid propellant, a pressurized gas is used to remove the liquid out of the propellant tank. To refuel the propellant tank again the pressurized gas has to be removed completely out of the propellant tank.

The state of the art systems with storable propellants use membranes between these two phases as shown in Figure 2a ([6]). Membranes increase mass and costs of propellant systems and on the other hand decrease the lifetime of the propellant tank. Furthermore due to material problems, membranes can not be used in cryogenic propellant systems. Therefore the EXPLORE experiment investigated a refueling system without the usage of membranes, by focusing on the influence of different refueling parameters on the propellant flow and final fill level, such as gravity, surface tension, geometry, temperature and inflow velocity, as shown in [13]. Hereby, the EXPLORE experiment especially investigated the influence of the flow velocity on the final fill level ([10]).

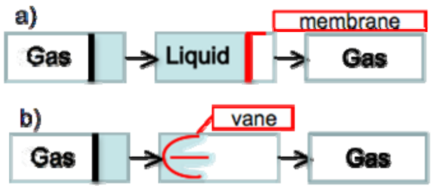

Figure 2. State of the art (a) and EXPLORE (b) investigation of refueling systems.

EXPLORE used small models of state-of-the-art propellant tanks, which have the same diameter to length ratio. For example the diameter to length ratio of the Space Shuttle Transport System equals 3.51, the ratio of the ARIANE V launcher equals 3.15, while the EXPLORE test chambers used a diameter to length ratio of 3.23 (length 11 cm, diameter 3.4 cm). Keeping this number in mind the transferability and scalability on bigger launching systems could be ensured.
In addition to that an inner structure was investigated for the test chambers to ensure a smooth and evenly liquid surface inside the test chambers without chaotic movement of the liquid during the microgravity phase, as seen in Figure 2b ([9] and [4]). A schematic view of the inner structure can be found in Figure 3.

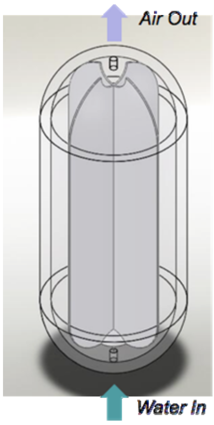

Figure 3. Inner structure (vanes) of the EXPLORE experiment.

The main experiment objectives are described as:

- Investigation of the influence of the flow rate on the filling process and final fill level
- Demonstration of fluid transfer, while minimizing mixture of fluids, without membrane
- Achievement of a fill level in at least one test chamber of >90%
- Identification of the best flow velocity (as fast as possible) to achieve the objectives above.

Numerical simulations have identified several promising flow velocity profiles to avoid gas cavities in the test chambers. Therefore the flow velocity profiles varied for each chamber in the experiment. Using acrylic test chambers and a video camera EXPLORE demonstrated and recorded the phase-separation during a microgravity environment. The experiment results will verify and optimize the numerical calculations. Both internal structure and filling profile of the EXPLORE experiment can then be used to inform large scale refueling simulations and demonstrations.
EXPLORE is based on the Fluid Acquisition and Resupply Experiment (FARE, as in [8]), as well as the Vented Tank Refueling Experiment (VTRE, as in [5]), which were flown by NASA in 1992 and 1993. According to NASA's FARE and VTRE program, the experiments achieved a final filling level of up to 99%, also using an inner structure inside the experiment tank. These experiments focused on the analysis of the vane geometry, the inlet geometry and the injection velocity.
The results of the VTRE experiment showed that the critical flow rate (the flow rate, where the fluid movement starts to be turbulent and separates from the vanes) is lower for a partly filled experiment tank, than for a complete empty one. This implicates an optimal filling by using variable injection velocities. Therefore, while the NASA experiments used constant flow rates, the EXPLORE experiment analyzed variable flow velocities, which will be discussed further on.

3. EXPERIMENT TECHNICAL CONCEPT

The experiment is installed in a payload compartment of the REXUS sounding rocket. It comprises the refueling system, the control and measurement electronics, and the structural mounting. In the refueling system, a central gas pressure tank pressurizes two identical liquid tanks, which again distribute the liquid fuel to the test chambers through mass flow controllers and adequate valves and tubing. EXPLORE uses six transparent test chambers, where relative geometric properties resemble typical propellant tanks. To avoid mixture of gaseous and liquid phase, the filling is supported by a customized internal structure in the test chambers. The structure will direct the fluid surface under microgravity and ensure proper extrusion of the pressurizing gas.

3.1. Mechanical Design

The central part of the experiment setup consists of:

- the fluid supply system
- the fluid distribution system
- six fluid tanks referred to as “test chambers”
- two overflow collection chambers
- the pressurized gas system

The fluid supply system and the pressurized gas system simulate the liquid propellant supply system of an on-orbit refueling station. The test chambers and the collection chambers simulate the liquid propellant tank and pressure tank of a spacecraft being refueled.
The pressurized gas subsystem provides the pressure needed to drain the fluid supply tanks and drive the fluid into the test chambers in microgravity. It consists of a pressurized gas supply tank, a gas pressure sensor and a pressure reduction valve.
The fluid supply system consists of two fluid tanks which hold the fluid used in the experiment before and during launch. The tanks are fully filled before launch in order to prevent any disturbance to the rocket stability due to fluid movement. Due to simplicity and safety reasons water mixed with anti-freeze fluid was used. Therefore the surface tension was reduced to an equal value of cryogenic propellants and non-freezing on the launch pad in Sweden could be guaranteed.

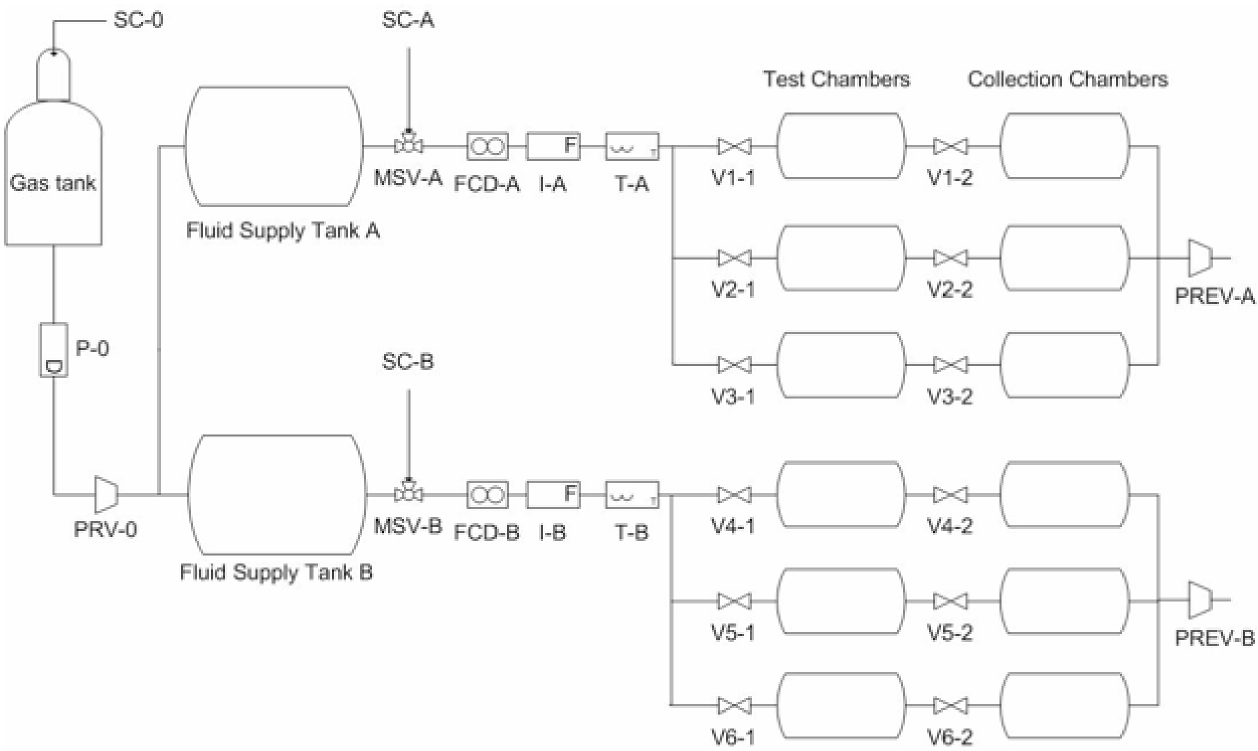

Figure 4. Block diagram of the EXPLORE experiment.

During the experiment the tanks are drained and the fluid is moved to the test chambers. A membrane provides separation of fluid and pressurized gas.

The fluid distribution system guides the fluid from the fluid supply system to the test chambers once the experiment is started. A series of hoses, electrically controlled magnetic solenoid valves, temperature sensors and flow control devices are used in the setup to control the fluid inflow velocity into the test chambers and the flow rate.

The test chambers are designed to resemble miniature propellant tanks. Here the actual experiment takes place when the chambers are being filled. The test chambers are made of transparent acrylic glass so that the filling process can be monitored and recorded by a camera.

Excess water and air from the test chambers is stored in the collection chambers. The residual air in the test chamber is released out of the system via a pressure relief valve once the air from the test chambers flows in. A membrane prevents any fluid from leaving the system and spilling into the REXUS rocket.

A camera is used as a recording system, which monitors and records the filling of the test chambers during the experiment. An additional camera was installed to record the outside environment during the flight.

An illumination system consisting of various LEDs provides sufficient light for the recording system. The illumination system is powered by the REXUS rocket onboard 12V DC power supply.

The structure is the central subsystem, which supports the other subsystems and transfers loads between REXUS rocket and the individual EXPLORE components.

In order to provide a more detailed understanding of the experiment setup the flow diagram in Figure 4 shows the individual components of the pressurized gas system, of the fluid supply and distribution system and the test chambers as well as the collection chambers.

The gas tank (pressure < 7 bar) of the pressurized gas system is connected to both fluid storage tanks. The pressure sensor (I-0) is monitoring tank pressure and reports data back to the microcontroller. This provides housekeeping data for the gas tank and allows for early detection of leakages. A pressure reduction valve (PRV-0) reduces the system pressure in the connected fluid storage tanks to 2.5 bar.

The two fluid storage tanks hold the fluid, used in the experiment, and are connected to the pressurized gas system on one side and to three test chambers each on the other side. Inside each fluid storage tank a membrane is installed, which separates the gas of the pressurization system and the fluid used for the experiment. A flow control device (FCD-A and FCD-B) at the outlet of every tank enables a continuous control of the fluid inflow speed via the microcontroller. A manually operated master safety valve (MSV-A and MSV-B) is installed after each tank to prevent fluid from escaping the tank during system tests of the magnetic solenoid valves. The master safety valves are to be opened before launch.

Before and after the test chambers electrically controlled magnetic solenoid valves (V1-1 to V6-2) are installed to control which chamber is being filled and to

preserve the condition in the chambers after filling is completed. During launch the fluid storage tank is completely filled and the test chambers and the collection chambers are empty. Once the experiment starts, the valves in the system are opened sequentially to fill two test chambers at the same time. One test chamber is filled from fluid supply tank A and the other one from fluid supply tank B. The test chambers being filled are arranged symmetrically around the center line of the REXUS rocket so that no significant center of gravity shifting occurs during the filling process.
The test chambers are finally connected to the collection chambers. The collection chambers feature a membrane, which works like an inflatable balloon and collects the excess volume (air and fluid) from the test chamber. As the balloon increases in size the residual air in the collection chamber outside the balloon leaves the system through the pressure relief valves PREV-A and PREV-B. This mechanism keeps the system pressure in the collection chambers and the test chambers constantly at a pressure level of 1 bar. At the same time it prevents any fluid from leaving the system and entering the REXUS experiment container. As a redundant system another fluid collection device (tissue) is installed above and beneath the experiment to avoid leaking water disturbing other experiments on the REXUS rocket.

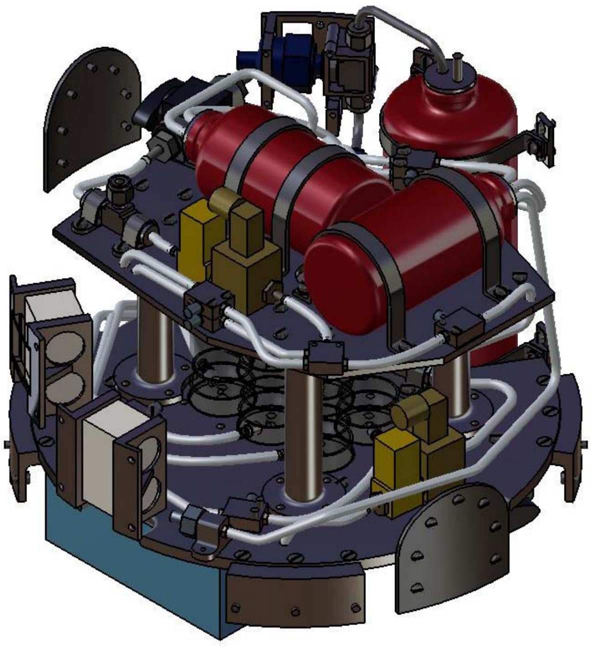

Figure 5. 3D-view of the EXPLORE setup.

In order to refill the gas tank and water supply tank after experiment testing, without having to dismantle the entire experiment, three service connectors are added to the tubing system. SC-0 is the connector for repressurization of the gas tank. SC-A and SC-B are used to refill the fluid supply tanks. The filling process is as follows: First any residual pressure in the gas tank has to be released and the valve of SC-0 has to remain open during the process. Then the required amount of liquid is supplied to the fluid tanks through SC-A and SC-B, while the valves before the test chambers are closed. After SC-A and SC-B are closed, pressurized air can be supplied to the gas tank through SC- 0. In order to drain the test chambers and the collection chambers quick connections are installed in the pipes before and after each test chamber. By opening these disconnections the test chambers can be drained without removing them from the experiment. The experiment setup can be seen in the CAD drawing in Figure 5.

3.2. Electrical Design

The EXPLORE Experiment will use the power provided by the REXUS service module to power its electronics consisting of one micro controller, two cameras, twelve solenoid valves, two flow controllers, two temperature sensors, one pressure sensor and five LED cluster lights. The 28 V from the service module will be converted into 5 V, 12 V and -5 V by commercial of the shelf DC/DC converters. The EXPLORE components need a total power consumption of approximately 0.08 Wh during the flight.
To trigger the EXPLORE experiment time signals, such as “lift off”, “start of data storage” and “start of experiment”, provided by the REXUS Service Module, were used. During the rocket flight the EXPLORE Experiment used the REXUS Service Module downlink to send collected housekeeping data (temperature, pressure, as well as flow control device status) to the ground station.
The electronics subsystem is divided into three main segments:

- Control and command segment (incl. microcontroller, REXUS interfaces and all associated electronic components)
- Flow control segment (incl. all electronic valves as well as flow control devices)
- Sensorics segment (incl. pressure and temperature sensors and two cameras).

A schematic overview of the EXPLORE electronics layout is shown in Figure 6. The control and command segment is dominated by the microcontroller, which is responsible for the overall experiment control, as well as the internal management of the data and the data exchange with the REXUS service module. The segment is mounted into a single electronics box comprising all necessary control logic. The heat produced by the electronics is very low and is absorbed and dissipated by the electronic box. The selected microcontroller (ATMega128) and all used electronic components are commercial of the shelf parts and were partly sponsored by Atmel. The ATMega128 is a low-power CMOS 8-bit microcontroller and is programmed via the AVR Studio 4.

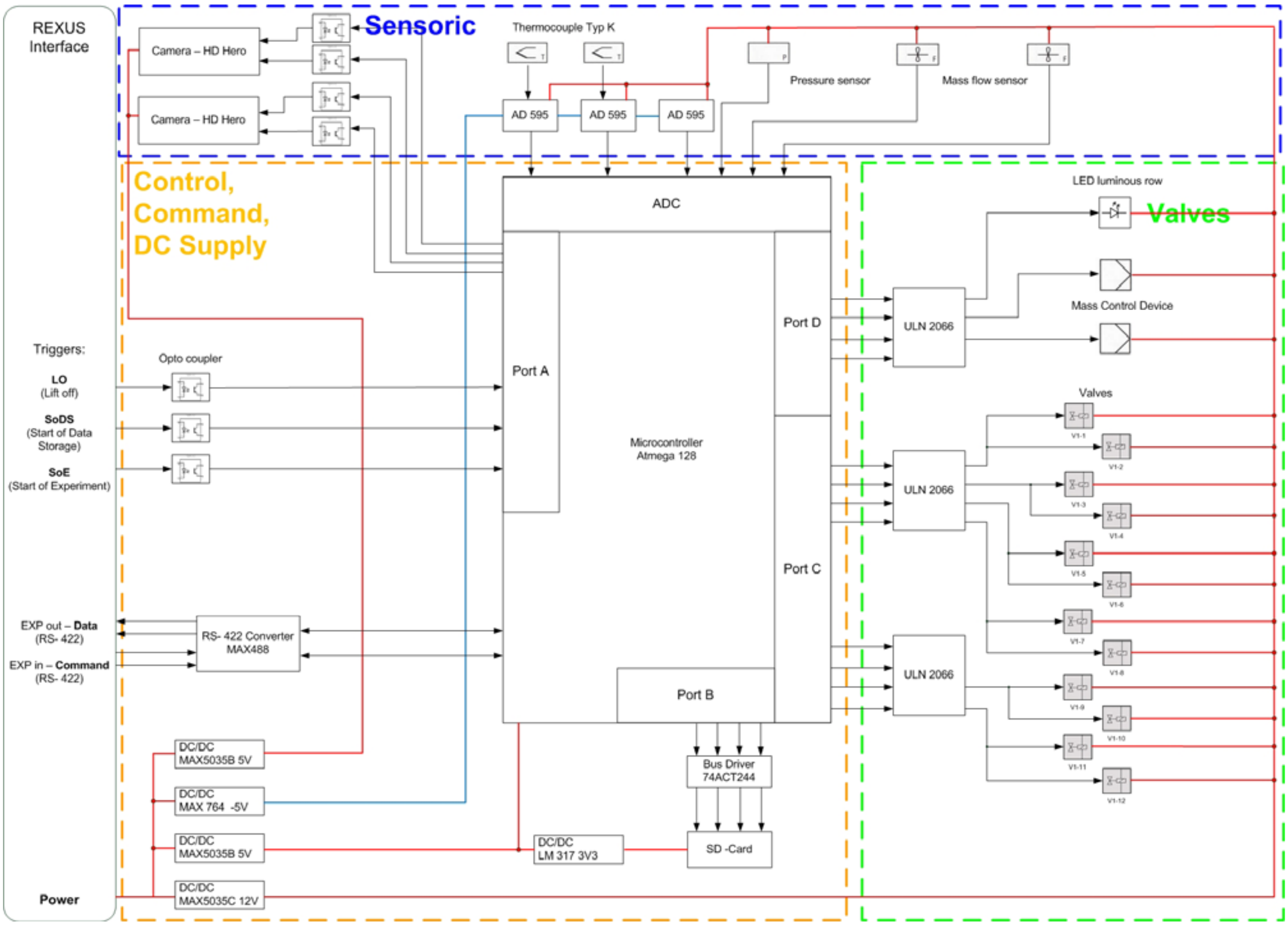

Figure 6. EXPLORE electrical setup schematics.

The flow control segment includes all electronic components that are in direct contact with the liquid and gaseous fluids in order to manage and control the inflow velocity. It includes twelve solenoid valves for the test chambers, sponsored by Staiger and two flow control devices, sponsored by Buerkert.

The used solenoid valves equal normally closed magnetic valves to allow a secure power-off mode of the EXPLORE experiment. Each valve simply opens as soon as power is provided and closes when no power is applied. The valves operate at a voltage of 12 V DC and need a power consumption of about 0.5 W each, while the flow control devices need a power consumption of about 2 W each.

The sensorics segment comprises all measurement devices that collect data throughout the EXPLORE experiment. In particular, data acquisition includes video, status of flow control devices, pressure and temperature measurements. A selected set of data is transmitted to the ground station via the REXUS service module in order to monitor the experiment status.

Temperature measurements will use standard thermocouples that have a long history in experimental setups. A miniaturized pressure sensor monitors the pressure of the gas reservoir. The device operates on a 12V DC power supply and provides an analogue data signal that is interpreted and transmitted by the microcontroller.

To record the EXPLORE experiment two Go Pro Hero HD video cameras are used to capture first the filling process and second the actual rocket flight The camera provides a USB 2.0, HDTV Out and an Audi Out connection for data transfer. Power will be supplied by one of the 5 V DC/DC converters and will be connected by USB.

3.3. Software Design

The software of the EXPLORE experiment runs on the microcontroller and thus controls the experiment and its components. The following diagram (Figure 7) gives an overview of the command and data flow of the EXPLORE experiment.

As it can be seen in Figure 7 the microcontroller handles the control signal for the valves and the mass flow control devices and also manages the data recorded by the temperature and pressure sensors as well as status reports. The recorded data is sent to the REXUS Service Module and down linked to a ground support station. The two cameras are using their own memory cards.

The program starts to send data after power on. When it receives the “start of data storage (SODS)” signal, the cameras begin their record. In the microgravity phase of the rocket flight the experiment starts when the program receives the "start of experiment (SOE)" signal from the REXUS Service Module.

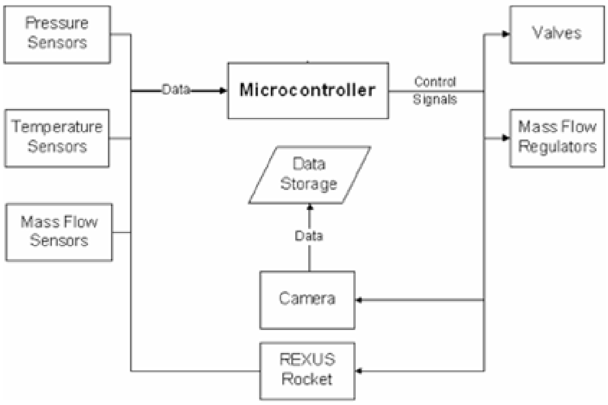

Figure 7. EXPLORE command and data flow.

After receiving the "lift off" signal, the REXUS Service Module has to transmit the SODS signal. In order to monitor the experiment the microcontroller will send housekeeping data to the ground station via the REXUS Service Module downlink. Additionally it has to be stated that the experiment was performing autonomously, so that no active controlling was possible during the complete rocket flight.

During various tests with the REXUS Service Module the EXPLORE experiment expected a loss of data of less than 2%.

In addition to the onboard software ground support software was developed to evaluate the recorded housekeeping data like the reading of temperature and pressure sensors. Using this program an on site evaluation and discussion of the results could be obtained.

4. RESULTS AND DISCUSSION

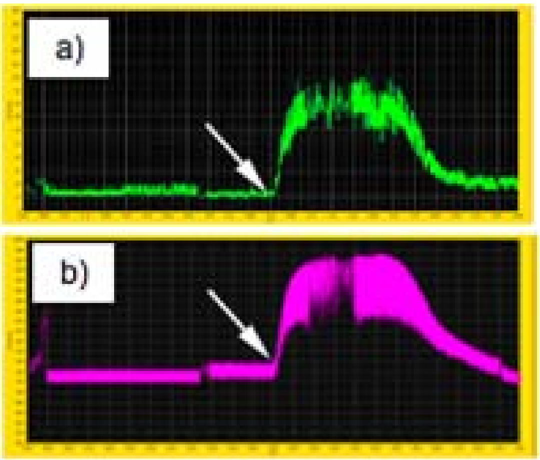

Figure 8. Temperature (a) and pressure (b) anomalies during the EXPLORE flight.

During the flight the ground support software showed perfect communication with the rocket. All housekeeping data, including temperature and pressure values, as well as the status of the flow controllers, valves and the rocket signals were received by the ground support software. A first evaluation of the temperature and pressure data on site showed some sensor distribution anomalies. Both the temperature and the pressure showed the same behavior as shown in Figure 8. With the lift-off of the REXUS rocket (white arrow) the received data went straight up and decreased again slowly to the original values. It is also obvious that the data showed great variations during the microgravity phase, which still have to be explained.

The most important goal of the EXPLORE experiment was to achieve a fill level of more than 90 percent in at least one test chamber. After evaluation of the experiment on site and the video material the filling levels of the test chambers were measured as follows:

Table 1. Measured filling levels of each test chamber after the rocket flight.

Test Chamber	Filling Level
1	80 %
2	30 %
3	30 %
4	60 %
5	60 %
6	30 %

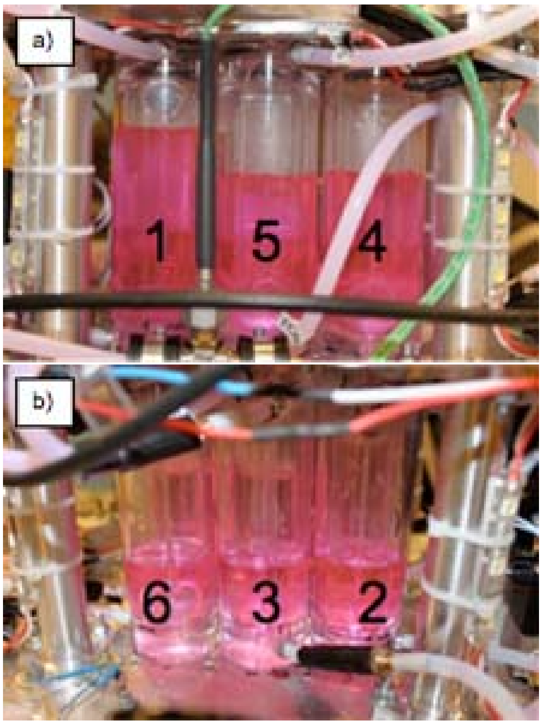

Figure 9. Filling levels of each test chamber after the rocket flight.

The fill levels of each test chamber can also be seen in Figure 9. The evaluation of the video material also showed a clear separation of the gaseous and liquid phase inside the test chambers. There was no turbulent mixture of gas and liquid observed. The structure inside the test chambers showed very good first results to separate gas and liquid. The evaluation is still ongoing, but the first results showed good accordance to the defined goals. It can be stated that the EXPLORE flight was a success.

5. CONCLUSION

The "EXPeriment for Liquid On-orbit REfueling" was a complex experiment in the REXUS program of DLR and SNSB. In a successful rocket flight on REXUS 9 in February 2011, the experiment investigated the influence of the flow velocity on the microgravity refueling process of a pressurized receiver tank with internal structure. It demonstrated the continuous separation of liquid and gaseous phase throughout the filling process.

The EXPLORE project was the first to investigate and to demonstrate technology and processes for future exploration on a small sounding rocket. It was an obvious success and provided important skills and experience to the team while advancing research and technology goals.

6. ACKNOWLEDGEMENTS

The EXPLORE team was constantly supported for the experiment realization, including technical and management expertise, hardware provisions and financial support. Therefore the EXPLORE team would like to acknowledge special support by:

- The Ministry of Economics (BMWi) through the German Aerospace Center (DLR). DLR was maintaining overall REXUS project management and supported the acquisition of hardware.
- The Institute of Space System (IRS) of the University of Stuttgart. Represented by its director Prof. H.-P. Roeser, the IRS provided access to local expertise and facilities as well as logistics support for EXPLORE.
- Prof. S. Schlechtriem, lecturer at IRS and head of DLR Lampoldshausen, and his research staff provided technical advice in the area of refueling and propulsion. They also provided initial test material for the fluid system to us, particularly tubing and fittings.
- The Institute of Aerospace Thermodynamics (ITLR) of the University of Stuttgart. The in-house mechanical workshop of the institute manufactured most of the customized EXPLORE components.
- Development and management of the EXPLORE website was supported by IT-Services Benjamin Ackermann in order to provide a flexible and powerful platform for outreach and communication.
- Primus AB of Stockholm, Sweden, supported the EXPLORE team with their expertise in fuel handling and provides gas and fluid tanks as well as manufacturing of components (tank caps and connectors) for the fluid system.
- The foundation of the federal state bank of Baden-Wuerttemberg (Landesbank Baden-Wuerttemberg, LBBW) supported EXPLORE financially with a substantial amount to procure components, raw material and test equipment.
- The Evonik business segment Acrylic Polymers is manufacturer of PLEXIGLAS® and offered special discount support for the EXPLORE raw material to build our test chambers.
- The German Ralf Bohle GmbH is market leader for bicycle tires in Europe with its Schwalbe label. Schwalbe valves were used to fill and pressurize the EXPLORE gas section.
- B.I.O-TECH e.K. supported EXPLORE as specialist for fluid sensorics. They provided miniature mass flow meters to monitor the exact propellant flow rate during the rocket flight.
- The Walther-Blohm-Stiftung supported EXPLORE financially for the procurement of experiment hardware and electronics as well as for the covering of general team costs due to outreach activities and travel costs.
- GoPro-Shop.com supported EXPLORE as an official distributor of GoPro HD camera products in Germany. They provided GoPro HD Hero helmet cameras for high quality video coverage of the experiment and flight.
- Staiger fluid systems supported EXPLORE by the provision of special discounts in the procurement of miniature fluid valves and by provision of additional mounting support elements and expertise.
- Hydrobar Hydraulik und Pneumatik GmbH of Boeblingen/Sindelfingen was supporting the EXPLORE experiment with their extensive fluid system expertise and by providing tubing hardware to the team.
- New Pig of Hazeldonk, the Netherlands, is an expert in absorption products and provided absorption pads to EXPLORE as fluid collection devices.
- The Studentenwerk Stuttgart e.V. is a local organization to support and to enable student projects at the University of Stuttgart and abroad. The Studentenwerk confirmed financial support to the team for hardware procurement and travel expenses.

- Financial support was also provided by the Erich-Becker-Stiftung to cover travel costs for several meetings abroad.

EXPLORE also thanks our friends Leonore Kleinkauf, Bernd Bilian and Michael Schnurr. Special thanks go also to the REXUS/BEXUS supervisors: Andreas Stamminger and Mark Fittock, as well as Olle Persson (SNSB).

7. REFERENCES

1. Dr. Chato D., *Cryogenic Fluid Transfer For Exploration*, NASA/TM—2008-215286 Cleveland, Ohio, 2008.
2. Dr. Chato D.J., *LOW GRAVITY ISSUES OF DEEP SPACE REFUELING*, AIAA 2005-1148, Reno, Nevada, 2005.
3. Dr. Chato D.J., *Technologies for Refueling Spacecraft On-Orbit*, AIAA-2000-5107, Long Beach, California, 2000.
4. Dr. Chato D.J., *Thermodynamic Modeling of the No-Vent Fill Methodology for Transferring Cryogens in Low Gravity*, AIAA-88-3403, Boston, Massachusetts, 1988.
5. Dr. Chato D.J. and Timothy A., *VENTED TANK RESUPPLY EXPERIMENT – FLIGHT TEST RESULTS*, NASA TM-107498, Cleveland, Ohio, 1997.
6. Collins F.G. et al, *The subscale orbital fluid transfer experiment*, N96-70677, Tullahoma, Tennessee.
7. Dr. Chung J.N. and Yuan K., *Two Phase Flow Characteristics and Boiling Heat Transfer Rates During Cryogenic Chilldown and Transport in Reduced Gravity*, NASA/CR2008-215440/PART3 Florida, 2008.
8. Dominick S.M. and Driscoll S., *Fluid Acquisition and Resupply Experiment (FARE I) Flight Results*, AlAA 93-2424, Monterey, California, 1993.
9. Dominick S.M. and Tegart J. R., *Low-G Propellant Transfer Using Capillary Devices*, AIAA-81-1507, Colorado Springs, Colorado, 1981.
10. Dominick S.M. and Tegart J.R., *Orbital Test Results of a Vaned Liquid Aquisition Device*, AIAA 94-3027, Indianapolis, Indiana, 1994.
11. Potter S.D. et al, *A Cryogenic Propellant Production Depot for Low Earth Orbit*, Albuquerque, New Mexico, 2001.
12. Rybak G.S. et al, *Feasibility Study for a Cryogenic On-orbit Liquid Depot-Storage, Acquisition and Transfer (COLD-SAT) Satellite*, NAS3-25054, Cleveland, Ohio, 1990.
13. Tegart J.R. and Kirkland Z., *On-Orbit Propellant Resupply Demonstration – Flight Results*, AIAA-85-1233, Monterey, California, 1985.