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DESIGN OF A MOONFIBRE SPINNING APPARATUS FOR THE USE ON A REXUS RESEARCH ROCKET

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ABSTRACT:

In-Situ Resource Utilisation is currently investigated to enhance the feasibility of a lunar settlement. As lunar regolith and basalt have similar composition, its use to produce continuous fibres for structural reinforcement is proposed.
In this paper the preliminary design of the first experimental microgravity *MoonFibre* spinning apparatus to fly aboard a REXUS research sounding rocket is presented. The suborbital flight provides approximately three minutes of microgravity during which a steady fibre production must be established. The proposed apparatus makes use of two concentric rotating parts to generate hydrostatic pressure and pull the fibres autonomously at the intended speed. The fibres are stored inside the experiment module and can be recovered and analysed after touchdown.
The experiment will deliver knowledge on how space environment, especially reduced gravity, impacts the spinning process and the fibre properties.

1. INTRODUCTION

For forty-eight years, mankind has not been to the Moon anymore. However, NASA is currently planning an initiative called Artemis, aiming to perform human landing on the Moon by 2024 and establish sustainable missions by 2028. [1] To ensure the financing, NASA administration is looking for additional funding and extensive international support. Furthermore, NASA plans to assure Artemis's success by relying on commercial partners. [1] To reach the long-term goal of Artemis, the establishment of a permanent base on the Moon, costs have to be kept at a minimum. Even with the massive reduction of launch costs, prices for launching a kilogram of payload to the lunar surface still range from 10.000 $/kg [2] up to 890.000 $/kg [3]. Sustainable exploration of the Moon cannot be achieved at such high costs. These costs can be reduced by utilizing local lunar resources. This concept is called the In-Situ Resource Utilisation (ISRU) [4]. As many lunar base components as possible must be produced on the Moon itself, thus avoiding expensive launches from Earth.
A novel ISRU technology developed at the RWTH Aachen University by the Institut für Textiltechnik (ITA) and the Institute for Structural Mechanics and Lightweight Design (SLA) is the *MoonFibre* technology [5]. The *MoonFibre* project aims to develop fibre-based resources from lunar regolith on the Moon's surface. Fibres can be used to produce a range of products that otherwise couldn't be manufactured on the Moon. These will then be used in various ways within the lunar settlement. The same technology could be utilised similarly on Mars. There are many possible use-cases for *MoonFibre* products. These are currently

investigated in a DLR-funded study. Some of them include reinforcement of structural habitat components, production of mechanical elements such as gears, axles, seals and pressure vessels and production of settlement equipment such as astronaut clothing and protective coveralls for Extra Vehicular Activity (EVA) suits. [5]

No fibres from real lunar regolith have been spun yet. However, Blay Semprere [6] investigated the fibre spinning process with two regolith simulants called ITALUS-1 and ITALUS-2 (ITA Lunar Simulant) within the framework of his thesis. The results of this thesis state both simulants can successfully be spun into continuous fibres and are expected to have similar mechanical properties as basalt fibres. Fig. 1 and Fig. 2 show the microscopic and macroscopic images of fibres produced using the ITALUS-2 simulant.

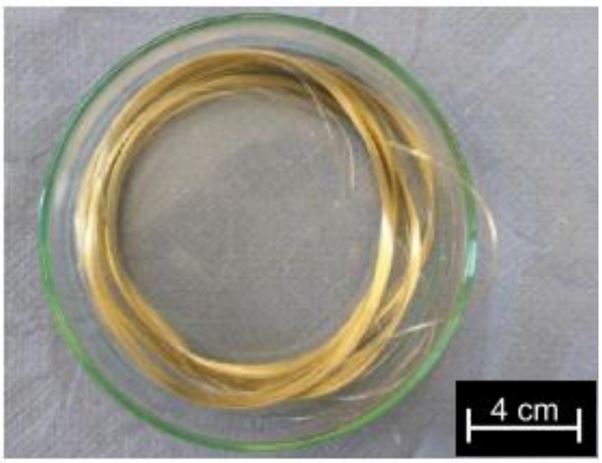

Figure 1. Macroscopic view of fibres made from ITALUS-2 [6]

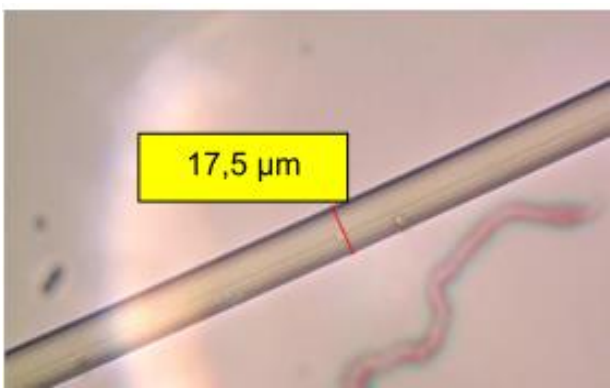

Figure 2. Microscopic view of fibres made from ITALUS-2 [6]

Lunar regolith is by its chemical composition similar to basalt. The most conventional way to produce continuous basalt fibres is the fibre drawing process [7]. Feedstock material is fed into an oven called bushing and melted at more than 1200 °C. The bushing is made of an inert Platinum-Rhodium alloy. The bottom of the bushing is equipped with multiple nozzles, through which molten material is drawn by the force of gravity and the rotation of a winder. As it leaves the nozzle, the melt is rapidly cooled by cooling fins and water spray cooling in order to avoid crystallization and the creation of an amorphous structure. Before finished fibres are winded, they are passed by equipment for static discharging and sizing, which protects the fibres against friction and improves the chemical bonding between them. This process and a schematic view of a conventional spinning facility are illustrated in Fig. 3. The produced continuous fibres can be as thin as 9 µm. [7]

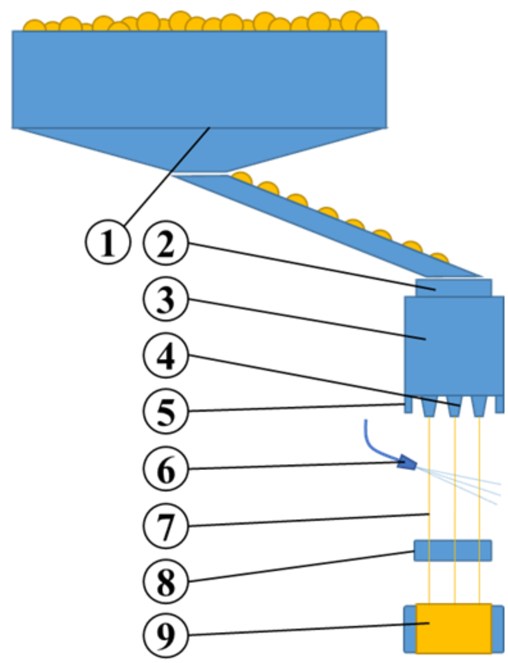

Figure 3. Terrestrial basalt fibre spinning process [5]; (1) – Raw material supply, (2) – Feeding & dosing system, (3) – Bushing, (4) – Nozzles, (5) – Cooling fins, (6) – Water spray for static discharging, (7) – Fibres, (8) – Sizing applicator, (9) – Winder

This process has many downsides regarding its application in space. It requires a gravitational force to feed raw material and draw the fibres. Convection through the atmosphere is needed to cool the fibres once they leave the nozzle. A water jet is used for static discharging. Hence, this process cannot be utilised in a vacuum and low or microgravity. The whole process is not autonomous and requires at least two technicians to oversee it. The smallest industrial machines are approx. 10 m tall. [5] Therefore, the main challenges of the *MoonFibre* project are to adapt this spinning process for the lunar environment and develop a miniaturized and autonomous spinning facility. The size and mass of this facility must be reduced to be launched on any currently existing or planned launcher. The spinning process must be automated to be used on the Moon efficiently and reduce the workload of astronauts. The facility must be adequately tested and qualified. [5]

The spinning apparatus adapted for the lunar environment is under development and considered proprietary information. It will be placed on an iBOSS platform developed by SLA [8], which will house the apparatus. The output of this facility will be continuous fibres which will be removed upon completion, either by an astronaut or a robot. [5] This concept is shown in Fig. 4.

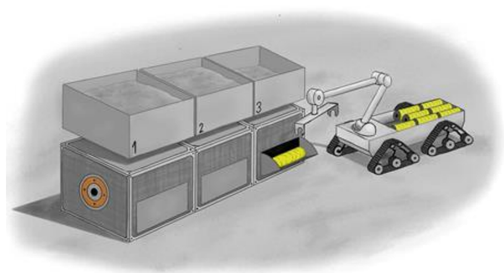

Figure 4. MoonFibre spinning facility on the Moon [5]

Apart from ZBLAN fibre, no fibre material has ever been spun in space. Note that ZBLAN is an optical fibre and therefore has a different production process than structural fibres such as *MoonFibre*. In 1992 NASA attempted to spin fibres from a lunar simulant material in low gravity during a parabolic flight. An accessible fibre drawing apparatus was installed aboard a NASA KC-135 aircraft. The production of continuous fibres from lunar simulant material in its natural state was not possible with the apparatus used. [9][12]

The ISRU *MoonFibre* Experiment (IMFEX) project was initiated to develop a spinning facility for continuous basalt fibres adapted for the operation in space environment. The fibres will be produced from a lunar regolith simulant. The experiment will be launched on a suborbital flight into space aboard a REXUS (Rocket Experiments for University Students) sounding rocket.

The REXUS program enables European students to launch scientific and technological microgravity experiments on suborbital flights. The experiments are flown aboard a single-stage rocket, which measures 5.6 m in length and 0.356 m in diameter. The maximum payload mass is 95 kg. Approximately 3 minutes of spaceflight and altitudes between 78 and 93 km can be reached. Fig. 5 depicts the REXUS rocket. Two of these are launched each year from SSC, Esrange Space Centre in Sweden. The experiments are recovered after flight and can be further analysed. [10]

Within these 3 minutes, the spinning of structural basalt fibres in microgravity environment will be attempted. The objectives, requirements and experiment design is presented in this paper.

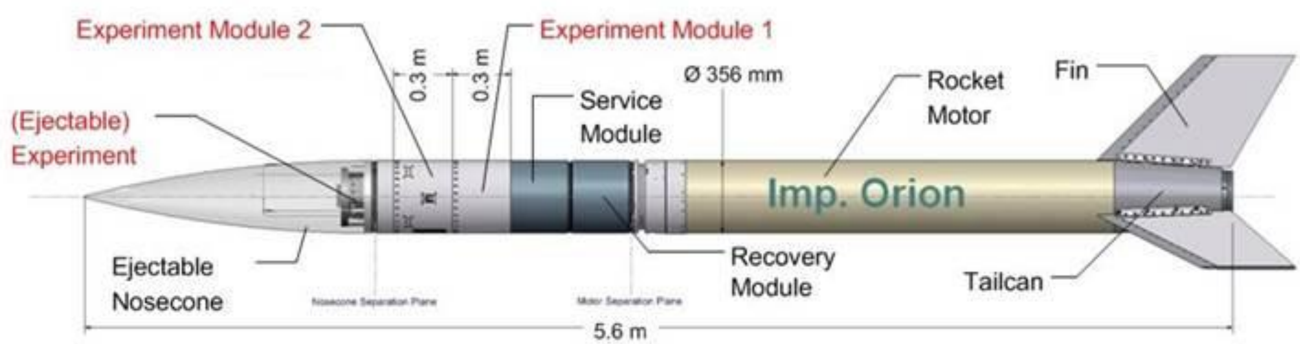

Figure 5. REXUS sounding rocket [10]

2. EXPERIMENT DESCRIPTION

IMFEX aims to develop, launch and operate an autonomous basalt fibre spinning apparatus adapted for the utilisation in space environment. By operating the experiment in-flight, fibres will be spun in reduced gravity. Recovered fibres will be tested and compared to fibres spun on Earth. Thereby, the impact of reduced gravity on the mechanical properties of basalt fibres can be investigated.

2.1. Experiment Overview

The centrepiece of the IMFEX concept is a rotating bushing that is heated by a heating wire and thermally isolated. Lunar regolith simulant is placed inside the bushing pre-flight. Once the bushing is spun up to the intended speed in microgravity, centrifugal forces push the molten simulant through two nozzles located opposite of each other at the wall of the bushing. Depending on the rotational speed of the bushing, the fibre properties such as diameter can be varied. The bushing rotor is surrounded by a larger outer rotor. The outer rotor spins in the opposite direction. It acts like a catching drum for the fibres and replaces the winder used in terrestrial spinning facilities. This layout saves space inside the module. If a fibre snaps, no particular action is needed to restart the process, for the new fibre can simply be spun over the older ones. The dual rotor design is chosen because it can be tested on the ground and operated with and without the influence of gravitational pull. About 1.4 km of fibres are expected to be produced. To ensure no melt leaves the bushing uncontrollably in case of failure, a nozzle tip closing mechanism is included. The bushing, the catching drum and the drivetrains for both rotors are placed within a pressure vessel and are operated within an air atmosphere at room temperature and the constant pressure of 1 bar. This way forced convection cools the fibres before they hit the catching drum. A cooling system including a compressor ensures sufficient heat exchange between the pressure vessel and a heat sink. A camera system records the spinning process, detects spun fibres and transmits data to a control system. A sensor system monitors pressure and temperature within the pressure vessel and forwards the data to a control system. The control system consists of a motor control unit, a heating control unit, a computer and a data processing system. A power system consists of an external power supply and an on-board battery. The bushing will be heated up on the launch pad using the external power supply. Shortly before take-off, the system switches to internal power.

A more detailed description of the experiment subsystems follows in the next sections. Fig. 6 depicts the whole experiment design.

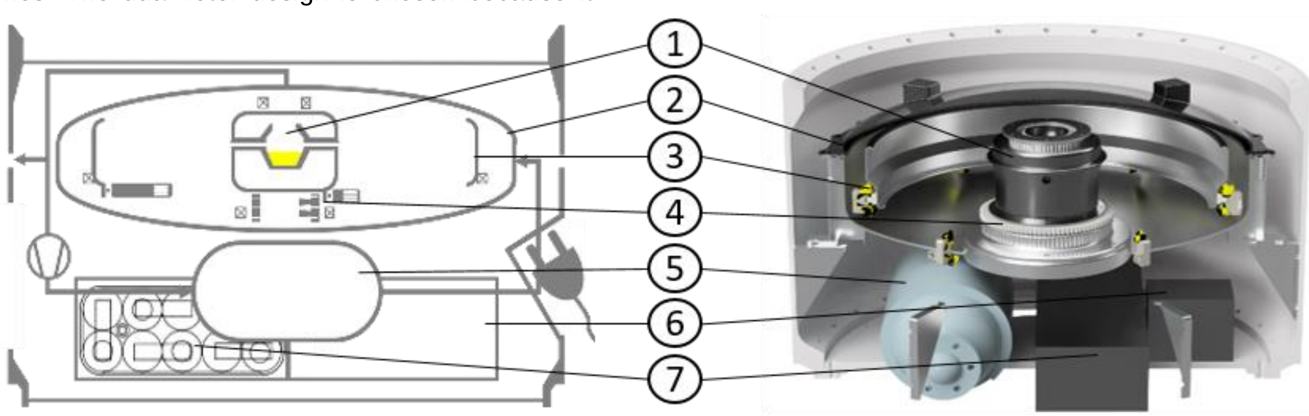

Figure 6. IMFEX Experiment concept: Schematic view (Left) and CAD Rendering (Right); (1) – Bushing, (2) – Pressure Vessel, (3) – Catching Drum, (4) – Bushing Drivetrain, (5) – Heat Exchanger, (6) – Computer Department, (7) – Battery Compartment

2.2. Experiment Requirements

To spin fibres, the temperature inside the bushing shall not exceed a certain temperature range and shall be upheld at all times. A substitute force shall be applied to the melt to compensate the reduced gravitational forces and pull the melt out of the bushing. As the melt leaves the nozzle it shall be cooled before the fibres are collected by the catching drum. For this purpose, a cooling system with a heat sink is required. A sensor system shall detect spun fibres during flight and transmit confirmation to the ground station. Visual data will be saved on-board and be retrieved afterwards. A control system must control the process autonomously. General requirements to be fulfilled concern the size and the operation of the experiment. The whole system shall fit into a 210 mm high cylinder with a diameter of 348 mm. And it shall not disturb nor harm the operation of other experiments nor the launcher itself.

2.3. Mechanical and Thermal Design

The following sections will give an overview of the individual mechanical and thermal subsystems, their main objectives and their set-up.

2.3.1. Bushing and Heating System

The bushing containing the lunar regolith simulant, is shown in Figure 7. The bushing, including the heating system, is pivoted about the vertical axis inside the pressure vessel. Bearings are placed at the top and the bottom of the assembly and are connected to the bushing's outer shell. A flange above the bushing, containing the bearing, is mounted on an aluminium support structure, which itself is mounted on the inner wall of the pressure vessel. The bushing's second bearing and the drivetrain are placed below the bushing and are mounted on strengthening ribs at the bottom of the pressure vessel.

The essential function of the heating system is to heat the regolith simulant to a temperature within the required temperature range. This is achieved through resistance heating. A heating wire is wound around the bushing. This wire must be electrically sealed, therefore, it is enclosed in a ceramic shell. The core bushing, which contains the simulant, is made of Platinum-Rhodium. Its inner shape is elliptical to guarantee a mass flow to the two outward-facing nozzles when spun.

To minimise the heat loss, the ceramic is insulated with a heat resistant wool and an outer layer of insulation material. The limiting factor to maintain the simulant at the desired temperature is the power output of the batteries. To ensure structural integrity, the entire system is enclosed by a steel shell. The top of the bushing is open to insert a thermocouple and to allow gas to flow in as melt leaves the bushing. The ceramic heating parts enclose the bushing from the top and the bottom, as well as around the nozzle extensions. The parts include gaps to allow thermal expansion of the bushing. Each ceramic part is connected directly to the steel shell.

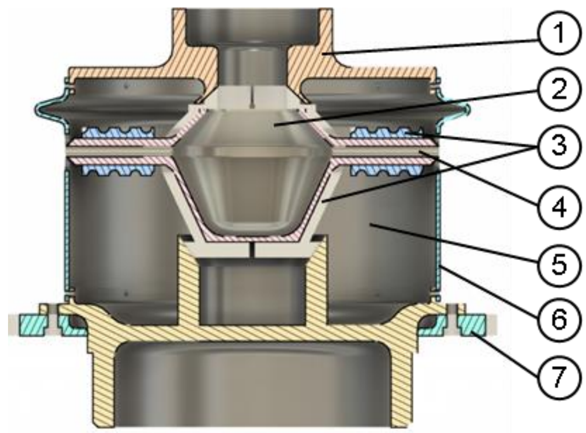

Figure 7. Bushing and its heating system and thermal isolation: (1) – Flange, (2) – PtRh Bushing, (3) – Ceramic Insulation for the heating wire, (4) – Nozzles, (5) – Wool insulation, (6) – Outer shell, (7) – Drivetrain gear

The maximum temperature of each material determines the thickness of the layer underneath. Options for insulation layers are given in Tab. 1.

Table 1. Insulation layer materials

Layer name (number as in Fig. 7)	Material
Bushing (2) & Nozzles (4)	Platin-Rhodium Alloy
Heating wire ceramic insulation (3)	Al_2O_3
Wool Insulation (5)	UltraBoard PCW® (1st layer) Promalight® mats (2nd layer)
Outer shell (6)	Steel

The heat flux in a steady-state case defines the power needed to keep the simulant at the same temperature during the flight and spinning process. This heat flux is estimated to be 50 W.

2.3.2. Closing System

In case of failure, the hot bushing endangers other experiments and the rocket. A closing mechanism for the nozzles is included as well as a closing mechanism for the top opening of the bushing. A shutdown procedure is integrated into the software to stop the spinning process and trigger the safety mode to ensure no leakage of molten simulant.

2.3.3. Catching Drum

The fibres are collected by an Al7075 catching drum which is concentric to the bushing and positioned inside the pressure vessel. The drum rotates in the opposite direction to the bushing and is driven by a separate drivetrain. It is supported by pairs of inclined bearings mounted to the wall of the pressure vessel. Fig. 8 depicts the bushing and the catching drum.

Figure 8. The bushing and the catching drum

2.3.4. Drivetrain

The drivetrain subsystem can be divided into two parts. One is responsible for the bushing rotation and the other one for the catching drum. Each part consists of a brushless electric motor with a planetary reduction gearbox, a pair of spur gears and a bearing. The whole drivetrain is located inside the pressure vessel. To generate a sufficient mass flux of molten simulant (about 10^5 kg/s per nozzle), the bushing rotates with 600 rpm. The drum rotates with 300 rpm to reach a processing speed of about 700 m/min of fibre per nozzle. Without the planetary reduction gearbox small scale electric motors cannot operate at these low speeds. For integration reasons the motors and gearboxes are mounted offset to the rocket's longitudinal axis. The power is transferred by the spur gear set to accommodate for the offset and to further raise the gear ratio.

2.3.5. Pressure Vessel

The pressure vessel maintains the atmosphere in which fibre cooling is possible. Therefore, it is filled with a cooling gas at atmospheric pressure and room temperature. It is designed to withstand a pressure of 2 bar. To avoid built-up of pressure, overpressure valves are installed. The pressure vessel consists of a cylindrical bottom part and an elliptical cover. The bottom part is manufactured from Al7075, the cover is made of carbon fibre composite. The bottom is reinforced by strengthening ribs on which the bushing and a camera system are mounted. The pressure vessel itself is mounted half way up on the inner wall of the experiment module. This configuration allows the subsystems outside the vessel to be positioned underneath.

2.3.6. Cooling System

The cooling system regulates the cooling gas temperature inside the pressure vessel. A compressor, mounted to the bulkhead of the REXUS experiment module underneath the pressure vessel, transports the heated gas through metal tubing to the heat exchanger. There, the gas is cooled down before it returns to the pressure vessel. The fibre temperature must be reduced from 1260 to 690 °C with a cooling rate that ensures optimal mechanical properties of the fibres. The cooling rate depends on multiple factors, such as type of fibres, basalt composition, heating conditions etc. Analytical models for optimal cooling rate do not deliver similar results as the ones empirically obtained [11][12]. The cooling for this experiment will be determined during ground tests described in 2.5.1.

The heat exchanger transfers the excess heat from the cooling circuit to the heat sink. There, it is absorbed by paraffin wax, a phase change material [13]. The heat causes the wax to melt, absorbing energy with a small temperature increase. This ensures that the gas stream can be cooled to the desired temperature even when large amounts of heat have already been stored. The heat sink is mounted directly to the bulkhead of the REXUS experiment module and has the shape of a gas cylinder. The inside contains an aluminium lattice structure which serves two purposes. It reinforces the structure of the heat sink and ensures that heat is homogeneously transferred to all regions of the wax, preventing the overheating of the already molten parts. This is necessary as paraffin has a thermal conductivity of 0.15 W/mK, which is further reduced once melted [13]. The lattice structure conducts heat homogenously through the whole wax volume. It is estimated that 100 kJ at 50 W will be delivered from the heat exchanger. The cylindrical walls of the heat sink contain a helical pipe through which gas flows. The helical shape ensures a large contact area between the heat sink and the fluid, while not disturbing the flow. Aluminium is chosen as the building material for the heat exchanger because of its good mechanical properties, low density and high thermal conductivity. The part will be manufactured using SLM (Selective Laser Melting). Air is chosen as cooling gas.

2.4. Electronics Design

The following sections will give an overview of the individual electrical subsystems, their main objectives and their set-up. The schematics of the electronics system is shown in Fig. 9.

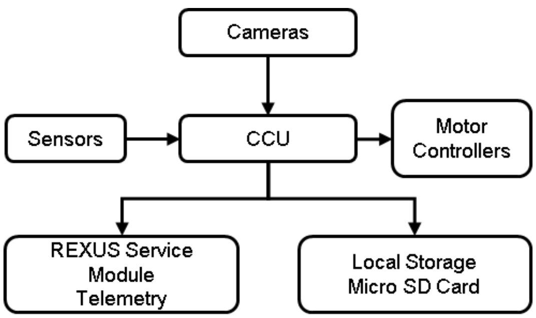

Figure 9. Schematics of the electronics system

2.4.1. Control System

The control system consists of a Central Control Unit (CCU) and a motor control unit. Each motor will be controlled by a separate motor controller which will be placed close to the motors. The central control system, including all units, is located in a computer department, which is mounted to the bulkhead of the REXUS module. As CCU, a Raspberry Pi® is chosen. It communicates with all other electronic devices via its two I2C Buses, multiple I/O Ports and PWMs. All collected data is stored locally on the Raspberry Pi's micro SD card.

2.4.2. Power System

External power supply is used to heat up the bushing on the launch pad. Shortly before launch, the experiment switches to internal power. The internal power system consists of a series of batteries, each holding around 300 mAh and delivering a nominal charge of 1.2 V. The batteries are stored within a housing, which is mounted to the bulkhead of the REXUS module. The batteries can deliver a stable current of up to 20 A and a peak current of 30 A each.

2.4.3. Sensor System

Sensors are used to monitor the temperature and pressure inside and outside the pressure vessel. A camera system is used to monitor the spinning process and to detect fibres. All sensor data is collected via the Raspberry Pi's I2C Bus. An action cam mounted on the strengthening ribs of the pressure vessel monitors the spinning process and saves images. Another camera observes the catching drum and detects whether fibres are collected. This information as well as sensor information can be transmitted to the ground station during flight. At the end of the experiment period computer vision edited images of the fibre screen are transmitted in case the experiment cannot be recovered.

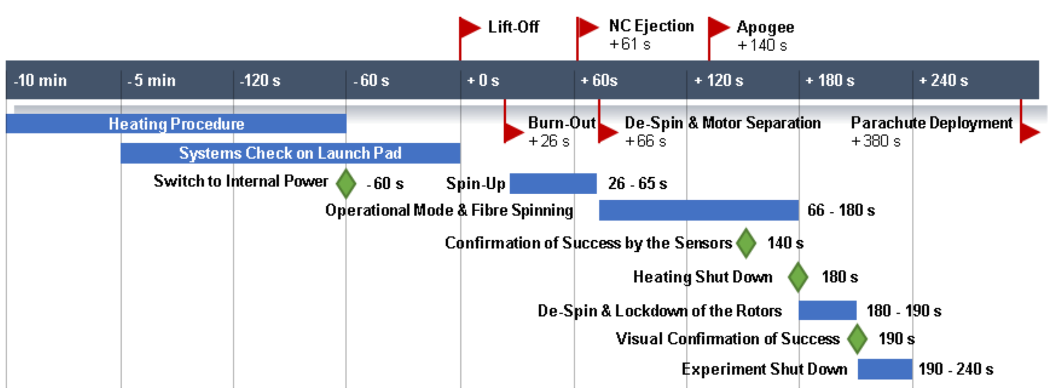

Figure 10. In-Flight Experiment Timeline

2.5. Expected Results and Data Analysis

The apparatus will be tested on ground as well as in-flight. The results of both will be compared. A more detailed description of the planned tests and expected results is given in the following sections.

2.5.1. Ground Tests

The IMFEX spinning apparatus can also be used on ground under the influence of gravity. Ground tests will be performed to find optimal spinning parameters for the chosen regolith simulant, which are rotating speed of both the bushing and catching drum, bushing temperature and cooling rate. The fibres will be investigated and their mechanical and geometrical properties, such as tensile strength and diameter will be determined. They will be used as reference and will be compared to the ones spun in microgravity.

The IMFEX spinning process differs from the fibre drawing process and is rather similar to rotational processes, such as the TEL-process. While rotating spinning facilities are used to produce fleece and wool materials, IMFEX intends to produce continuous fibres. It is expected that these fibres have different physical characteristics than fibres drawn in fibre drawing facilities. [14][7]

2.5.2. Flight Test

Fig. 10 shows the experiment timeline during flight. As soon as the launcher enters the phase of microgravity the spinning process will start. If fibres are produced and collected by the catching drum, they will be detected by the on-board camera. The confirmation of successful spinning will be transmitted to the ground station.

In case the fibres snap, single fragments will lie on top of each other. Sorting them by spinning time will not be possible and no conclusions could be drawn on the correlations between the fibres and the according spinning parameters. Therefore, the spinning parameters must be kept constant. All fibre fragments will be produced with the same parameters to be comparable to the ones produced on ground. The fibres will be investigated regarding their mechanical and geometrical properties. Referring to the NASA report from 1992, it is expected, that fibres spun in microgravity environment will have smaller diameters [15].

3. CONCLUSION AND OUTLOOK

The preliminary design of IMFEX, meeting all requirements, has been developed. The design will be finalized by July 2020 after which it will go through a test campaign which will qualify it for flight. The launch is set for March of 2021 from the Esrange Space Centre in Sweden. The data and samples acquired after the flight will be analysed and published by June 2021.

The experiment will deliver knowledge on how space environment, especially reduced gravity, impacts the spinning process and the fibre properties. It will allow to further understand the impact of gravity on the formation of fibres and provide the baseline for further experiments. The output of IMFEX will be used for the development of the actual *MoonFibre* spinning facility which will be launched to the Moon.

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