SED

Student Experiment Documentation

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Team Name: TUBULAR

Experiment Title: Alternative to AirCore for Atmospheric Greenhouse Gas Sampling

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The TUBULAR Team

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CHANGE RECORD

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1-0	2018-01-15	All	PDR
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Abstract:

Carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO) are three main greenhouse gases emitted by human activities. Developing a better understanding of their contribution to greenhouse effects requires more accessible, flexible, and scalable air sampling mechanisms. A balloon flight is the most cost-effective mechanism to obtain a vertical air profile through continuous sampling between the upper troposphere and the lower stratosphere. However, recovery time constraints due to gas mixture concerns geographically restrict the sampling near existing research centers where analysis of the recovered samples can take place. The TUBULAR experiment is a technology demonstrator for atmospheric research supporting an air sampling mechanism that would offer climate change researchers access to remote areas by minimizing the effect of gas mixtures within the collected samples so that recovery time is no longer a constraint. The experiment includes a secondary sampling mechanism that serves as reference against which the proposed sampling mechanism can be validated.

Keywords: Balloon Experiments for University Students, Climate Change, Stratospheric Air Sampling, AirCore, Sampling Bags, Greenhouse Gas, Carbon Dioxide (CO_2), Methane (CH_4), Carbon Monoxide (CO).

Contents

PREFACE

The Rocket and Balloon Experiments for University Students (REXUS/BEXUS) programme is realized under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Agency (SNSA). The Swedish share of the payload has been made available to students from other European countries through a collaboration with the European Space Agency (ESA).

EuroLaunch, a cooperation between the Esrange Space Center of SSC and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles. Experts from DLR, SSC, ZARM, and ESA provide technical support to the student teams throughout the project.

The Student Experiment Documentation (SED) is a continuously updating document regarding the BEXUS student experiment TUBULAR - Alternative to AirCore for Atmospheric Greenhouse Gas Sampling and will undergo reviews during the preliminary design review, the critical design review, the integration progress review, and final experiment report.

The TUBULAR Team consists of a diverse and inter-disciplinary group of students from Luleå University of Technology's Masters programme in Atmospheric Studies, Space Engineering, and Spacecraft Design. The idea for the proposed experiment stems from concerns over the realities of climate change as a result of human activity coupled with the complexity and limitations in obtaining greenhouse gas profile data to support climate change research.

Based above the Arctic circle in Kiruna, Sweden, the TUBULAR Team is exposed to Arctic science research with which it has collaborated in order to produce research detailing the air sampling methodology, measurements, analysis, and findings.

Acknowledgements

The TUBULAR Team wishes to acknowledge the invaluable support received by the REXUS/BEXUS organizers, SNSA, DLR, ESA, SSC, ZARM, Esrange Space Centre, and ESA Education. In particular, the team's gratitude extends to the following project advisers who show special interest in our experiment:

- **Dr. Rigel Kivi**, Senior Scientist at the Finnish Meteorological Institute (FMI). A key project partner, Dr. Kivi's research and experience in Arctic atmospheric studies serves as a knowledge-base reference that ensures proper design of the experiment.
- **Mr. Pauli Heikkinen**, Scientist at FMI. A key project partner, Dr. Heikkinen's research and experience in Arctic atmospheric studies serves as a knowledge-base reference that ensures proper design of the experiment.
- **Dr. Uwe Raffalski**, Associate Professor at the Swedish Institute of Space physics (IRF) and the project's endorsing professor. Dr. Raffalski's research and experience in Arctic atmospheric studies serves as a knowledge-base reference that ensures proper design of the experiment.
- **Dr. Thomas Kuhn**, Associate Professor at Luleå University of Technology (LTU). A project course offered by Dr. Kuhn serves as a merited university module all while providing the team with guidance and supervision.
- **Mr. Olle Persson**, Operations Administrator at Luleå University of Technology (LTU). A former REXUS/BEXUS affiliate, Mr. Persson has been providing guidance based on his experience.
- **Mr. Grzegorz Izworski**, Electromechanical Instrumentation Engineer at European Space Agency (ESA). Mr. Izworski is the team's mentor supporting design and development of the project to ensure launch success.
- **Mr. Koen Debeule**, Electronic Design Engineer at European Space Agency (ESA). Mr. Debeule is the team's supporting mentor.
- **Mr. Vince Still**, LTU alumni and previous BEXUS participant with project EXIST. Mr Still assists the team as a thermal consultant.

The TUBULAR Team would also like to acknowledge component sponsorship from the following manufacturers and suppliers all of which showed authentic interest in the project and provided outstanding support:

- **Restek** develops and manufactures GC and LC columns, reference standards, sample prep materials, and accessories for the international chromatography industry.
- **SMC Pneumatics** specializes in pneumatic control engineering to support industrial automation. SMC develops a broad range of control systems and equipment, such as directional control valves, actuators, and air line equipment, to support diverse applications.
- **SilcoTek** provides coatings solutions that are corrosion resistant, inert, H2S resistant, anti-fouling, and low stick.

- **Swagelok** designs, manufactures, and delivers an expanding range of fluid system products and solutions.
- **Teknolab Sorbent** provides products such as analysis instruments and accessories within reference materials, chromatography and separation technology.
- **Lagers Masking Consulting** specializes in maintenance products and services for industry, construction, and municipal facilities.
- **Bosch Rexroth** manufactures products and systems associated with the control and motion of industrial and mobile equipment.
- **KNF** develops, produces, and distributes high quality diaphragm pumps and systems for gases, vapors, and liquids.
- **Eurocircuits** are specialist manufacturers of prototype and small batch PCBs.

1 Introduction

1.1 Scientific Background

The ongoing and increasingly rapid melting of the Arctic ice cap has served as a reference to the global climate change. Researchers have noted that "the Arctic is warming about twice as fast as the rest of the world" [20] and projecting an ice-free Arctic Ocean as a realistic scenario in future summers similar to the Pliocene Epoch when "global temperature was only 2–3$^{\circ}C$ warmer than today" [4]. Suggestions that additional loss of Arctic sea ice can be avoided by reducing air pollutant and CO_2 growth still require confirmation through better climate effect measurements of CO_2 and non-CO_2 forcings [4]. Such measurements bear high costs, particularly in air sampling for trace gas concentrations in the region between the upper troposphere and the lower stratosphere which have a significant effect on the Earth's climate. There is little information on distribution of trace gases at the stratosphere due to the inherent difficulty of measuring gases above aircraft altitudes.

Trace gases are gases which make up less than 1% of the Earth's atmosphere. They include all gasses except Nitrogen, and Oxygen. In terms of climate change, the main concern for the scientific community is that of CO_2 and CH_4 concentrations which make up less than 0.1% of the trace gases and are referred to as Greenhouse gases. Greenhouse gas concentrations are measured in parts per million (ppm), and parts per billion (ppb). They are the main offenders of the greenhouse effect caused by human activity as they trap heat into the atmosphere. Larger emissions of greenhouse gases lead to higher concentrations of those gases in the atmosphere thus contributing to climate change.

1.2 Mission Statement

There is little information on the distribution of trace gases at the stratosphere due to the inherent difficulty and high cost of air sampling above aircraft altitudes [4]. The experiment seeks to contribute to and support climate change research by proposing and validating a low-cost air sampling mechanism that reduces the current complexities and limitations of obtaining data on stratospheric greenhouse gas distribution.

1.3 Experiment Objectives

Beyond providing knowledge on greenhouse gas distributions, the sampling obtained from the experiment serves as a reference to validate the robustness and reliability of the proposed sampling system through comparative analysis of results obtained with a reference sampling system.

The primary objective of the experiment consisted of validating the proposed sampling system as a reliable mechanism that enables sampling of stratospheric greenhouse gases in remote areas. Achieving this objective consisted of developing a cost-effective and re-usable stratospheric air sampling system (i.e. AAC). Samples collected by the proposed mechanism were to be compared against samples collected by a proven sampling system (i.e. CAC). The proven sampling system is to be part of the experimental payload as a reference that will validate the proof-of-concept air sampling system.

The secondary objective of the experiment was to analyze the samples by both systems in a manner that will contribute to climate change research in the Arctic region. The trace gas profiles to be analyzed were that of carbon dioxide (CO_2), methane (CH_4), and carbon oxide (CO)[1]. The research activities will culminate in a research paper written in collaboration with FMI.

1.4 Experiment Concept

The experiment sought to test the viability and reliability of a proposed cost-effective alternative to the The AirCore Sampling System. The AirCore Sampling System consisted of a long and thin stainless steel tube shaped in the form of a coil which takes advantage of changes in pressure during descent to sample the surrounding atmosphere and preserve a profile (see Figure 83 in Appendix C.2). Sampling during a balloon's Descent Phase resulted in a profile shape extending the knowledge of distribution of trace gases for the measured column between the upper troposphere and the lower stratosphere [6]. The experiment consisted of two sampling subsystems: a conventional implementation of AirCore as described above, henceforth referred to as CAC, and a proposed alternative, henceforth referred to as Alternative to AirCore (AAC).

The proposed AAC system was primarily motivated by the CAC sampling mechanism lacking flexibility in choice of coverage area due to the geographical restriction imposed by the irreversible process of gas mixing along the air column sampled in its stainless tube. Because of this, the sampling region for the CAC system needs to remain within proximity to research facilities for post-flight gas analysis. The AAC sampling system is a proposed alternative configuration to the CAC sampling system that has been designed to address this limitation all while improving cost-effectiveness. The AAC sampling system consists of a series of small independent air sampling bags (see Figure 84 in Appendix C.2) rather than the CAC's single long and coiled tube. Each sampling bag was allocated a vertical sampling range capped at 500 meters so that mixing of gases becomes a lesser concern.

The use of sampling bags in series rather than a single long tube is meant to tackle limitations of the CAC by 1) reducing system implementation cost inherent to the production of a long

[1] The third gas being sampled was changed from N_2O to CO. The main reason for changing this was that the model of analyzer used was only able to detect CO_2, CH_4 and CO.

tube and 2) enabling sampling of remote areas by reducing the effect of mixing of gases in post-analysis. However, the AAC comes with its own limitations as its discrete sampling does not allow for a the type of continuous profiling made possible by the CAC coiled tube. Overall design of AAC was be approached with miniaturization, cost-effectiveness, and design for manufacturability (DFM) in mind with the purpose of enabling ease of replication.

1.5 Team Details

The TUBULAR Team consists of diverse and inter-disciplinary team members all of which are studying at the Masters level at LTU's space campus in Kiruna, Sweden.

Natalie Lawton - Management and Electrical Division

Current Education: MSc in Spacecraft Design.

Previous Education: MEng in Aerospace Engineering. Previous experience in UAV avionic systems and emissions measurement techniques.

Responsibilities: Acting as Systems Engineer/Project Manager from the CDR until the end of the project. Previously was acting as deputy to these roles and in the electrical division. Ensured testing was planned and executed. Oversaw manufacture, maintaining coordination between different teams and preventing project creep. Coordinating between different teams, project stakeholders, and documentation efforts.

Georges L. J. Labrèche - Management Division

Current Education: MSc in Spacecraft Design.

Previous Education: BSc in Software Engineering with experience in technical leadership and project management in software development.

Responsibilities: Acting as Systems Engineer / Project Manager and managing overall implementation of the project until the Critical Design Review (CDR). Establishing and overseeing product development cycle. Coordinating between different teams, project stakeholders, and documentation efforts.

Nuria Agües Paszkowsky - Scientific Division

Current Education: MSc in Earth Atmosphere and the Solar System.

Previous Education: BSc in Aerospace Engineering.

Responsibilities: Defining experiment parameters; data analysis; interpreting and documenting measurements; research on previous CAC experiments for comparative analysis purposes; contacting researchers or institutions working on similar projects; exploring potential partnership with researchers and institutions, evaluating the reliability of the proposed AAC sampling system; conducting measurements of collected samples; documenting and publishing findings.

Kyriaki Blazaki - Scientific Division

Current Education: MSc in Earth Atmosphere and the Solar System.

Previous Education: BSc in Physics.

Responsibilities: Coordinating between the Scientific Division and the Project Manager; defining experiment parameters; data analysis; interpreting and documenting measurements; research on previous CAC experiments for comparative analysis purposes; evaluating the reliability of the proposed AAC sampling system; conducting measurements of collected samples; documenting and publishing findings.

Emily Chen - Mechanical Division

Current Education: MSc in Space Engineering (5th Year).

Responsibilities: Mechanical designing and assembly of CAC subsystem; analyzing the test results and changing the design as needed in collaboration with the team leader; integrating and assembling final design.

Jordi Coll Ortega - Mechanical Division

Current Education: MSc in Spacecraft Design.

Previous Education: BASc in Aerospace Vehicle Engineering.

Responsibilities: Designing or redesigning cost-effective mechanical devices using analysis and computer-aided design; developing and testing prototypes of designed devices; analyzing the test results and changing the design as needed in collaboration with the team lead; integrating and assembling final design.

Gustav Dyrssen - Software Division

Current Education: MSc in Space Engineering (5th Year).

Responsibilities: Leading quality assurance and testing efforts; Enforcing software testing best practices such as continuous integration testing and regression testing; reviewing requirements and specifications in order to foresee potential issues; provide input of functional requirements; advising on design; formalizing test cases; tracking defects and ensuring their resolution; facilitating code review sessions; supporting software implementation efforts.

Erik Fagerström - Thermal Division

Current Education: MSc in Space Engineering (5th Year).

Responsibilities: Coordinating between the Thermal Division and the Project Manager. Planning project thermal analysis and testing strategy. Thermal simulations of proposed designs and analyze results.

Pau Molas Roca - Mechanical Division

Current Education: MSc in Spacecraft Design.

Previous Education: BSc in Aerospace Technology Engineering, Mechanical experience.

Responsibilities: Coordinating between the Mechanical Division and the Project Manager; designing or redesigning cost-effective mechanical devices using analysis and computer-aided design; producing details of specifications and outline designs; overseeing the manufacturing process for the devices; identifying material and component suppliers; integrating and assembling final design.

Emil Nordqvist - Electrical Division

Current Education: MSc in Space Engineering (5th Year).

Responsibilities: Quality assurance of circuit design and implementation. Developing, testing, and evaluating theoretical designs.

Muhammad Ansyar Rafi Putra - Software Division

Current Education: MSc in Spacecraft Design.

Previous Education: BSc in Aerospace Engineering.

Responsibilities: Coordinating between the Software Division and the Project Manager; gathering software requirements; formalizing software specifications; drafting architecture design, detailed design; leading software implementation efforts.

Hamad Siddiqi - Electrical Division

Current Education: MSc Satellite Engineering.

Previous Education: BSc in Electrical Engineering with experience in telecommunication industry and electronics.

Responsibilities: Coordinating between the Electrical Division and the Project Manager; designing and implementing cost-effective circuitry using analysis and computer-aided design; producing details of specifications and outline designs; developing, testing, and evaluating theoretical designs; identifying material as well as component suppliers.

Ivan Zankov - Thermal Division

Current Education: MSc in Spacecraft Design.

Previous Education: BEng in Mechanical Engineering.

Responsibilities: Thermal analysis of proposed designs and analysis result based recommendations.

2 Experiment Requirements and Constraints

Requirements in this section does not list obsolete requirements. For a complete list of requirements that include obsolete ones, refer to Appendix N.

2.1 Functional Requirements

F.2 The experiment *shall* collect air samples by the CAC.

F.3 The experiment *shall* collect air samples by the AAC.

F.9 The experiment *should* measure the air intake flow to the AAC.

F.10 The experiment *shall* measure the air pressure.

F.11 The experiment *shall* measure the temperature.

2.2 Performance Requirements

P.12 The accuracy of the ambient pressure measurements *shall* be -1.5/+1.5 hPa for 25°C.

P.13 The accuracy of temperature measurements *shall* be +3.5/-3°C (max) for condition of -55°C to 150°C.

P.23 The temperature sensor sampling rate *shall* be 1 Hz.

P.24 The temperature of the Pump *shall* be between 5°C and 40°C.

P.25 The minimum volume of air in the bags for analysis *shall* be 0.18 L at ground level.

P.26 The equivalent flow rate of the pump *shall* be between 8 to 3 L/min from ground level up to 24 km altitude.

P.27 The accuracy range of the sampling time, or the resolution, *shall* be less than 52.94 s, or 423.53 m.

P.28 The pressure sensor sampling rate *shall* be 1 Hz.

P.29 The airflow sensor sampling rate *shall* be 1 Hz.

P.30 The accuracy of the pressure measurements inside the tubing and sampling bags *shall* be -0.005/+0.005 bar for 25°C.

2.3 Design Requirements

D.1 The experiment *shall* operate in the temperature profile of the BEXUS flight[8].

D.2 The experiment *shall* operate in the vibration profile of the BEXUS flight[8].

D.3 The experiment *shall* not have sharp edges or loose connections to the gondola that can harm the launch vehicle, other experiments, and people.

D.4 The experiment's communication system *shall* be compatible with the gondola's E-link system with the RJF21B connector over UDP for down-link and TCP for up-link.

D.5 The experiment's power supply *shall* have a 24v, 12v, 5v and 3.3v power output and be able to take 28.8v input through the Amphenol PT02E8-4P connector supplied from the gondola.

D.7 For the supplied voltage of 28.8 V, the total continuous DC current draw *should* be below 1.8 A.

D.8 The total power consumption *should* be below 374 Wh.

D.16 The experiment *shall* be able to autonomously turn itself off just before landing.

D.17 The experiment box *shall* be placed with at least one face exposed to the outside.

D.18 The experiment *shall* operate in the pressure profile of the BEXUS flight[8].

D.19 The experiment *shall* operate in the vertical and horizontal accelerations profile of the BEXUS flight[8].

D.21 The experiment *shall* be attached to the gondola's rails.

D.22 The telecommand data rate *shall* not be over 10 kb/s.

D.23 The air intake rate of the air pump *shall* be equivalent to a minimum of 3 L/min at 24 km altitude.

D.24 The temperature of the Brain[2] *shall* be between -10°C and 25°C.

D.26 The air sampling systems *shall* filter out all water molecules before filling the sampling bags.

D.27 The total weight of the experiment *shall* be less than 28 kg.

D.28 The AAC box *shall* be able to fit at least 6 air sampling bags.

D.29 The CAC box *shall* take less than 3 minutes to be removed from the gondola without removing the whole experiment.

D.30 The AAC *shall* be re-usable for future balloon flights.

D.31 The altitude from which a sampling bag will start sampling *shall* be programmable.

D.32 The altitude from which a sampling bag will stop sampling *shall* be programmable.

[2]The Brain is a central command unit which contains Electronic Box and pneumatic sampling system.

2.4 Operational Requirements

O.13 The experiment *should* function automatically.

O.14 The experiment's air sampling mechanisms *shall* have a manual override.

2.5 Constraints

C.1 Constraints specified in the BEXUS User Manual.

3 Project Planning

3.1 Work Breakdown Structure

The team was categorized into different groups of responsibilities with dedicated leaders who reported to and coordinated with the Project Manager. Leadership was organized on a rotational basis when the need arose. The formation of these divisions constituted a work breakdown structure which is illustrated in Figure 1.

The Management was composed of a Project Manager and a Deputy Project Manager, both acted as Systems Engineer and managed the overall implementation of the project. The Project Manager was responsible for establishing and overseeing product development cycle; coordinating between different teams, project stakeholders, and documentation efforts; outreach and public relations; Fundraising; monitoring and reporting; system integration; and quality assurance. Once all subsystems had been assembled, the Project Manager was also responsible for overseeing the integration processes leading to the final experiment setup and put emphasis on leading quality assurance integration testing efforts. The Deputy Project Manager assisted the Project Manager in all management duties in a manner that ensured replaceability when necessary.

The Scientific Division was responsible for defining experiment parameters; data analysis; interpreting and documenting measurements; researching previous CAC experiments for comparative analysis purposes; evaluating the reliability of the proposed AAC sampling system; conducting measurements of collected samples; documenting and publishing findings; defining experiment parameters; contacting researchers or institutions working on similar projects; exploring potential partnership with researchers and institutions; documenting and publishing findings.

The Mechanical Division was responsible for designing or redesigning cost-effective mechanical devices using analysis and computer-aided design; producing details of specifications and outline designs; overseeing the manufacturing process for the devices; identifying material and component suppliers; developing and testing prototypes of designed devices; analyzing test results and changing the design as needed; and integrating and assembling final design.

The Electrical Division was responsible for designing and implementing cost-effective circuitry using analysis and computer-aided design; producing details of specifications and outline designs; developing, testing, and evaluating theoretical designs; identifying material as well as component suppliers; reviewing and testing proposed designs; recommending modifications following prototype test results; and assembling designed circuitry.

The Software Division was responsible for gathering software requirements; formalizing software specifications; drafting architecture design; leading software implementation efforts; leading quality assurance and testing efforts; enforcing software testing best practices such as continuous integration testing and regression testing; reviewing requirements and specifications in order to foresee potential issues; providing input for functional requirements; advising on design; formalizing test cases; tracking defects and ensuring their resolution; facilitating code review sessions; and supporting software implementation efforts.

The Thermal Division was responsible for ensuring thermal regulation of the payload as per operational requirements of all experiment components; evaluating designs against thermal simulation and propose improvements; managing against mechanical design and electrical power limitations towards providing passive and active thermal control systems.

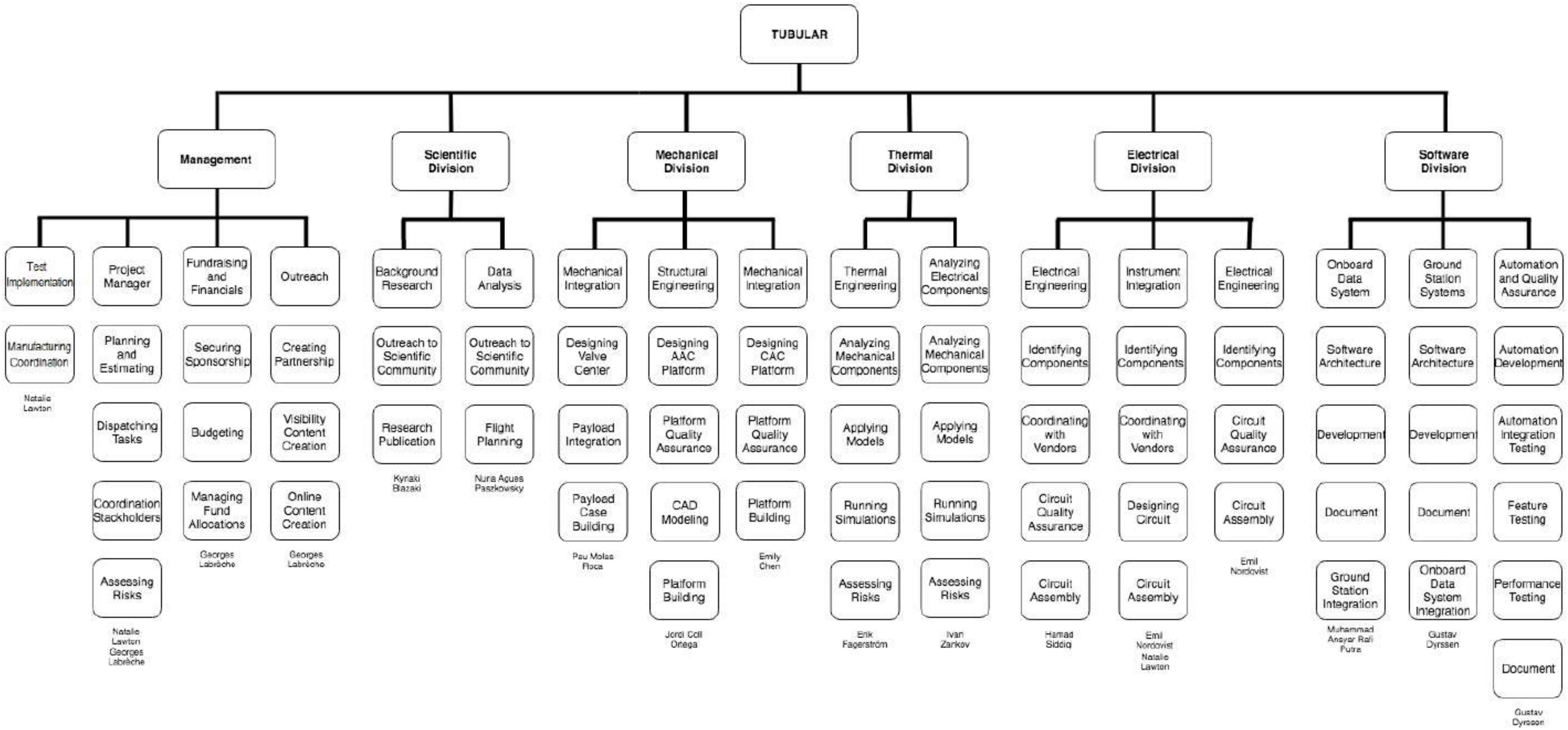


Figure 1: Work Breakdown Structure.

3.2 Schedule

Scheduling of the project is presented in a Gantt Chart overview on Figure 2. Exam period constraints were included in order to evaluate risks in person-day allocations to project implementation. It was expected during exam periods the team work output would be lower than usual but project activities did continue, with time planned accordingly to accommodate this:

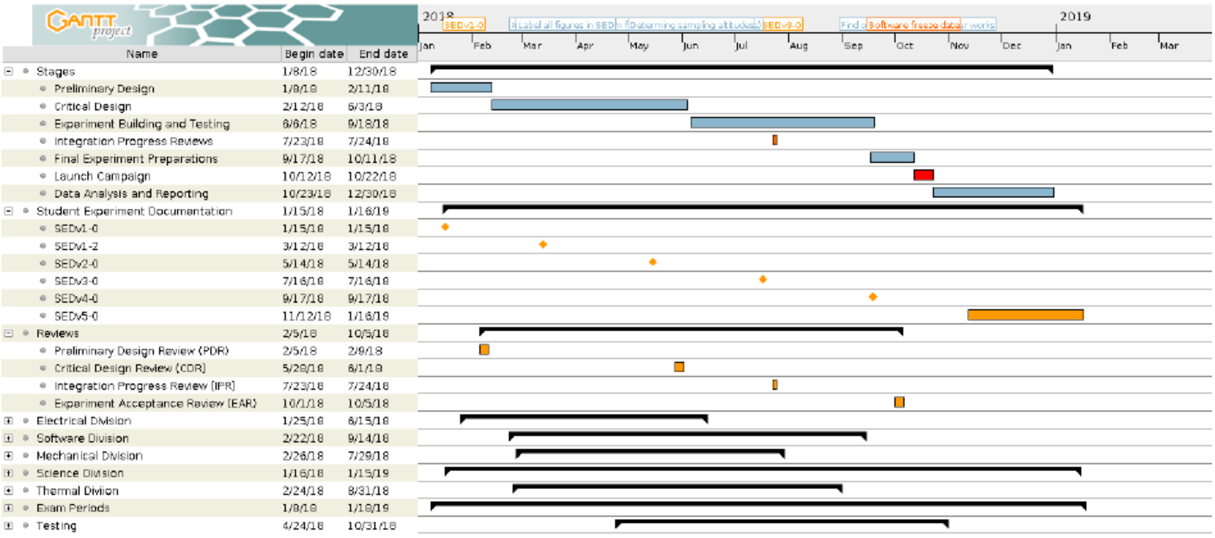


Figure 2: Project Schedule Gantt Chart.

An expanded version of the Gantt Chart with detailed listing of all sub-tasks not shown in Figure 2 can be found in Appendix F. This expanded Gantt Chart includes all tasks related to the test plan and internal deadlines were set so that a first draft of the documentation was completed one week in advance to allow contents to be checked. Build and test internal deadlines were also placed one week in advance to allow a buffer in case things did not go as expected. The tests were scheduled for as early as possible to allow time for rescheduling if the result was a fail. With some high priority tests, see Section 5.2.1, it was expected these would be very difficult to reschedule therefore extra time was built into the test duration to allow for multiple attempts at the test.

3.3 Resources

3.3.1 Manpower

The TUBULAR Team is categorized into divisions as summarized in Table 3:

Management	Scientific	Mechanical	Electrical	Thermal	Software
Natalie Lawton*	Kyriaki Blazaki*	Pau Molas Roca*	Hamad Siddiqi*	Erik Fragerström*	Muhammad Ansyar Rafi Putra*
Georges L. J. Labrèche	Nuria Agues Paszkowsky	Jordi Coll Ortega	Emil Nordqvist	Ivan Zankov	Gustav Dyrssen
		Emily Chen			

Table 3: Project Divisions and Members (Asterisks Denote Division Leaders).

The experience of TUBULAR Team members are listed in Table 4:

Team Member	Project Related Experience
Natalie Lawton	MSc in Spacecraft Design (2nd Year). MEng in Aerospace Engineering. Previous experience in UAV avionic systems and emissions measurement techniques.
Nuria Agues Paszkowsky	MSc in Earth Atmosphere and the Solar System (2nd Year). BSc in Aerospace Engineering.
Kyriaki Blazaki	MSc in Earth Atmosphere and the Solar System (2nd Year). BSc in Physics.
Emily Chen	MSc in Space Engineering (5th Year).
Jordi Coll Ortega	MSc in Spacecraft Design (2nd Year). BSc in Aerospace Vehicle Engineering.
Gustav Dyrssen	MSc in Space Engineering (5th Year).
Erik Fagerström	MSc in Space Engineering (5th Year).
Georges L. J. Labrèche	MSc in Spacecraft Design (2nd Year). BSc in Software Engineering.
Muhammad Ansyar Rafi Putra	MSc in Spacecraft Design (2nd Year). BSc in Aerospace Engineering.
Pau Molas Roca	MSc in Spacecraft Design (2nd Year). BSc in Aerospace Technology Engineering, Mechanical experience.
Emil Nordqvist	MSc in Space Engineering (5th Year).
Hamad Siddiqi	MSc Satellite Engineering (4th Year) BSc in Electrical Engineering. Experience in telecommunication industry and electronics.
Ivan Zankov	MSc in Spacecraft Design (2nd Year). BEng in Mechanical Engineering.

Table 4: Project Related Experience of Team Members.

The initial projected effort to be contributed by each team member was averaged at 1.5 hour per person per day corresponding to a team total of 15 hours per day. Since then, 3 new members had been included in the team thus increasing the projected daily effort to 19.5 hours per day. During the summer period many team members were away which meant that the team hours put in had little significant overall change. The period of these different effort capacities are listed in Table 5:

From	To	Capacity (hours/day)
08/01/2018	18/03/2018	15
19/03/2018	08/04/2018	16.5
09/04/2018	09/05/2018	18
10/05/2018	15/08/2018	19.5
15/08/2018	22/10/2018	19.5
23/10/2018	31/01/2019	19.5

Table 5: Projected Daily Team Effort per Period.

Taking into account all team members and the mid-project changes in team size, the efforts/-capacity projected to be allocated to each stages of the project during 2018 are summarized in Table 6:

Stage	**Start Date**	**End Date**	**Duration (days)**	**Effort (hours)**		
				Capacity	**Actual**	**Diff. (%)**
Preliminary Design	08/01	11/02	35	525	708	+29.68
Critical Design	12/02	03/06	112	1,680	2,649	+57.66
Experiment Building and Testing	04/06	16/09	105	2,048	1,943	-5.40
Final Experiment Preparations	17/09	11/10	25	488	571	+17.00
Launch Campaign	12/10	22/10	10	390	777	+99.23
Data Analysis and Reporting	23/10	30/01	69	1,346	245	-81.78
		Total:	**356**	**7,989**	*6939*	*-13.14*

Table 6: Project Effort Allocation per Project Stages.

It can be seen that it was necessary at some stages to work more than was projected and at other stages less work was required to achieve the aims.

All TUBULAR Team members are based in Kiruna, Sweden, just 40 km from Esrange Space Center. Furthermore, all team members are enrolled in LTU Master programmes in Kiruna and thus remained in LTU during the entire project period. Special attention was made for planning tasks during the summer period where many team members traveled abroad. A timeline of team member availability until January 2019 is available in Appendix E. A significant risk was observed during the summer months from June to August where most members were only partially available and some completely unavailable. As such, team member availability and work commitments over the summer were negotiated across team members in order to guarantee that at least one member per division was present in Kiruna over the Summer with the exception of the Software Division which could work remotely. Furthermore, the

Project Manager role was assigned to the Deputy Project Manager due to an extended full time unavailability after the CDR.

As part of their respective Master programmes, most TUBULAR Team members are enrolled in a project course at LTU. The TUBULAR project acts as the course's project for most team members from which they will obtain ECTS credits. This course is supervised by Dr. Thomas Kuhn, Associate Professor at LTU.

3.3.2 Budget

The experiment had a total mass of 24 kg at a cost of 33,211 EUR. An error margin was included in the budget corresponding to 10% of the total costs of components to be purchased. A complete budget is available in Appendix M and a detailed component mass and cost breakdown is available in Section 4.3 Experiment Components. This breakdown does not include spare components accounted for in the total costs. Dimensions and mass of the experiment are summarized in Table 16 in Section 4.4 and Table 50 in Section 6.1.1. A contingency fund of 900 EUR was allocated for unseen events such as component failures. Component loan and donations from sponsors account for 85% of the project's total cost. LTU and SNSA funding accounts for the remaining 15%.

The project benefited from component donations from Restek, SMC Pneumatics, Teknolab Sorbent, KNF, Eurocircuits, and Lagers Masking Consulting as well as component loans from FMI. Furthermore, discounts were offered by Teknolab Sorbent and Bosch Rexroth. Euro value allocation of these sponsorships are presented in Table 7.

Sponsor	Type	Value	Allocated	Unalloc.	% Alloc.	Status
LTU	Funds	2,500.00	2,301.57	1,874.62	75	Received
SNSA	Funds	2,909.80	2,634.40	275.40	91	Received
FMI	Component loan	22,561.45	22,561.45	0.00	100	Received
Restek	Component donation	1,120.00	1,120.00	0.00	100	Received
Teknolab	Component donation	380.00	380.00	0.00	100	Received
SMC	Component donation	860.00	860.00	0.00	100	Received
Lagers Maskin	Component donation	300.00	300.00	0.00	100	Received
Swagelok	Component donation	1,863.82	1,863.82	0.00	100	Received
KNF	Component loan	350.00	350.00	0.00	100	Received
SilcoTek	Component donation	840.00	840.00	0.00	100	Received
Eurocircuits	Component donation	426.95	426.95	0.00	100	Received
	Total	**34,112.01**	**33,211.24**	**900.77**	**97**	

Table 7: Allocation of Sponsorship Funds and Component Donation Values. Amounts in EUR.

3.3.3 External Support

Partnership with FMI, and IRF has provided the team with technical guidance in implementing the sampling system. FMI's experience in implementing past CAC sample systems provide invaluable lessons learned towards conceptualizing, designing, and implementing the proposed AAC sampling system.

FMI was a key partner in the TUBULAR project, its scientific experts have advised and supported the TUBULAR project by sharing knowledge, experience, and granting accessibility of equipment. As per the agreement shown in Appendix G, FMI had provided the TUBULAR Team with the AirCore stainless tube component of the CAC subsystem as well as the post-flight gas analyzer. This arrangement required careful considerations on the placement of the experiment in order to minimize hardware damage risks. These contributions resulted in significant cost savings regarding equipment and component procurement.

Daily access to LTU's Space Campus in Kiruna exposed the team to scientific mentorship and expert guidance from both professors and researchers involved in the study of greenhouse gases and climate change. Dr Uwe Raffalski, IRF, Associate professor (Docent) was one of many researchers involved in climate study whom mentored the team.

3.4 Outreach Approach

The experiment as well as the REXUS/BEXUS programme and its partners has been be promoted through the following activities:

- Published research papers co-authored with FMI, detailing the sampling methodology, measurement result, analysis, and findings [3] [11].
- Collected data licensed as open data to be freely available to everyone to use and republish as they wish, without restrictions from copyright, patents or other mechanisms of control.
- A website to summarize the experiment and provide regular updates. Backend web analytics included to gauge interest on the project through number of visitors and their origins (See Appendix B).
- Dedicated Facebook page used as publicly accessible logbook detailing challenges, progress, and status of the project. Open for comments and questions (See Figure 77 in Appendix B).
- An Instagram account for short and frequent image and video updates (See Figures 78 in Appendix B).
- GitHub account to host all project software code under free and open source license (See Figure 79 in Appendix B). Other REXUS/BEXUS teams were invited to host their code in this account.
- "Show and Tell" trips to local high schools and universities. Team members were responsible to organize such presentations through any of their travel opportunities abroad.
- Articles and/or blogposts about the project in team members' alma mater websites.
- In-booth presentation and poster display in the seminars or career events at different universities.
- A thoroughly documented and user-friendly manual on how to build replicate and launch CAC and AAC sampling systems will be produced and published.

3.5 Risk Register

Risk ID

TC – Technical/Implementation

MS – Mission (operational performance)

SF – Safety

VE – Vehicle

PE – Personnel

EN – Environmental

OR - Outreach

BG - Budget

Adapt these to the experiment and add other categories. Consider risks to the experiment, to the vehicle and to personnel.

Probability (P)

A Minimum – Almost impossible to occur

B Low – Small chance to occur

C Medium – Reasonable chance to occur

D High – Quite likely to occur

E Maximum – Certain to occur, maybe more than once

Severity (S)

1. Negligible – Minimal or no impact
2. Significant – Leads to reduced experiment performance
3. Major – Leads to failure of subsystem or loss of flight data
4. Critical – Leads to experiment failure or creates minor health hazards
5. Catastrophic – Leads to termination of the REXUS/BEXUS programme, damage to the vehicle or injury to personnel

The rankings for probability (P) and severity (S) were combined to assess the overall risk classification, ranging from very low to very high and being coloured green, yellow, orange or red according to the SED guidelines.

SED guidelines were used to determine whether a risk was acceptable or unacceptable. For acceptable risks, details of the mitigation undertaken were included which reduced the risk to an acceptable level.

ID	Risk (& consequence if)	P	S	P * S	Action
TC10	Software fails to store data	B	2	Very Low	Acceptable Risk: Extensive testing has been done. Using telemetry, all data gathered from sensors will be sent to ground station.
TC20	Failure of several sensors	B	2	Very Low	Acceptable Risk: Thermal test (Test Number 5) approved the functionality of the experiment.
TC30	Critical component is destroyed in testing	B	1	Very Low	Acceptable Risk: Spare components can be ordered but for expensive ones, they were ordered and tested early in the project in case we needed to order more.
TC40	Electrical connections dislodges or short circuits because of vibration or shock	B	4	Low	Acceptable Risk. D-sub connections will be screwed in place. It was be ensured that there were no loose connections and zip ties were used to help keep wires in place. Careful soldering and extensive testing was applied.
TC50	Experiment electronics fail due to long exposure to cold or warm temperatures	B	3	Low	Acceptable Risk: Thermomechanical and thermoelectrical solutions were simulated and tested in detail to help prevent this from happening.
TC60	Software and electrical fail to control heaters causing temperature to drop or rise below or above operational range	B	2	Very Low	Acceptable Risk: Tests were performed prior to the flight to detect and minimize the risk of occurrence. The system was be monitored during flight and handled manually if it was necessary.
TC70	Software fails to enter safe mode (may result in loss of data)	B	1	Very Low	Acceptable Risk: Extensive testing was be done.
TC80	On-board memory will be full (flight time longer than expected)	A	2	Very Low	Acceptable Risk: The experiment went through testing and analysis to guarantee the onboard memory size was sufficient.
TC90	Connection loss with ground station	A	2	Very Low	Acceptable Risk: Experiment was designed to operate autonomously.
TC100	Software fails to control valves autonomously	B	2	Very Low	Acceptable Risk: Extensive testing was done. Telecommand could also be used to manually control the valves.
TC110	Software fails to change modes autonomously	B	2	Very Low	Acceptable Risk: Extensive testing was done. Telecommand could also be used to manually change experiment modes.

TC120	Complete software failure	B	4	Low	Acceptable Risk: A long duration testing (bench test) was performed to catch the failures early.
TC130	Failure of fast recovery system	B	2	Very Low	Acceptable Risk: Clear and simple instructions were given to the recovery team. A test took place before launch to ensure someone unfamiliar with the experiment could remove the CAC box. Test number: 12.
TC140	The gas analyzer isn't correctly calibrated and returns inaccurate results	B	3	Low	Acceptable Risk: Gas analyzer was calibrated before use.
TC150	Partnership with FMI does not materialize, resulting in loss of access to CAC coiled tube.	B	2	Very Low	Acceptable Risk: Signed agreement has been obtained. AAC sample analysis results can be validated against available historical data from past FMI CAC flights.
MS10	Down link connection is lost prematurely	B	2	Very Low	Acceptable Risk: Data was also be saved on SD card.
MS20	Condensation on experiment PCBs which could causes short circuits	A	3	Very Low	Acceptable Risk: The Brain was sealed to prevent condensation.
MS30	Temperature sensitive components that are essential to full the mission objective might be below their operating temperature.	C	3	Low	Acceptable Risk: Safe mode to prevent the components to operate out of its operating temperature range.
MS40	Experiment lands in water causing electronics failure	B	1	Very Low	Acceptable Risk: All the necessary data was be downloaded during the flight.
MS50	Interference from other experiments and/or balloon	A	2	Very Low	Acceptable Risk: no action.
MS60	Balloon power failure	B	2	Low	Acceptable Risk: Valves default state was closed so if all power is lost valves would automatically close preserving all samples collected up until that point.
MS70	Sampling bags disconnect	B	3	Low	Acceptable Risk: The affected bags could not collect samples. The connection between the spout of the bags and the T-union was double checked before flight. The system has passed vibration testing with no disconnects.

MS71	Sampling bags puncture	B	3	Low	Acceptable Risk: The affected bags could not collect samples. Inner styrofoam walls have been choosen and no sharp edges were exposed to avoid puncture from external elements.
MS72	Sampling bags' hold time is typically 48h	B	2	Very Low	Acceptable risk: Validation studies have demonstrated acceptable stability for up to 48 hours.
MS80	Pump failure	B	3	Low	Acceptable Risk: A pump was chosen based on a previous similar experiment. The pump has also been tested in a low pressure chamber down to 10hPa and has successfully turned on and filled a sampling bag. The CAC subsystem is not reliant on the pump therefore would still operate even in the event of pump failure.
MS90	Intake pipe blocked by external element	C	3	Low	Acceptable Risk: The bags would not be filled and thus the AAC system would fail. An air filter was placed in both intake and outlet of the pipe to prevent this.
MS100	Expansion/Contraction of insulation	B	2	Very Low	Acceptable Risk: The insulation selected has flown successfully on similar flights in the past. Test was done to see how it reacts in a low pressure environment.
MS110	Sampling bags are over-filled resulting in bursting and loss of collected samples.	B	3	Low	Acceptable Risk: Test was performed at target ambient pressure levels to identify how long the pump needs to fill the sampling bags. A static pressure sensor on board monitored the in-bag pressure during sampling and no bag would ever be over pressured. In addition an airflow rate sensor monitored the flow rate and a timer started when a bag valve is opened. The sampling would stop when either the maximum allowed pressure or maximum allowed time is reached.
SF10	Safety risk due to pressurized vessels during recovery.	A	1	Very Low	Acceptable Risk: The volume of air in the AAC decreases during descent because the pressure inside is lower than outside. The CAC is sealed at nearly sea level pressure, therefore there is only a small pressure difference.

SF20	Safety risk due to the use of chemicals such as magnesium perchlorate.	A	4	Very Low	Acceptable Risk: The magnesium perchlorate was be kept in a sealed container or filter at all times. Magnesium perchlorate filters are made of stainless steel which has high durability, and have been used before without any sealing problems.
VE10	SD-card is destroyed at impact	B	2	Very Low	Acceptable Risk: All data was be transmitted to the ground. Most of the data is the gas stored in the AAC and CAC.
VE20	Gondola Fixing Interface	B	4	Low	Acceptable Risk: The experiment box could detach from the gondola's rails and the two boxes could detach one from the other. The experiment will be secured to the gondola and to each other with multiple fixings. These were also be tested.
VE30	Structure damage due to bad landing	B	3	Low	Acceptable Risk: Landing directly on a hard element could break the structure or the protective walls. Consistent design implemented to prevent it.
VE40	Hard landing damages the CAC equipment	C	3	Low	Acceptable Risk: Structural analysis has been done and choosing a wall consisting of an aluminum sheet and Styrofoam to dampen the landing.
VE50	Hard landing damages the AAC equipment	C	3	Low	Acceptable Risk: Structural analysis has been done and choosing a wall consisting of an aluminum sheet and Styrofoam to dampen the landing.
EN10	Vibrations from pump affect samples	C	1	Very Low	Acceptable Risk: Vibrations do not affect the sampled air. No action required.
EN20	The air samples must be protected from direct sunlight and stored above $0°C$ to prevent condensation	C	3	Low	Acceptable Risk: Stratospheric air is generally dry and water vapor concentrations are higher closer to the surface. In addition magnesium perchlorate dryers were used to minimize the risk of condensation.

PE10	Change in Project Manager after the CDR introduces a gap of knowledge in management responsibilities.	E	1	Low	Acceptable Risk: A Deputy Project Manager was selected at an early stage and was progressively handed over project management tasks and responsibilities until complete handover after the CDR. The previous Project Manager remotely assisted the new Project Manager until the end of the project. The Deputy Project Manager was also part of the Electrical Division so a new team member has been included to that division in order compensate for the Deputy Project Manager's reduced bandwidth to work on Electrical Division tasks once she is appointed Project Manager.
PE20	Team members from the same division are unavailable during the same period over the summer.	C	2	Low	Acceptable Risk: Summer travel schedules have been coordinated among team members so that there is at least one member from each division available during the summer.
PE30	No one from management is available to oversee the work for a reasonable period.	B	2	Very Low	Acceptable Risk: Management summer travel schedules have been planned to fit around known deadlines. There was always be at least one member from management available via phone at all times. All team members were made aware of which members will be available at what times so work could be planned accordingly.
PE40	Miscommunication between team members results in work being incomplete or inaccurate	B	2	Very Low	Acceptable Risk: Whatsapp, Asana and Email were used in combination to ensure that all team members are up to date with the most current information.

Table 8: Risk Register.

4 Experiment Design

4.1 Experiment Setup

The experiment consisted of the AAC subsystem, with six sampling bags, and the CAC coiled tube subsystem. Shown in Figure 3, the AirCore was fitted into the CAC box, and the alternative sampling system with bags in the AAC box, together with the pneumatic system and the electronics placed inside the *Brain*. The principal aim was to validate the AAC sampling method. To do so, it was necessary to sample during Descent Phase in order to compare the results with the ones obtained from the CAC. This was because the CAC collected its air sample passively by pressure differentials in the descent. Flight speeds mentioned in this section were obtained from the BEXUS manual as well as through analysis of past flights. Figure 4 shows a generic block diagram of the main subsystems interconnection.

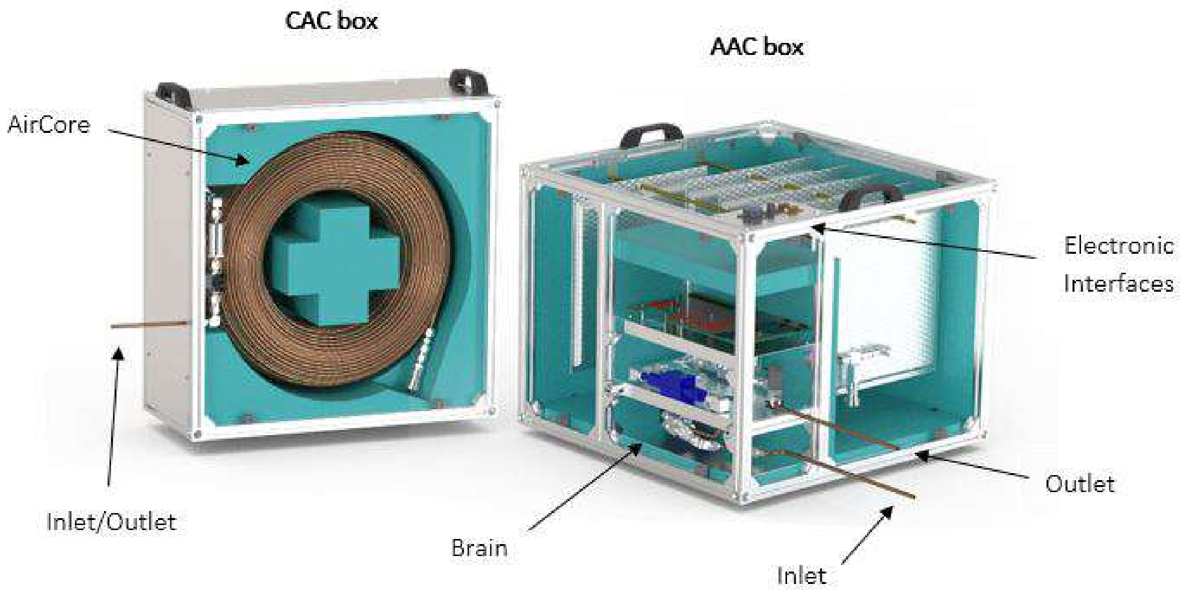


Figure 3: Physical Setup of the Experiment.

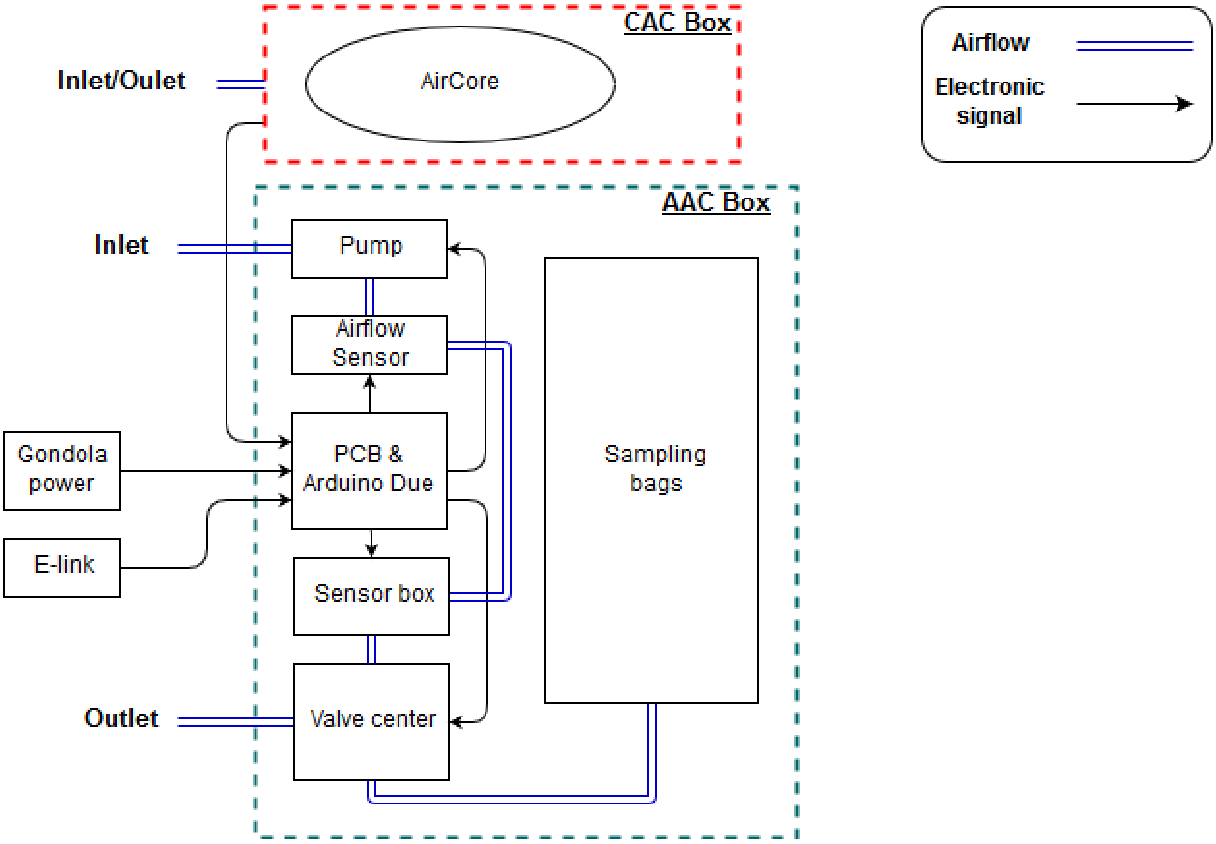


Figure 4: Block Diagram of the Experiment.

The primary concern regarding the AAC air sampling subsystem occured after the cut-off while the gondola was tumbling and falling at an average speed of 50 m/s for approximately two minutes [8]. This descent speed was too large in order to sample air at the desired vertical resolution, capped at 500 m. As such, sampling could only be done after the gondola had stabilized at a descent speed of 8 m/s [8]. The tumbling phase was vertically spanned for approximately 8 km. With a Float Phase altitude of approximately 27.3 km, sampling during the Descent Phase would have commenced at approximately 19 km in altitude. However, the primary region of interest in terms of sampling was in the stratosphere, particularly between 19 km and 27.3 km in altitude. This was why sampling was planned to also occur during the Ascent Phase. Out of the six sampling bags present in the payload, two were planned to be used during the Ascent Phase at 18 km and 21 km and four during the Descent Phase at 17.5 km, 16 km, 14 km and 12 km as seen in Table 9. Details regarding the sampling strategy can be found in Appendix H.

The maximum pressure that the sampling bags could withstand had to be taken into account in order to avoid bursting. Decreasing pressure during the Ascent Phase would have posed a risk to sampling bags which already contained samples as the gas inside would expand which may cause the bag to burst. In order to avoid this, the sampling bags were not planned to be completely filled. Filling the sampling bags up to a maximum pressure of 2 psi/0.14 bar/140 hPa or alternatively filling the sampling bag up to 80% of its capacity was recommended by the manufacturers for the Multi-Layer Foil sampling bags that were used. Therefore, the expected maximum pressure inside the bags, that were filled during the Ascent Phase, would be 1.6 psi/0.11 bar/110 hPa. The inverse was also true for the Descent Phase where compression would occur. As such, the sampling bags had to be fully filled during the Descent Phase in order to ensure that enough samples were collected for analysis. During the Descent Phase, the expected maximum pressure inside the bags was expected to be 1.98 psi/0.13 bar/130 hPa. Past research had revealed that the selected sampling bags were able to withstand pressure difference of 310 hPa at 30 km of altitude, which was equivalent to 0.31 bar [5]. Test 16 and 18, shown in Table 33 respective Table 35, were conducted in order to confirm the maximum allowable pressure for the bags.

The maximum operating pressure for the tubes, according to the manufacturers, was 2.2 psi/0.15 bar/150 hPa. The valve's leakage rate, given by the manufacturers, was 0.001 l/min.

Due to the difference in pressure between sea level and sampling altitudes, the volume of the sample taken would have been considerably reduced when it reached sea level. This shrinking had to be taken into account as the minimum volume that had to be present in the sampling bag at sea level in order to obtain results with the Picarro analyzer. A minimum amount was required for the analyzer to detect concentrations of the targeted trace gases. This minimum amount was 0.18 L at sea level and it had to be specially considered for the samples taken at higher altitudes. The samples taken at lower altitudes were exposed to smaller changes in pressure, therefore their size was not critically reduced. Table 9 shows the minimum volume of air that was needed to be sampled at different altitudes in order to assure the minimum air sample of 0.18L left at sea level.

This was the worst case scenario, and testing had shown that the higher the volume of the air sample left at sea level, the better the results. This was why the aimed volume of the samples, at sea level was at least 0.6L.

	Minimum Sampling Volume	**Sampling Altitudes**	**Ambient Pressure**	**Ambient Temperature**
Ascent Phase	1.8 L	18 km	75.0 hPa	216.7 K
	2.4 L	21 km	46.8 hPa	217.6 K
Descent Phase	1.7 L	17.5 km	81.2 hPa	216.7 K
	1.3 L	16 km	102.9 hPa	216.7 K
	1.0 L	14 km	141.0 hPa	216.7 K
	0.7 L	12 km	193.3 hPa	216.7 K

Table 9: Sampling Altitudes as well as the Corresponding Ambient Pressures and Temperatures According to the 1976 US Standard Atmosphere and the Minimum Sampling Volume at Each Altitude to Obtain Enough Air to Perform a Proper Analysis (0.18 L at Sea Level), Appendix H.

The AAC needed an air pump for sampling due to low ambient pressure at stratospheric altitudes. The air pump was also needed in order to assure the intake flow rate and obtain a good resolution. An air pump with an intake rate of at least 3 L/min was used to ensure that the vertical resolution of the sampling air remained under 500 m during the Ascent Phase's ascent speed of 5 m/s and the Descent Phase's descent speed of 8 m/s. A flushing valve (see Figure 28, No.23) was used to flush the AAC system before each bag would have been filled and make sure that each bag would have been filled with fresh air from the corresponding altitude. This filling/flushing procedure was planned to occur twice, the first time during the Ascent Phase for the first two sampling bags and the second time during the Descent Phase for the remaining four sampling bags.

Shortly after the launch, the CAC valve was opened in order to allow the fill gas that was inside the tube to flush, while the AAC valves were closed until reaching the sampling altitude. Flushing of the CAC tube happened passively through the progressive decrease in air pressure during the balloon's Ascent Phase and it was emptied by the time it reached the Float Phase. Filling of the CAC tube also happened passively through the progressive increase in air pressure during the balloon's Descent Phase. The CAC valve was planned to remain open at all time during the Ascent, Float, and Descent phases. Due to some problems, it was briefly closed and opened again for a few times without really compromising the results. The valve should have been closed just before hitting the ground in order to preserve the sample.

The ambient pressure was measured by three pressure sensors located outside the experiment box. Only one of them was necessary for AAC and CAC, but using three, redundancy was provided. To measure the pressure inside the bag that was currently being filled, one analogue static pressure sensor was connected to the pneumatic system. To measure the ambient temperature in the CAC, three sensors were allocated in the CAC box (in the Styrofoam). Temperature inside the coil was assumed to quickly adjust to the ambient temperature inside the CAC box, therefore there would not be differentiation in temperature between the air inside the tube and the air surrounding the tube. For the bags three more temperature sensors were placed in the bags' box (in the Styrofoam). To control the temperature for the pump and the valves in pneumatic subsystem, one temperature sensor was used for each of them. In total, there were three pressure sensors and eight temperature sensors.

The sampling of the AAC was triggered by the pressure reading from the sensors outside the experiment box. When the required pressure was reached, as seen in Table 9 the valve inside the manifold corresponding to the bag that was to be sampled, should have opened and the sampling should have started. The closing of the valve depended on two conditions and it was triggered when either one of the conditions was true. These conditions were: maximum sampling time or maximum pressure difference between inside/outside the bags. They were determined from past research [5]. A first estimation of the maximum sampling time had already been made, from Test 18 shown in Table 35. Completed tests, such as Test 14 and Test 18, shown in Table 25 respective Table 35, the maximum pressure condition had been determined and the maximum sampling times had been confirmed.

The CAC emptying as well as the AAC and CAC sampling sequence is represented in Figures 5 and 6. It should be kept in mind that the different pressures were what should have triggered the opening of the valves.

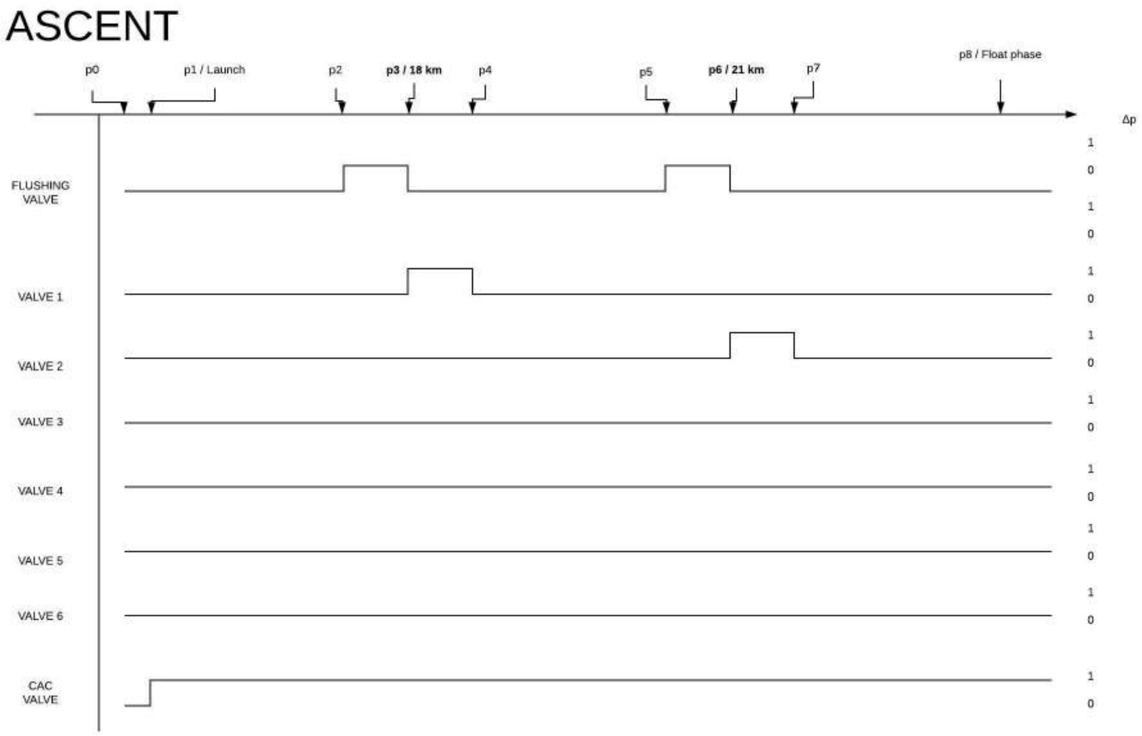


Figure 5: The Emptying and Sampling Sequence-Ascent Phase.

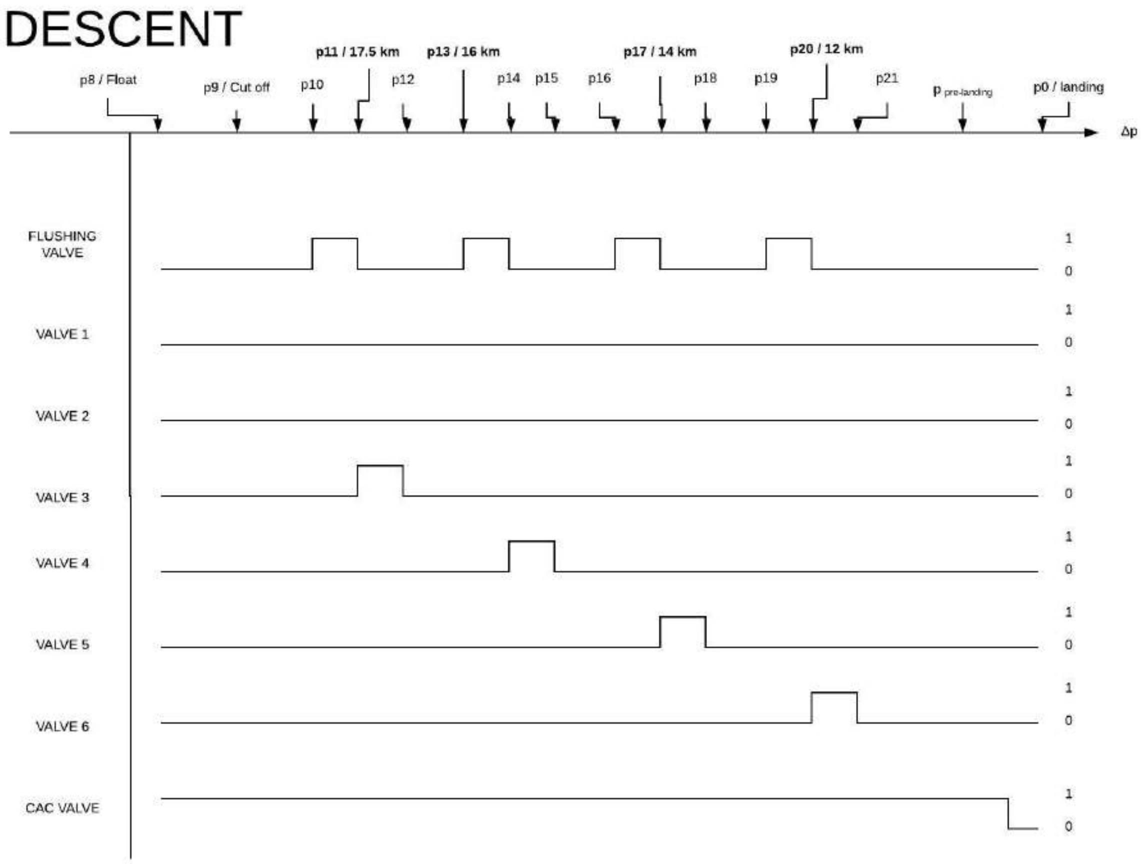


Figure 6: The Emptying and Sampling Sequence-Descent Phase.

In the diagrams, 0 denotes closed/off and 1 denotes opened/on. The horizontal axis denotes the different pressure levels throughout the flight, with p_0 being the sea level pressure and p_8 being the pressure during Float Phase.

The ambient pressure dependent timeline of the experiment was planned to be as follow:

Ascent Phase:

$p_0 - p_1$

- CAC valve shall be closed.
- AAC valves shall be closed.

$p_1 - p_2$

- CAC valve shall be opened.
- CAC tube shall start flushing.

$p_2 - p_3$

- AAC flushing valve shall be opened, allowing for the system to flush.

- CAC valve should remain open.

$p_3 - p_4$

- AAC flushing valve shall be closed.
- Valve 1 shall be opened, allowing for air to enter the first bag.
- CAC valve should remain open.

$p_4 - p_5$

- Valve 1 shall be closed.
- AAC flushing valve shall be closed.
- CAC valve should remain open.

p_5 - p_6

- AAC flushing valve shall be opened, allowing the system to flush.
- CAC valve should remain open.

p_6 - p_7

- AAC flushing valve shall be closed.
- Valve 2 shall be opened, allowing for air to enter the second bag.
- CAC valve should remain open.

p_7 - p_8

- Valve 2 shall be closed.
- AAC flushing valve shall be closed.
- CAC shall finish flushing.

Float Phase:
No action was taken other than continued telemetry.

Descent Phase:

$p_9 - p_{10}$

- CAC shall start sampling.
- AAC valves shall be closed.

$p_{10} - p_{11}$

- AAC flushing valve shall be opened allowing the system to flush.
- CAC valve should remain open.

$p_{11} - p_{12}$

- AAC flushing valve shall be closed.

- Valve 3 shall be opened, allowing for air to enter the third bag.
- CAC valve should remain open.

$p_{12} - p_{13}$

- Valve 3 shall be closed.
- AAC flushing valve shall be closed.
- CAC valve should remain open.

$p_{13} - p_{14}$

- AAC flushing valve shall be opened allowing the system to flush.
- CAC valve should remain open.

$p_{14} - p_{15}$

- AAC flushing valve shall be closed.
- Valve 4 shall be opened, allowing for air to enter the fourth bag.
- CAC valve should remain open.

$p_{15} - p_{16}$

- Valve 4 shall be closed.
- AAC flushing valve shall be closed.
- CAC valve should remain open.

$p_{16} - p_{17}$

- AAC flushing valve shall be opened, allowing the system to flush.
- CAC should remain open.

$p_{17} - p_{18}$

- AAC flushing valve shall be closed.
- Valve 5 shall be opened, allowing for air to enter the fifth bag.
- CAC valve should remain open.

$p_{18} - p_{19}$

- Valve 5 shall be closed.
- AAC flushing valve shall be closed.
- CAC valve should remain open.

$p_{19} - p_{20}$

- AAC flushing valve shall be opened, allowing the system to flush.
- CAC valve should remain open.

$p_{20} - p_{21}$

- AAC flushing valve shall be closed.
- Valve 6 shall be opened, allowing for air to enter the sixth bag.
- CAC valve should remain open.

$p_{pre-landing}$

- Valve 6 shall be closed.
- AAC flushing valve shall be closed.
- CAC valve shall be opened.

$p_{0-landing}$

- CAC valve shall be closed.

Note: The AAC system's air pump is only on during sampling into the air sampling bags and flushing of the system.

4.2 Experiment Interfaces

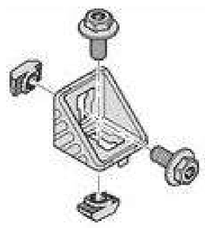
4.2.1 Mechanical Interfaces

Component	Interface	Amount	Dimensions	Total weight
Bracket standard 20/20 slot 6/6	AAC-Gondola	8	$20 \times 20 \times 20$ mm	40 g
Tolerance holes bracket	CAC-Gondola	2	$20 \times 30 \times 52$ mm	50 g
4-hole plate	AAC-CAC	6	$1 \times 60 \times 45$ mm	100 g
Rubber bumpers M6	AAC-Gondola, CAC-Gondola	10	$19 \times 19 \times 15$ mm	300 g
T-nut slot 6 M4	AAC-CAC, AAC-Gondola, CAC-Gondola	44	$4 \times 5.9 \times 11.5$ mm	132 g
T-nut slot 8 M6	AAC-Gondola, CAC-Gondola	10	$6 \times 11 \times 16$ mm	60 g
Steel bolt M4	AAC-CAC, AAC-Gondola	44	8 mm length	34 g
Steel washer M4	AAC-CAC, AAC-Gondola	24	$ID = 4.3$ mm $OD = 9$ mm	4.8 g
Styrofoam bars	AAC-Gondola, CAC-Gondola	4	see Appendix C.6	450 g
Handles	CAC & AAC	4	$18.6 \times 25.2 \times 112.5$ mm	80 g

Table 10: Summary of Gondola-AAC-CAC Interfaces Components.

Gondola - TUBULAR joining

The experiment box was fixed to the gondola rails by means of 10 brackets interfacing the experiment outside structure with the hammer nuts in the rails. Two different types of brackets were used to be flexible with respect to the gondola rails distances, which can be modified by use after previous BEXUS campaigns. Eight small 20/20 brackets (Figure 7a) were used to fix the AAC box to specific rails placement, and two other big brackets (Figure 7b) were used to fix the CAC box to the nearest rail. This method is secure as well as fast enough to provide an accessible and easy recovery for later analysis.



(a) Rexroth 20/20.

(b) Tolerance Holes.

Figure 7: Bracket Components.

CAC - AAC joining

A simple but reliable fixing interface between the two boxes of the experiment has been designed to ensure the fast recovery of the CAC box. The latter required only unscrewing 12 bolts as well as unplugging a D-Sub connector marked in RED, see Figure 14. Once the CAC box was detached, the AAC Box still remained fixed in the gondola. Table 10 includes all the components required to fix the experiment to the gondola.

Handles

Four top handles, as shown in Figure 8 were mounted to facilitate the experiment box manipulation when moving it in and out of the gondola.

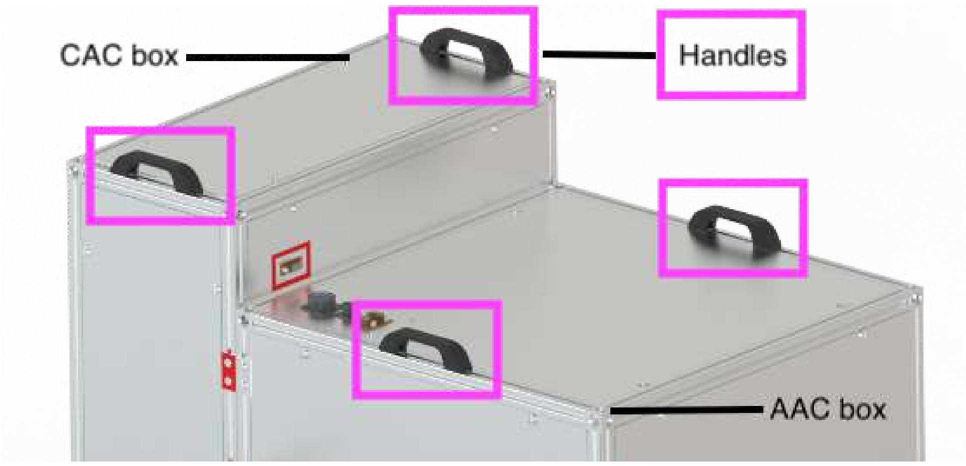


Figure 8: Handling Interfaces.

Inlet/Outlet Pipes

In order to collect reliable air samples, the experiment was required to be mounted with at least one side exposed to the outside. This reduced the pipe length used to collect clean air. As it can be seen in Figure 3, three pipes were extended from the experiment box face: one for the CAC sampling and two, input and output, for the AAC sampling.

These pipes were welded/drawn 304 grade stainless steel tubes from RESTEK company, which were specially recommended for chromatography applications and gas delivery systems with low pressures and inert environments. These tubes were sulfinert, which is a required treatment for metal components when analyzing for parts-per-billion levels of organo-sulfur compounds.

The tubes, which were the same ones used in the pneumatic system of the *Brain* (see Section 4.4.5), had an outer diameter $OD = 6.35\ mm$ ($1/4$ inches) and an inner diameter $ID = 4.57\ mm$ (0.18 inches).

Pump vibration

To mitigate the vibrations produced by the pump, an extra piece of styrofoam has been added between the pump's anchor plate and the surface of the level 1 of the brain, where this key component is fixed.

4.2.2 Thermal Interfaces

Both main structural components and external walls of the two boxes of the experiment were made by aluminum and steel components. For this reason, since these were conductive materials, a direct attachment to the gondola creates many heat paths with the internal space and subsystems of the experiment. Considering that the temperature gradient between the gondola and the operative requirements of the electronic components can be quite high, this conductive connections drastically decrease the efficiency of the thermal insulation. Therefore, a system based on rubber bumpers and styrofoam bars (see Figure 10) has been designed to remove heat bridges and minimize temperature leaks from the inside of the experiment to the outside.

Figure 9 shows a CAD model of the bumper component and how it looks like when attached to the gondola with the brackets explained in the previous section.

Figure 9: Rubber Bumper.

The styrofoam bars were attached directly to the rails of the experiment structure by M4 plastic screws and big washers.

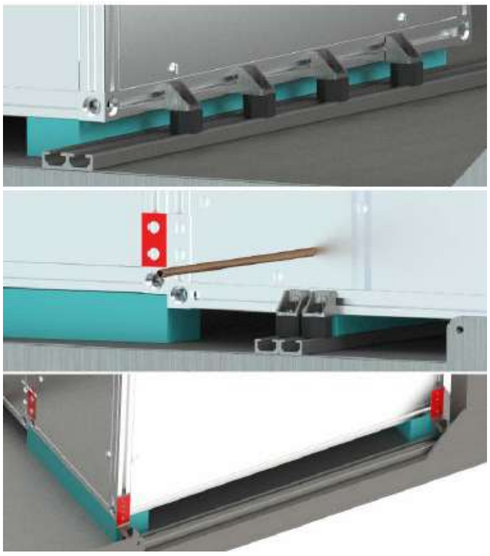


Figure 10: Thermal Interfaces TUBULAR-Gondola.

4.2.3 CAC Interfaces

An uncoupled quick connector, shown in Figure 11, was attached at each end of the coiled tube to seal the opening. It remained tightly sealed until the quick connectors were manually coupled.

Figure 11: Swagelok Quick Connector Body.

The interfaces between the other parts in the CAC set up were joined with specific tube fittings, listed in Table 11. All the chosen interfaces were from Swagelok. Using products from the same manufacture minimizes the risk for leakage or mismatched interfaces in the system.

Component	Interface	Amount	Fitting Size
Quick connector body SS-QC4-B-200	Outlet of coiled tube	1	1/8 in.
Quick connector body SS-QC4-B-400	Inlet of coiled tube	1	1/4 in.
Quick connector stem SS-QC4-D-400	Inlet of coiled tube - Filter	1	1/4 in.
Male connector SS-400-1-2	Tube fitting - Solenoid valve	2	Tube OD 1/8 in. to Tube OD 1/4 in.
Straight Tube Union SS-200-6	Quick connector 1/8 in. - Tube 1/8 in.	1	1/8 in.
Tube Reducer SS-400-6-2	Tube 1/8 in. - Tube 1/4 in.	1	Tube OD 1/8 in. to Tube OD 1/4 in.
Straight Tube Union SS-400-6	Tube 1/4 in. - 90 degree connector	1	1/4 in.
Union 90-degree connector SS-400-9	Between certain tube fittings Outlet tube	3	1/4 in.
Tube fitting SS-401-PC	Between certain tube fittings Magnesium dryer filter	5	1/4 in.

Table 11: Interfaces within CAC Setup.

4.2.4 AAC Interfaces

In the AAC system, the interfaces between various components were a mixture of eleven different types of tube fittings from Swagelok. The selected types were straight and elbow union, T-union, female and male elbows, male and female connectors, tube fittings, and quick coupling with a certain specifications. Some of them are shown in Figure 12. Information regarding the fitting's placement in the AAC and fitting sizes are summarized in Table 12.

Figure 12: From Left to Right: Male Connector, Male Elbow, T-union, Straight Union and Female Connector.

Component	Interface	Amount	Fitting Size
Male connector SS-400-1-2	Tube to Manifold - Flushing valve Flushing valve - Outlet tube Manifold valve - Tube to bag	8	Male 1/8 in. to Tube OD 1/4 in.
Male connector SS-400-1-4	Manifold - Tube to Flushing valve	1	Male 1/4 in. to Tube OD 1/4 in.
Male elbow SS-400-2-4	Static pressure sensor - Manifold	1	Male 1/4 in. to Tube OD 1/4 in.
Female elbow SS-400-8-4	Pump tube - Airflow sensor Airflow sensor - Static pressure sensor	2	Female 1/4 in. to Tube OD 1/4 in. in.
Female connector SS-4-TA-7-4RG	Static pressure sensor - T-Union	1	Female 1/4 in. and Tube OD 1/4 in. in.
Straight union SS-400-6	Filter - Tube filter Tube filter - Pump	3	Tube OD 1/4 in.
Elbow union SS-400-9	Pump tube - Filter tube	1	Tube OD 1/4 in. in.
T-Union SS-400-3	Static pressure sensor	3	Tube OD 1/4 in.
T-Union SS-400-3-4TTM	Tube valve - Bag valve - Quick Connector	5	Male 1/4 in. and 2 x Tube OD 1/4 in.
T-Union SS-400-3-4TMT	Tube valve - Bag valve - Quick Connector	1	Male 1/4 in. 2 x Tube OD 1/4 in.
T-Union SS-6M0-3	Pump Inlet and Outlet	2	Tube OD 6mm
Tube Fitting SS-401-PC	Filter - Pump	1	Tube OD 1/4in.
Tube Fitting Reducer SS-400-R-6M	Filter - Pump Pump - Airflow sensor	2	Tube OD 1/4in. to Tube OD 6mm
Tube Inserts SS-6M5-4M	Pump Inlet and Outlet	2	OD 6mm - ID 4mm
Tube Fitting Female SS-4-TA-7-4RG	Static pressure sensor	1	Tube OD 1/4in. to female 1/4"
Quick Coupling SS-QC4-B-4PF	T-Union of bags	6	SS female 1/4"
Tube adapter SS-300-R-4	T-Union - Bag valve	6	Tube OD 1/4in. to Tube OD 3/16"

Table 12: Interface Descriptions Inside AAC System.

4.2.5 Electrical Interfaces

The experiment was connected to the gondola electrically via a 4 pin, male, box mount receptacle MIL - C-26482P series 1 connector with an 8-4 insert arrangement (MS3112E8-4P)

[8]. It was connected to one 28.8 V/1 mA battery pack which consisted of eight SAFT LSH20 batteries in series where each had a 5 A fuse[8]. The expected maximum current is 1.1 A.

Figure 13: Connectors.

The E-Link connection shall be made between the experiment and the E-Link system using a RJ45 connection which was supplied by SSC and an Ethernet protocol. The Amphenol RJF21B connector was mounted on either the front or the side of the experiment[8].

The CAC and AAC were connected together with a D-SUB 9-pin connector where power, ground and signals for the sensors in the CAC were connected. A female connector was located on the AAC wall and a male connector on the CAC wall.

Another female D-SUB 9-pin connector was located on the wall of the AAC in which the connections for the three ambient pressure sensors were located. Connectors with different pin configuration are shown in Figure 13.

The expected data rate was 1.58 kbits/s for downlink and 1.08 kbits/s for uplink.

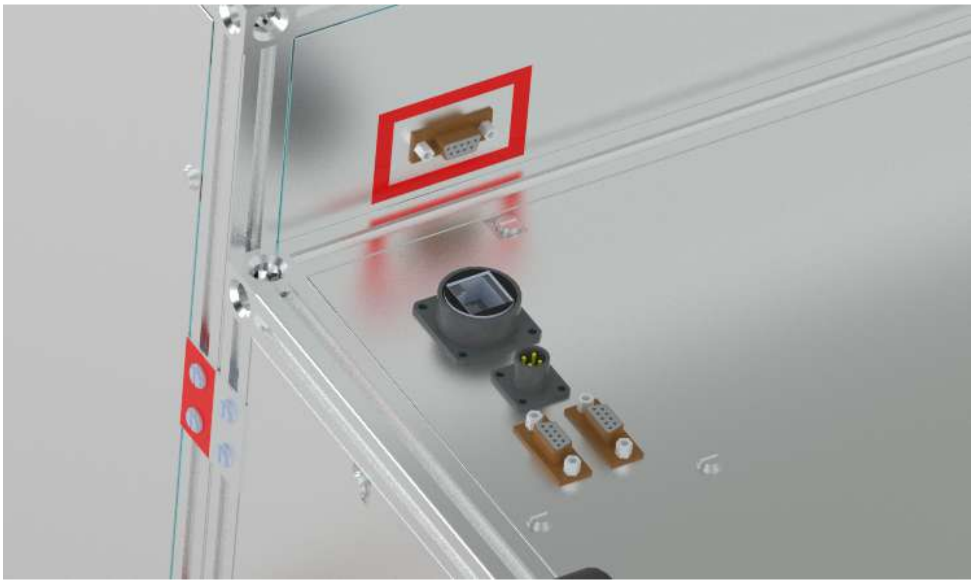


Figure 14: Electrical Interfaces.

4.3 Experiment Components

Component tables were generated from the project budget spreadsheet in Appendix M using the scripts included in Appendix K.

4.3.1 Electrical Components

Table 13 shows all required electrical components with their total mass and price.

ID	Component Name	Manufacturer	Manufacturer Code	Qty	Total Mass [g]	Total Cost [EUR]	Note	Status
E1	Arduino Due with headers	Arduino	A000062	1	36	35	Fast and has many analog, and digital pins	Received
E2	Ethernet Shield	SEEED Studio	SKU 103030021	1	36	28	Can be mounted on top of the board	Received
E3	Miniature diagphram air pump	KNF	NMP 850.1.2 KNDC-B	1	430	350		Received
E4	Pressure sensor	SENSOR SOLUTIONS	MS560702BA03-50	4	20	9.2	High resolution, large measuring range	Received
E5	Sampling Valve (inlet and outlet 1/8" female)	SMC	VDW22UANXB	1	100	45		Received
E6	Airflow sensor	Honeywell	AWM5102VN	1	60	130	0-10 SLPM	Received
E7	Heater	Minco	HK5160R157L12	4	16	380	Easy to mount, compact size	Received
E9	Temperature sensor	Maxim Integrated	DS1631+-ND	8	16	24	I2C digital output interface, temperature range down to -55 $^{\circ}C$	Received

E10	DC/DC converter 24 V	Traco Power	S24SP24003PDFA	2	92	98	Provides required output voltage and power, 93% efficiency	Received
E12	MicroSD	Kingston Technology	SDCIT/16GB	1	0.5	20	Small, good temperature range, sufficient storage	Received
E13	Logic CAT5E Network	Valueline	VLCT85000Y30	1	90	7	For testing and ground station	Received
E14	Resistors	n/a	n/a	25	25	0		Received
E15	Capacitors (0.1 uF, 5uF, 10 uF, 100uF)	n/a	n/a	7	7	0		Received
E16	Mosfet for current control	IR	IRLB8748PBF	11	22	7.7	Cheap, good temperature range	Received
E17	Diodes for DCDC converters	Diotec Semiconductor	1N5059	4	1.6	0.4	Cheap, good temperature range	Received
E18	LED 3.3 V	Wurth Elektronik	151034GS03000	16	6.4	8.3	For monitoring, testing	Received
E19	15-pin D-SUB Female connector with pins	RND Connect	RND 205-00779	2	22	1.5	For connecting distributed components	Received
E20	9-pin D-SUB Female connector with pins	RND Connect	RND 205-00777	3	26	2	For connecting distributed components	Received
E21	9 pin D-SUB Female connector with soldering cups	RND Connect	RND 205-00704	3	27	1.7	For connecting distributed components	Received
E22	9 pin D-SUB Male connector with soldering cups	RND Connect	RND 205-00700	6	54	2.9	For connecting distributed components	Received
E23	15-pin D-SUB Male connector with soldering cups	RND Connect	RND 205-00701	2	22	1.2	For connecting distributed components	Received

E24	9-pin D-SUB backing	Enchitech	MHDTZK-9-BK-K	6	240	17	For connecting distributed components	Received
E25	15-pin D-SUB backing	Enchitech	MHDTZK-15-BK-K	2	130	6.1	For connecting distributed components	Received
E26	Wall mounting bolts	RND Connect	RND 205-00786	3	7.5	3.1	For connecting distributed components	Received
E28	3.3 V Zener diode	RND Components	RND 1N746A	15	7.5	1.1	Regulate indication LED voltage	Received
E29	Male connector on PCB	Binder	Serie 768	1	5	8.5		Received
E30	Female connector from wall	Binder	Serie 768	1	11	12		Received
E31	Grounding contact	Vogt	DIN 46234	4	2.3	8.6	1 pack of 100 pcs	Received
E32	Logic CAT5 E-link for inside box 0.5m	Valueline	VLCP85121E05	1	20	1.3	To connect from wall to Arduino shield	Received
E33	Signal wire	Alpha Wire	5854/7 YL005	1	120	34	Roll of 30 m. Half will be used approximately	Received
E34	Flushing valve (inlet and outlet 1/8" female)	SMC	VDW22UANXB	1	100	45		Received
E35	Valves manifold (outlet 1/8" female)	SMC	VDW23-5G-1-H-Q	6	600	240		Received
E36	Power wire - Back	Alpha Wire	5856 BK005	1	73	46	Roll of 30 m. A fifth will be used approximately	Received
E37	Electrical Tape for marking wires - White	Hellerman Tyton	HTAPE-FLEX15WH-15X10	1	14	0.82	Roll of 10 m. A forth will be used approximately	Received
E38	Electrical Tape for marking wires - Black	Hellerman Tyton	HTAPE-FLEX15BK-15X10	1	13	0.82	Roll of 10 m. A forth will be used approximately	Received

E39	Electrical Tape for marking wires - Green	Hellerman Tyton	HTAPE-FLEX15GN-15X10	1	14	0.82	Roll of 10 m. A forth will be used approximately	Received
E40	Electrical Tape for marking wires - Violet	Hellerman Tyton	HTAPE-FLEX15VT-15X10	1	14	0.82	Roll of 10 m. A forth will be used approximately	Received
E41	Electrical Tape for marking wires - Gray	Hellerman Tyton	HTAPE-FLEX15GY-15X10	1	14	0.82	Roll of 10 m. A forth will be used approximately	Received
E42	Electrical Tape for marking wires - Brown	Hellerman Tyton	HTAPE-FLEX15BN-15X10	1	14	0.82	Roll of 10 m. A forth will be used approximately	Received
E43	Electrical Tape for marking wires - Blue	Hellerman Tyton	HTAPE-FLEX15BU-15X10	1	14	1.9	Roll of 10 m. A forth will be used approximately	Received
E48	Power wire - Red	Alpha Wire	5856 RD005	1	73	46	Roll of 30 m. A fifth will be used approximately	Received
E50	6-pin male double row header	RND Connect	RND 205-00634	2	2	0.44		Received
E51	8-pin male single row header	RND Connect	RND 205-00629	5	5	1.4		Received
E52	10-pin male single row header	Prostar	SD-2X5-T1-7/3MM	1	1	0.26		Received
E53	36-pin male double row header	Würth Elektronik	61303621121	1	2	1.7		Received
E54	DC/DC converter 12 V	Delta	R-7812-0.5	2	40	68	12V,1.67A, 20W DCDC	Received
E55	Potentiometer 50 kOhm	Bourns	3296Y-1-503LF	10	10	18		Received

E56	Static Pressure Sensor	Gems Sensors and Controls	3500S0001A05E000	1	53	120		Received
E57	Connector for the Static Pressure Sensor	Schneider Electric	XZCPV1141L2	1	14	14	-25 to 80 celcius, female 4 pin M12 connector with 2 meter wire	Received
E58	PCB board	Eurocircuits	n/a	1	100	180	Will be custom-made	Received
E59	Pressure sensor PCB	Eurocircuits	n/a	3	75	42	Will be custom-made	Received
E60	Arduino Due without headers	Arduino	2	1	36	34		Received

Table 13: Electrical Components Table

4.3.2 Mechanical Components

Table 14 shows all required mechanical components with their total mass and price.

ID	Component Name	Manufacturer	Manufacturer Code	Qty	Total Mass [g]	Total Cost [EUR]	Note	Status
M1	Strut profile 20x20 M6/M6, length: 460 mm	Bosch - Rexroth	3842993231	16	2900	93	Railed geometry, Structural element	Received
M2	Strut profile 20x20 M6/M6, length: 360 mm	Bosch - Rexroth	3842993231	4	580	22	Railed geometry, Structural element	Received
M3	Strut profile 20x20 M6/M6, length: 190 mm	Bosch - Rexroth	3842993231	4	300	21	Railed geometry, Structural element	Received
M4	T-nut N6 M4	Bosch - Rexroth	3842536599	100	300	74	Wall, Protective element	Received
M5	Sliding block N6 M4	Bosch - Rexroth	3842523140	100	300	90	Wall, Protective element	Received
M6	Bracket standard 20x20 N6/6	Bosch - Rexroth	3842523508	100	500	52	Wall, Protective element	Received
M7	Variofix block S N6 20x20	Bosch - Rexroth	3842548836	100	500	62	Wall, Protective element	Received
M8	Cubic connector 20/3 N6	Bosch - Rexroth	3842523872	16	160	39		Received
M9	Strap-shaped handle	Bosch - Rexroth	3842518738	4	80	19		Received
M10	Retainer ring M4	Bosch - Rexroth	3842542328	100	50	5.4		Received
M11	DIN 7984 M4x8 bolts	n/a	n/a	150	150	0		Received
M12	M6x16 bolts	Bossard	79850616	48	240	6.2		Received

M13	ISO 4762 bolts	n/a	n/a	8	16	0		Received
M14	Washers	n/a	n/a	20	4	0		Received
M15	Aluminum sheets	-	204599	1	2500	25		Received
M16	Styrofoam 250 SL-A-N	Isover	3542005000	1	1800	97		Received
M17	Fixing bar for the bags	Maskindelen	n/a	2	26	6		Received
M18	Flat plate interface for fixing bar	Alfer	n/a	4	130	0	The cost is included in M20	Received
M19	CAC-AAC interface 6-hole plate	Alfer	n/a	4	65.6	0	The cost is included in M20	Received
M20	Steel sheet 500x250x0.75 mm	Alfer	n/a	3	0	17.6	Used for M18 and M19	Received
M22	DIN 7984 M4x8 bolts	n/a	n/a	26	26	0		Received
M23	DIN 7984 M4x30 bolts	n/a	n/a	16	32	0		Received
M24	Nut M4	n/a	n/a	42	42	0		Received
M26	15mm M3 Standoff/Spacer for PCB	Keystone Electronics	24339	10	20	7.8		Received
M27	Lock nut M3 (DIN985) for PCB	n/a	n/a	5	5	0		Received
M28	M3 Cheese Head Screws 6mm	n/a	n/a	5	4	0		Received
M32	Coiled tube	FMI	n/a	1	6200	22000	-	Received
M34	Interface tube-screw male (OD 1/4" - ID 5/32" to male 1/8")	Swagelok	SS-400-1-2	2	26	20		Received
M36	Interface attached to the coiled tube outlet, quick connector	Swagelok	SS-QC4-B-200	1	91	65		Received
M37	Interface attached to the coiled tube inlet, quick connector	Swagelok	SS-QC4-B-400	1	68	50		Received

M38	Interface quick connector stem with valve	Swagelok	SS-QC4-D-400	1	58	40		Received
M43	Gas Sampling Bag, Multi-Layer Foil, 3L, 10"x10", 5pk	Restek	22951	6	30	120		Received
M44	Manifold (inlet and outlet 1/8" female)	SMC	VV2DW2-H0601N-F-Q	1	440	140		Received
M45	Interface tube-screw male (OD 1/4" - ID 5/32" to male 1/8")	Swagelok	SS-400-1-2	8	100	110		Received
M46	Interface tube-screw male 90 degree(OD 1/4" - ID 5/32" to male 1/8")	Swagelok	SS-400-2-2	3	39	48		Received
M47	Male 90-degree connector (OD 1/4" - ID 5/32" to male 1/4")	Swagelok	SS-400-2-4	1	16	14		Received
M49	Interface T-Union (male 1/4")	Swagelok	SS-400-3	1	71	33		Received
M51	Tubing, Sulfinert 304SS Welded/Drawn 50ft (OD 1/4" - ID 0.21")	SilcoTek	29255	1	600	840		Received
M52	Quick Coupling female 1/4"	Swagelok	SS-QC4-B-4PF	6	270	300		Received
M53	90 degree elbow 1/4"	Swagelok	SS-400-9	1	55	19		Received
M54	Interface female 90-degree connector (OD 1/4" - ID 5/32" to female 1/4")	Swagelok	SS-400-8-4	2	120	47		Received

M55	Female tube adapter (Tube OD 1/4" to female 1/4" ISO)	Swagelok	SS-4-TA-7-4RG	1	46	20		Received
M56	Tube Fitting Reducer (OD 3/16 in. to 1/4 in. Tube OD)	Swagelok	SS-300-R-4	6	120	72		Received
M57	Tube plug 1/4 in.	Swagelok	SS-400-C	4	0	27	Will only be used before and after flight	Received
M58	Magnesium filter tube with interface	FMI	n/a	1	65	150		Received
M59	T-Union 6 mm Tube OD	Swagelok	SS-6M0-3	2	100	54		Received
M60	Tube Fitting Reducer (1/4 in. to 6 mm Tube OD)	Swagelok	SS-400-R-6M	2	60	25		Received
M61	Tubing Insert, 6 mm OD x 4 mm ID	Swagelok	SS-6M5-4M	4	40	11		Received
M62	Male Branch Tee (OD 1/4" - 1/4" Male NPT)	Swagelok	SS-400-3-4TTM	5	320	92		Received
M63	Male Branch Tee (OD 1/4" - 1/4" Male NPT)	Swagelok	SS-400-3-4TMT	1	63	63		Received
M64	Male connector (OD 1/4" - 1/4" Male NPT)	Swagelok	SS-400-1-4	1	30	8.6		Received
M65	Straight tube union (OD 1/4" - ID 5/32")	Swagelok	SS-400-6	1	30	13		Received
M66	Straight reducing tube union (OD 1/4" to OD 1/8")	Swagelok	SS-400-6-2	1	25	17		Received
M67	90 degree elbow 1/4"	Swagelok	SS-400-9	3	170	58		Received

M68	Port Connector, 1/4 in. Tube OD	Swagelok	SS-401-PC	5	25	32		Received
M69	Magnesium filter with interface	FMI	n/a	1	65	150		Received
M70	Aluminum sheets	n/a	204599	1	100	1		Received
M71	Styrofoam (bulk - 1 piece from 1.16)	Isover	3542005000	1	110	0	The cost is included in M16	Received
M72	Strut profile 20x20 M6/M6, length: 360 mm	Bosch - Rexroth	3842992888	2	290	6		Received
M73	Strut profile 20x20 M6/M6, length: 170 mm	Bosch - Rexroth	3842992888	2	140	4.5		Received
M74	Strut profile 20x20 M6/M6, length: 263 mm	Bosch - Rexroth	3842993230	1	110	4.2		Received
M75	Sliding block N8 M6	Bosch - Rexroth	3842547815	10	30	11		Received
M76	Straight tube union (OD 1/8" - ID 5/32")	Swagelok	SS-200-6	1	30	13		Received
M77	Rubber bumper	n/a	n/a	10	355	0		Received

Table 14: Mechanical Components Table

4.3.3 Other Components

Table 15 shows other components which contribute to the mass and/or price.

ID	Component Name	Manufacturer	Manufacturer Code	Qty	Total Mass [g]	Total Cost [EUR]	Note	Status
O1	Hand Tube Bender 1/4 in	Swagelok	MS-HTB-4T	1	-	250		Received
O2	Tube Cutter (4 mm to 25 mm)	Swagelok	MS-TC-308	1	-	35		Received
O3	Tubing Reamer	Swagelok	MS-TDT-24	1	-	26		Received
O4	Travel to FMI for sample bag testing	n/a	n/a	1	-	250		Completed
O5	Travel to FMI for integration testing	n/a	n/a	1	-	250		Completed
O6	Shipping costs	n/a	n/a	n/a	-	430		n/a
O7	Error margin	n/a	n/a	n/a	2400	220		n/a
O8	PTFE Tape Thread Sealant, 1/4"	Swagelok	MS-STR-4	1	-	1.9		Received
O9	Double-Sided Adhesive Tape	3M	180-89-682	8	-	78		Received
O10	PTFE Tape, 32.9 m	3M	60-1"X36YD	1	-	68		Received
O11	Microfibre cloth	n/a	180-63-478	1	-	9.4		Received
O12	IPA Cleaner Spray, 400 ml	RND Lab	RND 605-00129	3	-	12		Received
O13	IPA Cleaner fluid, 1000 ml	Electrolube	EIPA01L	2	-	35		Received
O14	Disposable gloves L	Eurostat	51-675-0032	1	-	12		Received

O15	Electronic Leak Detector	Restek	22655-R	1	-	1000		Received
O16	Thermal Adhesive	Fischer Elektonik	WLK 10	1	-	18		Received
O17	Flushing process (nitrogen or dry calibrated gas)	n/a	n/a	2	-	200	-	Received

Table 15: Other Components Table

4.4 Mechanical Design

The experiment consisted of two rectangular boxes, one stacked next to the other, shown in Figure 16. The higher but narrower box (CAC box) allocated the heaviest element, the CAC. The main box (AAC box) contained the pneumatic system with six sampling bags and the central command unit: The Brain. The Brain contained the general Electronic box (EB) as well as the pneumatic sampling system.

The two-box design allowed ease of access and manipulation of both the CAC and AAC subsystems. In addition, the AAC sampling system is designed to be re-usable for future handover to the FMI, as such, it can be mounted on any standard balloon flight without having to introduce major design changes. The experiment would only require its own batteries as a power unit. In order to help balance the AAC box center of mass, they would be allocated in the corner opposite to the Brain, see Figure 15. This also maintains the space for 6 bags inside the AAC box.

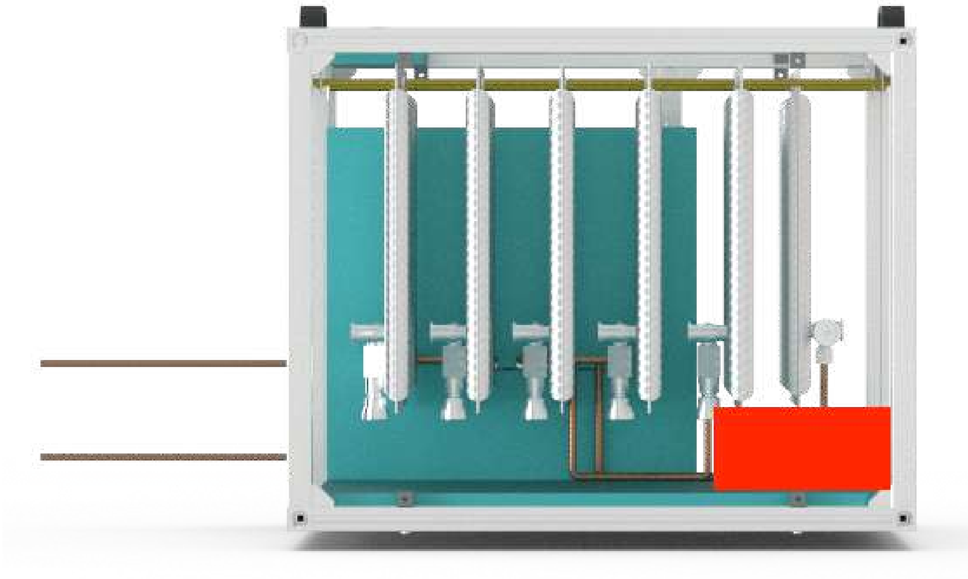


Figure 15: Layout Including a Battery (in Red).

Since the CAC was the heaviest component in the whole experiment its positioning and orientation inside the gondola directly affected the stress analysis of the structure. In the worst case scenario, without a proper study of the aforesaid interface, shear in the screws could be produced after a violent landing stress or unexpected shaking. The larger the distance to the fixed points, the bigger the momentum produced by the component. For this reason, the CAC box was securely attached to the AAC box by means of six anchor points with four screws each. This fixing interface can be seen in red in Figure 16 to help the fast recovery. Taking into account also the two extra anchor points to the gondola, the fast recovery of CAC then only required unscrewing 16 screws and unplugging a D-Sub connector.

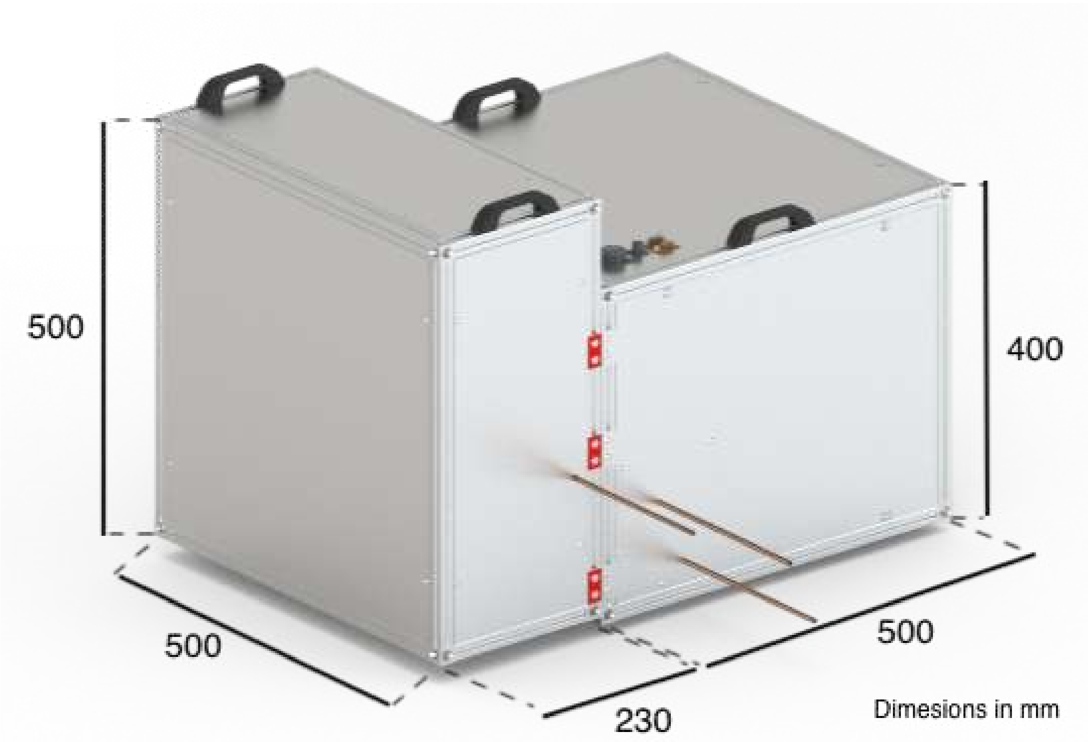


Figure 16: General Dimensions of the Experiment.

The main mechanical characteristics of the experiment are summarized in Table 16, where the values are based on the reference axis shown in Figure 17. The Center Of Gravity for the whole experiment was determined to be located just on the plate of the third level of the Brain, which coincides with the location of the electronics PCB. This outcome was quite advantageous in terms of stability for one of the most sensitive subsystems of the experiment in terms of shakes and loads.

	CAC	AAC	TOTAL
Experiment mass [kg]	11.95	12.21	24.16
Experiment dimensions [m]	$0.23 \times 0.5 \times 0.5$	$0.5 \times 0.5 \times 0.4$	$0.73 \times 0.5 \times 0.5$
Experiment footprint area [m^2]	0.115	0.25	0.365
Experiment volume [m^3]	0.0575	0.1	0.1575
Experiment expected COG position	$X = 23.51\ cm$ $Y = 10\ cm$ $Z = 22.57\ cm$	$X = 29.04\ cm$ $Y = 16.63\ cm$ $Z = 16.2\ cm$	$X = 26.31\ cm$ $Y = 24.99\ cm$ $Z = 19.35\ cm$

Table 16: Experiment Summary Table.

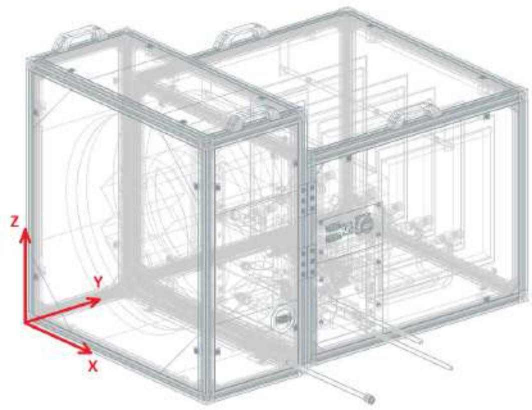


Figure 17: Reference Axis for the Total Center of Gravity.

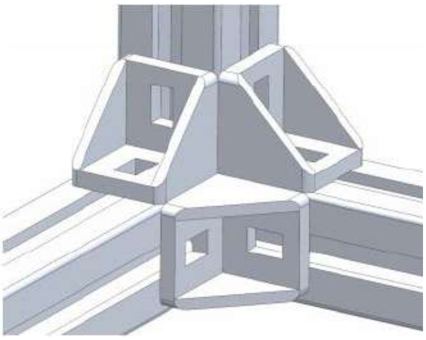
4.4.1 Structure

The main purpose of the experiment box structure was to provide overall mechanical integrity and maintain the system geometry. It was able to carry the loads of all the phases of the flight and ensure that all the components and subsystems could withstand them. Test 9 in Table 29 helped to confirm the frame could withstand these vibrations.

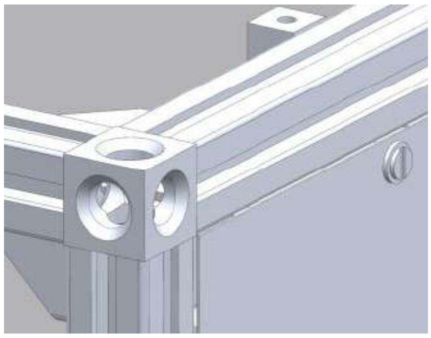
Moreover, other considerations such as electrical and, especially, thermal conductivity were also a concern since the experiment flown up to $25\ km$ in the Polar Circle and many critical subsystems had tight operative ranges values.

Figure 18: Structure Overview.

For this purpose, two boxes built with straight frames were chosen as the best option as shown in Figure 18. The frame of these boxes were strut profiles made of aluminum, with a characteristic cross-section of $20 \times 20\ mm$, and with $M6$ thread at each side. The rails allowed an easy interface between bars and other elements. In turn, these profiles were joined together in each corner with aluminum cubic connectors of $20 \times 20\ mm$ (see Figure 19b) and $M6 \times 16$ bolts aligned with the bars axis. At the same time, these nodes were reinforced by three $20/20$ brackets (see Figure 19a), each was fixed to the frames with $M4 \times 8$ bolts and the corresponding $M4$ T-nut. All these components were manufactured by Bosch Rexroth.



(a) Brackets Reinforcement.



(b) Cubic Connector.

Figure 19: Strut Profiles Connections.

Table 17 shows the main mechanical properties of the Bosch Rexroth $20/20$ strut profiles used in the structure. For further details see Table 59.

Section surface	**Mass**	**Moment of Inertia ($I_x = I_y$)**	**Moment of resistance ($W_x = W_y$)**
$1.6\ cm^2$	$0.4\ kg/m$	$0.7\ cm^4$	$0.7\ cm^3$

Table 17: Intrinsic Characteristics of the Strut Profiles.

4.4.2 Walls and Protections

Since the experiment was placed close to the outside of the gondola, it was very exposed to both external elements impacts and also possible broken parts from other experiments in the gondola due to unexpected rapid movements, and a probable hard landing impact. Therefore, the experiment box was shielded with removable aluminum walls along with a thick layer of Styrofoam attached to each wall. This thickness varied from two to three centimeters in the AAC box, and five centimeters to protect the AirCore. Besides protection, the thickness of the styrofoam was also motivated by thermal control issues.

To mount the experiment a combination of three different elements were used, as shown in Figure 20. The walls were screwed to the Variofix blocks by means of $M4 \times 8$ bolts. In between the aluminum walls and the bolts, a $M4$ retainer ring was placed to improve the fixation of each spot. Eight fixation points for each wall were considered sufficient to keep the experiment safe from any impact.

The styrofoam sheets were attached to the aluminum walls with double sided tape.

Tables 60 and 61 show the main properties of the materials used to build the walls of the boxes.

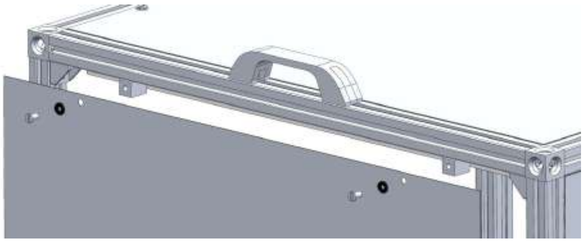


Figure 20: Exploit View of the Attachment of the Walls.

4.4.3 CAC Box

The CAC subsystem was designed to fit a 300 m stainless steel coiled tube, a solenoid valve provided by SMC controlling it, tube fittings manufactured by Swagelok, an air filter and three temperature sensors. A schematic of this subsystem can be seen in Figure 22. The CAC consisted of a combination of a 200 m coiled tube of $1/8$ inches diameter and a 100 m coiled tube of $1/4$ inches diameter. The outlet of the CAC was sealed with a quick connector provided by FMI. The inlet was sealed the same way but it could be opened by another interface plugged into the quick connector. A custom made filter by FMI was placed between this orifice and the solenoid valve. The filter contained magnesium perchlorate powder with stone wool at both ends of the tube. It ensured that no moisture entered the coil during any testing or sampling. A piece of stainless steel tube, manufactured by Silcotek, was attached to the solenoid valve that goes outside the box, thus having a direct outside outlet and inlet for the whole CAC system, as seen in Figure 21.

A D-sub cable was used to connect the electrical components to the control unit in the AAC box. Both boxes had their own D-sub connector, which was located on one of the box's walls.

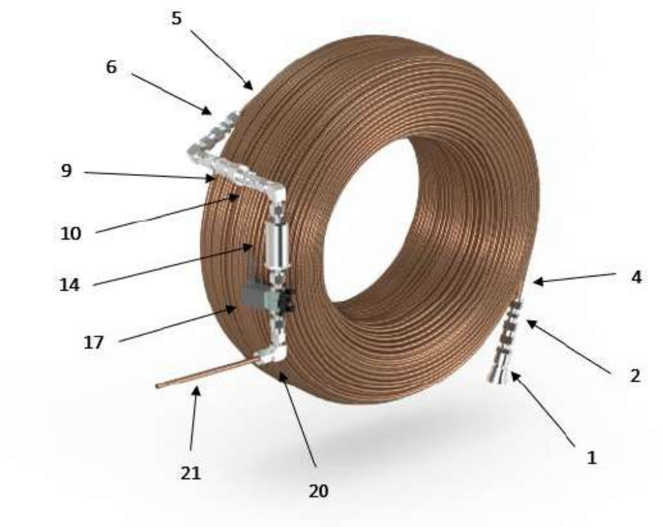
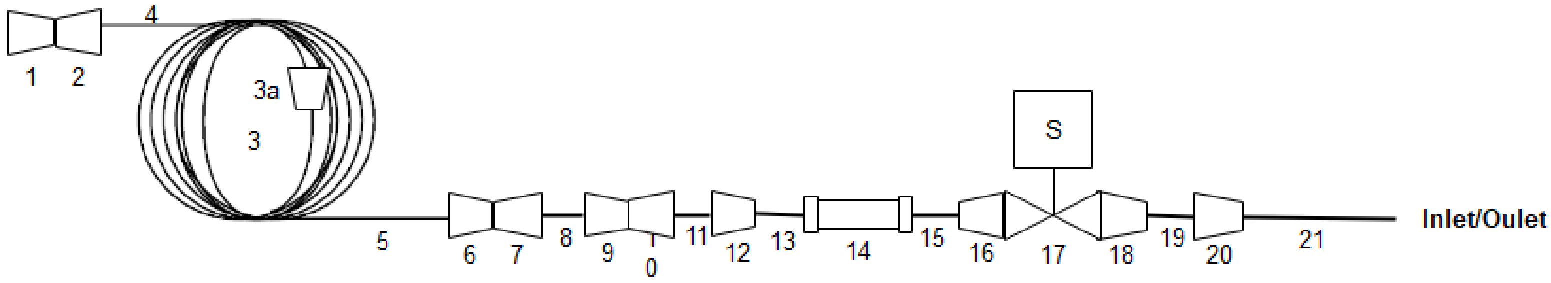


Figure 21: 3D Model of the Aircore and its pneumatic fittings. The Numbers Correspond to the main components in Figure. 22.

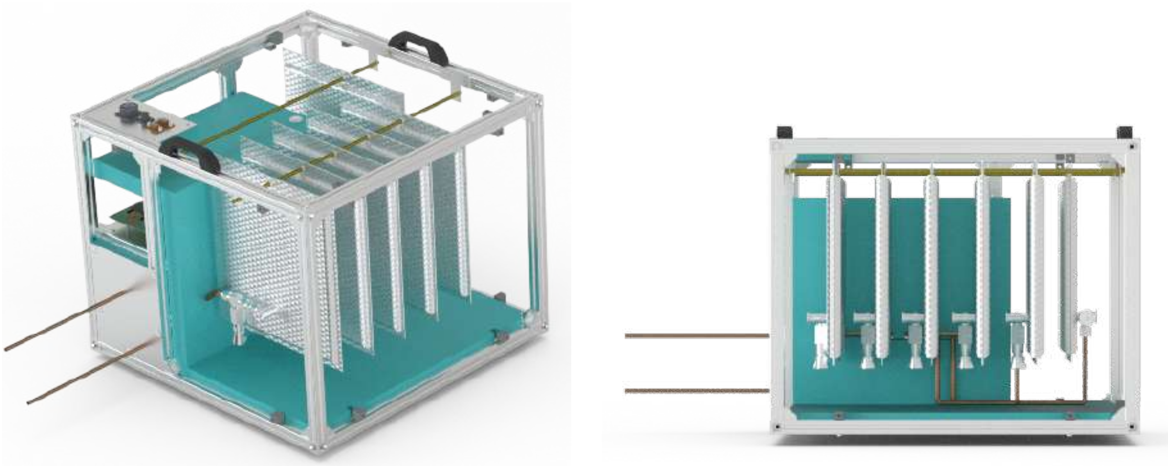


1. Quick connector body (SS-QC4-B-200): Q.C body 1/8"
2. Straight tube union (SS-200-6): 1/8" Tube OD
3. AirCore-HR: 300m, consist of Tube 1 and Tube 2
3a. Straight tube redcuing union between Tube 1 and Tube 2 (SS-400-6-2): 1/8" to 1/4" Tube OD
4. Tube 1: 200m, 1/8" Tube OD
5. Tube 2: 100m, 1/4" Tube OD
6. Straight tube union (SS-400-6): 1/4" Tube OD
7. Union 90-degree connector (SS-400-9): 1/4" Tube OD
8. Tube fitting (SS-401-PC): 1/4" Tube OD
9. Quick connector body (SS-QC4-B-400): Q.C body 1/4"
10. Quick connector with stem (SS-QC4-D-400): Q.C stem with valve 1/4"
11. Tube fitting (SS-401-PC): 1/4" Tube OD
12. Union 90-degree connector (SS-400-9): 1/4" Tube OD
13. Tube fitting (SS-401-PC): 1/4" Tube OD
14. Magnesium dryer filter: 1/4" Tube OD
15. Tube fitting (SS-401-PC): 1/4" Tube OD
16. Male connector (SS-400-1-2): male 1/8" NPT to OD 1/4" - ID 0.21"
17. Solenoid valve (VDW22UANXB): inlet and outlet female 1/8" NPT
18. Male connector (SS-400-1-2): male 1/8" NPT to OD 1/4" - ID 0,21"
19. Tube fitting (SS-401-PC): 1/4" Tube OD
20. Union 90-degree connector (SS-400-9): 1/4" Tube OD
21. Tube: 16cm, OD 1/4" - ID 0,21"

Figure 22: Schematic of CAC.

4.4.4 AAC Box

The AAC box has been designed and manufactured to be as compact as possible. An analysis regarding the variation of the bags dimensions to different sampled volume, was made and is summarized in Appendix C.3. From these results it was shown that the AAC subsystem was able to fit six $3\ L$ sampling bags, provided by RESTEK, together with The Brain that included the pneumatic system and the electronic box. Each bag had a dedicated valve in the Valve Center (VC) to allow emptying and filling processes as well as to close the bag when needed. The bags hung from a bar that was attached to the structure frame by two anchor points on the top. The distribution layout can be seen in Figures 23a and 23b. To ensure a properly built pneumatic system with the minimal leakage risk, all tubes manufactured by Silcotek in the system were exclusively connected to tube fittings which were provided by Swagelok.



(a) Isometric View of the AAC Box. (b) Lateral View of the AAC Box.

Figure 23: Distribution Inside the AAC Box.

The tubes going from the valve centre to the bags were sized as short as possible following science concerns regarding length.

The Brain

The Brain was an essential part of the experiment. It was a three-level structure containing both the pneumatic system and the electronics of the experiment, seen in Figure 24. Its design made it compact enough to both allow a proper thermal control and to fit into the space left next to the sampling bags. It was placed in a corner of the AAC box. Therefore, The Brain took advantage of the vertical space inside the AAC box. It had three different levels: Level 1 - Pump, Level 2 - Valve Center, and Level 3 - Electronics.

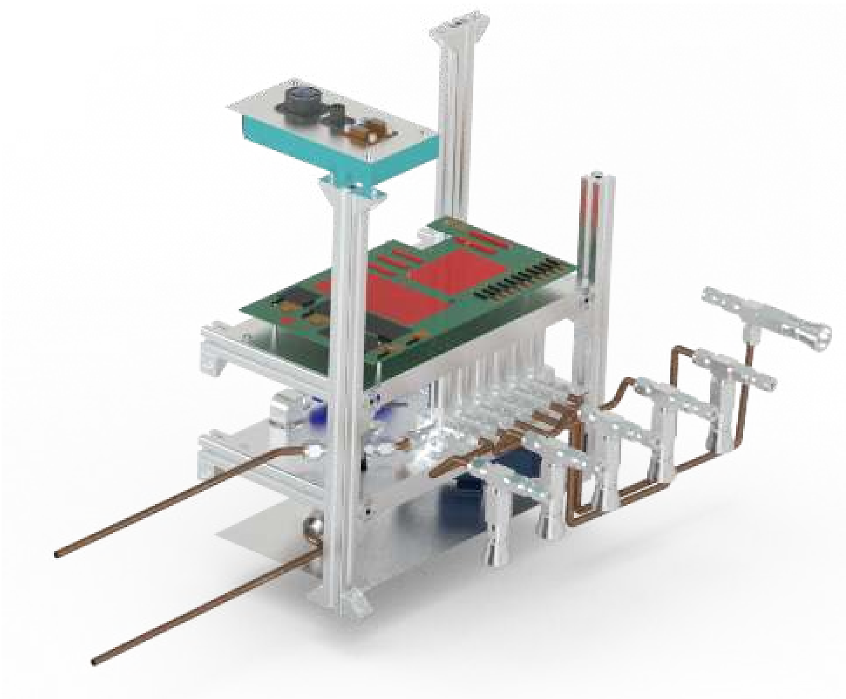


Figure 24: Inside view of The Brain.

Level 1 of The Brain was lying on the base wall styrofoam. It contained the beginning of the pneumatic sampling system. The inlet tube passed through the wall and interfaced with the filter. From here the system continued through the pump provided by KNF, and to Level 2. The reason for having the pump in Level 1 was to have the minimum vibration transmitted to the other components. As explained in section 4.2.1, a piece of styrofoam was added between the pump and the level 1 plate to help mitigate its vibrations. The pump had two heaters on it that were used to regulate its temperature.

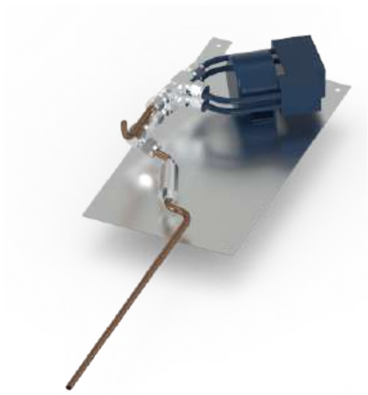
The second level of The Brain was responsible for the distribution of the air to the selected sampling bag. From Level 1, the air passed through the airflow sensor and the static pressure sensor that allowed for monitoring the behavior of the system. The manifold with six solenoid valves, manufactured by SMC, was the main component. From here, the tubes were connected with the bags. A T-Union connection was used just before the bag valve. This interface allowed the pre-flight flushing of the tubes connecting with the valves as well as the post-flight analysis as explained previously.

The flushing valve was responsible to ensure a proper flushing of the system before each sampling period. From the flushing valve, an outlet tube reached the outside environment.

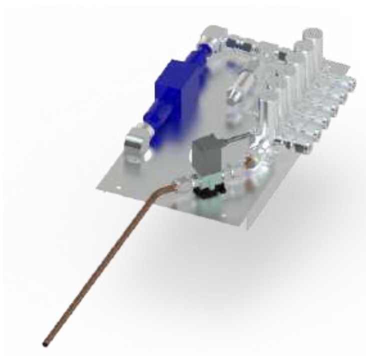
This can be seen in Figure 25b.

The OBC and its external elements were allocated in the third level of The Brain. The PCB was fixed to the aluminum plate by means of 10 standoffs. As shown in Figure 25c, it had a hole, as well as the level plate, to collect all the wires connecting with levels 1 and 2. This level had its own outside top wall which contained the electrical interfaces. The latter allowed the wall to be opened without having to remove all the sockets attached with screws and a female in the inside of the wall. The styrofoam shielding of The Brain had a hole on top to allow the temperature sensors wires to reach the inside of the AAC Box.

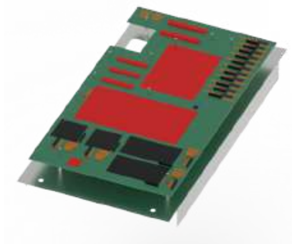
A more detailed content of the components for each level is summarized in Appendix C.4.



(a) Isometric View of Level 1.



(b) Isometric View of Level 2.



(c) Isometric View of Level 3.

Figure 25: Distribution in Each Level.

This distribution allowed easy access to the PCB from the top and provided the physical desired separation between electronics and pneumatic circuit.

The structure of The Brain provided versatility in terms of implementation and construction. It was made out of strut profiles: four bars placed vertically and four bars placed horizontally. The railed bars allowed the possibility to fix all the pieces together and to provide the anchor points for the lateral and top styrofoam shield as well as to fix the whole unit to the box structure bars.

The bulk dimensions of The Brain were 260 mm long, 150mm wide and 290 mm high. If the shielding styrofoam walls were taken into account, the dimensions were 290 mm long, 180 mm wide and 300 mm high. Therefore, accounting for the space the column bars took, each plate had a surface of 258 mm x 158 mm. The distance between levels was variable depending on the components dimensions. Level 1 had a height of 7 cm, Level 2 had a height of 9 cm and Level 3 had 8 cm to the top styrofoam shielding. The Brain with styrofoam shielding can be seen in Figure 26.

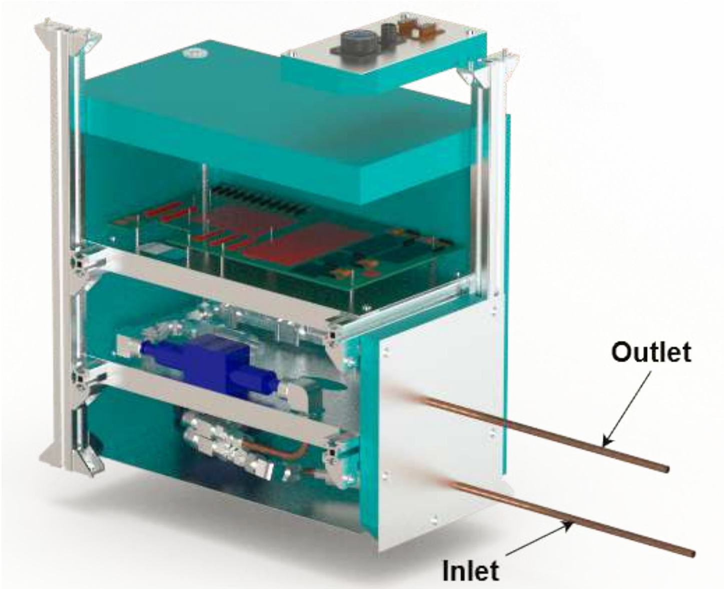


Figure 26: Isometric View of The Brain.

In order to allocate the electrical interfaces required (E-Link, Power Supply and D-Sub Connectors) as well as to allow the tubes of the sampling system to reach the outside environment, the outside facing wall and the top wall were divided in two pieces each. This made it easy to manipulate when having to open the box walls since the little pieces contained the interfaces and the tubes holes, were remained attached. The bottom piece covers Level 1 and 2 while the other, which contained the electrical connections, sat above Level 3. These pieces had the same layout as the main wall.

Shielding and anchor points

The most critical components in terms of required thermal control were inside The Brain. These were the pump and the valves. In order to provide a passive thermal shielding, 3 cm thick removable styrofoam walls were placed in the three walls (top, lateral, and rear) facing the interior of the AAC box, shown in Figure 26. The lateral wall was fixed by means of four bolts that penetrated inside the styrofoam. The top wall was fixed to the rear wall and both were kept in place by means of a stoper. The larger lateral wall, where the tubes from the valves were, was divided in two pieces so it could be removed without having to disconnect the tubes.

The Brain structure was integrated in the AAC box structure to provide the required stiffness to this element.

4.4.5 Pneumatic Subsystem

In order to be able to collect separated samples of air, a pneumatic subsystem was developed and implemented. The schematics and components of this can be seen in Figure 28. The system was formed by almost 100 components located inside The Brain and the AAC Box.

In between these components, the same Sulfinert-treated stainless steel tubing as the ones used for the Inlet/Outlet pipes explained in Section 4.2.1 were chosen.

The schematic for the pneumatic system can be seen in Figure 28. The air was sucked from the outside through the inlet tube (No.1), the lower tube in Figure 27, and it went through the filter (No.2) inside the pump (No.9). From here, and changing to Level 2, it passed through the airflow sensor (No.15), which allowed the airflow rate to be monitored. Thereafter the air passed through the static pressure sensor (No.20) before getting to the six station manifold (No.23). It was in here where the air was directed to the desired bag (No.36) thanks to its dedicated solenoid valve (No.30).

When flushing the pneumatic system before each sampling period, the flushing valve (No.27) was opened so that the outlet of the system was open and new air ran through the main part of the pneumatic system.

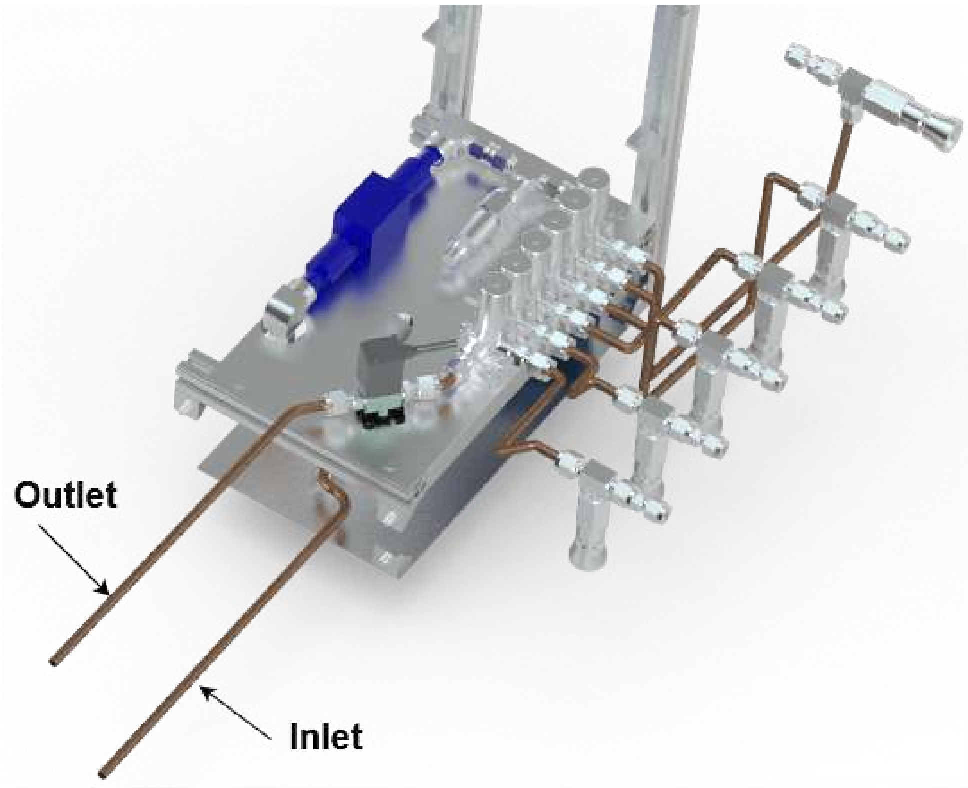
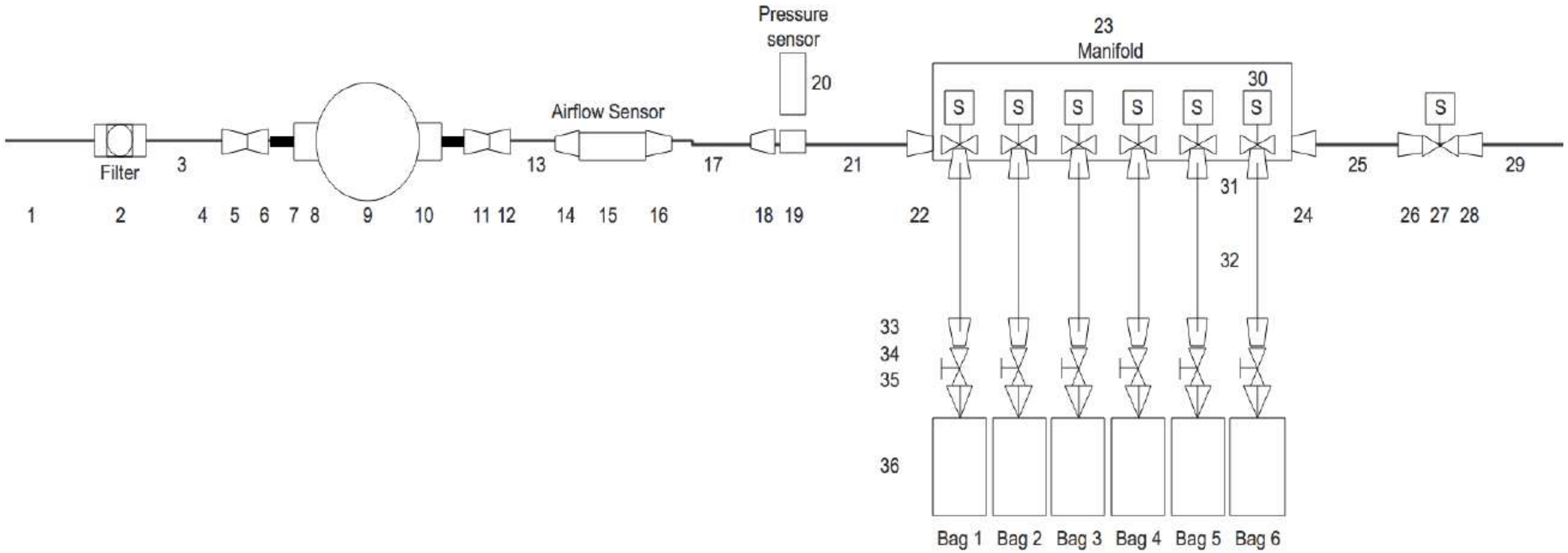


Figure 27: Pneumatic System Top View.



1. Inlet tube (29255): SS OD 1/4" - ID 0,21" ; 180mm
2. Magnesium Filter: Tube OD 1/4"
3. Tube Filter - Pump (29255): SS OD 1/4" - ID 0,21"
4. 90-degree Union (SS-400-9): OD 1/4" - ID 5/32"
5. Tube fitting (SS-401-PC): Tube OD 1/4"
6. Tube fitting reducer (SS-400-R-6M): Tube OD 1/4" to Tube OD 6mm
7. T-Union (SS-6M0-3): Tube OD 6mm
8. Tube inserts (SS-6M5-4M): OD 6mm - ID 4mm
9. Pump: OD 6mm - ID4 (ID 5/32")
10. Tube inserts (SS-6M5-4M): OD 6mm - ID 4mm
11. T-Union (SS-6M0-3): Tube OD 6mm
12. Tube fitting reducer (SS-400-R-6M): Tube OD 1/4" to Tube OD 6mm
13. Tube Pump - Airflow sensor (29255): SS OD 1/4" - ID 0,21"
14. Interface female 90-degree connector (SS-400-8-4): OD 1/4" - ID 5/32" to female 1/4"
15. Airflow sensor (AWM5102VN): 1/4" male - 1/4" male
16. Interface female 90-degree connector (SS-400-8-4): OD 1/4" - ID 5/32" to female 1/4"
17. Tube Airflow sensor - Pressure sensor (29255): SS OD 1/4" - ID 0,21"
18. T-Union to pressure sensor (SS-400-3): Tube OD 1/4"
19. Interface to pressure sensor (SS-4-TA-7-4RG): OD 1/4" - ID 5/32" to female 1/4"
20. Pressure sensor (3500S0001A05E000): male 1/4" - M12 x 1P

21. Tube Pressure sensor - Manifold 1 (29255): SS OD 1/4" - ID 0,21"
22. Interface male 90-degree connector (SS-400-2-4): OD 1/4" - ID 5/32" to male 1/4"
23. Manifold (VV2DW2-H0601N-F-Q): 6 stations, Inlet and outlet female 1/4"
24. Interface male connector (SS-400-1-4): OD 1/4" - ID 5/32" to male 1/4"
25. Tube Manifold - Flushing Valve (29255): SS OD 1/4" - ID 0,21"
26. Interface male connector (SS-400-1-2): OD 1/4" - ID 5/32" to male 1/8"
27. Flushing Valve (VDW22UANXB): inlet and outlet 1/8" female
28. Interface male connector (SS-400-1-2): OD 1/4" - ID 5/32" to male 1/8"
29. Outlet tube (29255): SS OD 1/4" - ID 0,21", 18mm

For 6 bags:
30. Valve (VDW23-5G-1-H-Q): female 1/8"
31. Interface male connector (SS-400-1-2): OD 1/4" - ID 0,21" to male 1/8"
32. Tube Valve - T-Union (29255): SS OD 1/4" - ID 0,21"
33. T-Union (SS-400-3-4TTM & SS-400-3-4TMT): male 1/4" and 2 x Tube OD 1/4"
1 x Quick Coupling (SS-QC4-B-4PF): SS female 1/4"
34. Tube fitting reducer (SS-300-R-4): Tube OD 1/4" to Tube OD 3/16"
35. Bag valve: Tube OD 3/16"
36. Bag: 3L

Figure 28: AAC Pneumatic System Diagram and Components.

4.5 Electrical Design

4.5.1 Block Diagram

The electronics design can be seen in Figure 29 which shows the connections, grounding, voltages, and signals.

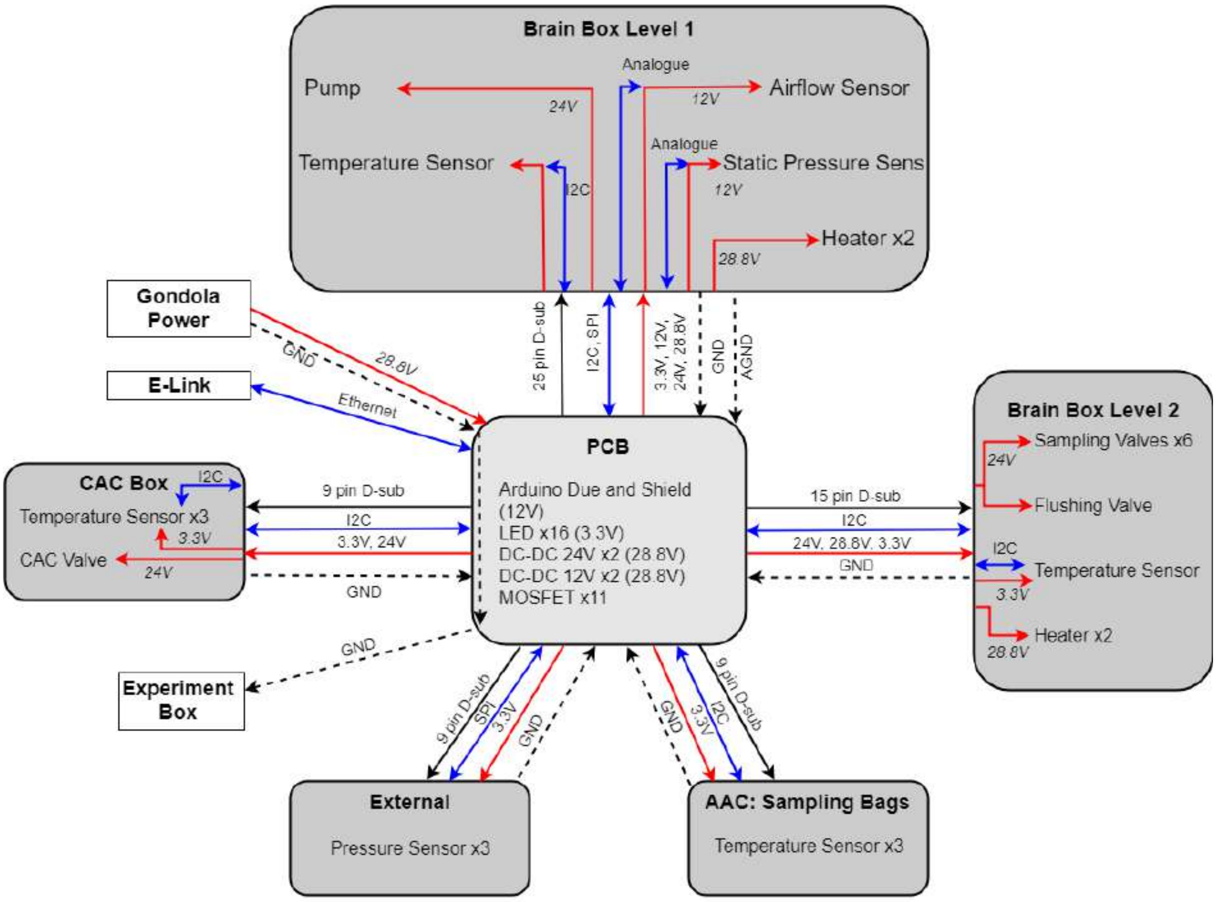


Figure 29: Block Diagram for all Electronic Components Showing the Connection, Signal and Power Connections.

Most of the electronics were located in the Brain inside the AAC box. However, there were six distinct areas:

1. The Brain level 3, where the PCB is located with the Arudino and shield, two 24 V DC-DC, two 12 V DC-DC, 11 MOSFETs and 16 LEDs.
2. The Brain level 2, where the valve manifolds with six sampling valves, the flushing valve, two heaters, airflow sensor, static pressure sensor and one temperature sensor were located.
3. The Brain level 1, where the pump, two heaters and one temperature sensor were located.

4. The AAC box, where 3 ambient temperature sensors were located.
5. The CAC box, where the CAC valve and 3 ambient temperature sensors were located.
6. Outside of the experiment box, where 3 ambient pressure sensors were located.

From the PCB, on level 3, five D-sub connectors were used to connect to the other five areas. Fifteen pin connectors were used for level 1 and level 2. For the CAC box, AAC box sampling bags area, and the external pressure sensors, nine pin connectors were used. In addition there was a connection to the gondola power and gondola E-link.

All of the power distribution was done through the PCB using two 24 V DC-DC and two 12 V DC-DC converters in parallel with a forwarding diode.

- $28.8\,V \Longrightarrow 24\,V$ By DC-DC converters
- $28.8\,V \Longrightarrow 12\,V$ By DC-DC converters

The heaters did not require the voltage to be stepped down and so were powered directly from the gondola battery.

The Arduino was used to control all of the sensors, valves, heaters and the pump from the PCB. Sensors were directly connected to the Arduino. The valves, heaters and the pump were connected via a switching circuit.

The LEDs were used as visual indicators that displayed whether different parts of the circuit are active or not. They gave indications on the status of the valves, pump, heaters, DC-DC converters and Arduino.

Grounding was done following a distributed single point grounding, with all ground connections meeting at a single star point ensuring there were no floating grounds. As not all components were connected via DC-DC converters the experiment was not isolated from the gondola power supply therefore there was a connection between the star point and the gondola ground. The star point was located on the main PCB board which was then grounded to the experiment box. The grounding can be seen in Figure 29 where it is indicated by dashed lines labeled GND. The analog sensors that were used on level 1 in the brain used a separate grounding wire(AGND) onto the main PCB where there was a separate trace connecting to the ground pins on the Arduino board. Furthermore the upper and lower level of the main PCB board were making use of the common grounding plane where possible.

4.5.2 Miniature Diaphragm Air Pump

The pump which was selected was the 850.1.2. KNDC B, Figure 30, which is manufactured by KNF. One of the reasons this pump was selected is that it was successfully flown on a similar flight in the past where it managed to pump enough air at 25 km altitude to have 180 mL remaining at sea level [5]. However, to ensure the pump will operate as intended, several tests were carried out. These tests — 4, 5, 18, 28 and 29, can be seen in Tables 25, 26, 35, 41, and 42.

At sea level conditions the pump was tested and found to have a flow rate of 8.0 L/min and a current draw of 250 mA. The peak current draw was recorded as 600 mA which lasts for less than one second and occurs when the pump is switched on.

From the results of Test 18, in Section 7.3.5, the flow rate was shown to be around 3.36 L/min at the lowest pressure that will be seen in flight. This was in line with requirement D23. The results found in Test 28, in Section O.1, appeared to be inline with the information given by the manufacturer, seen in Figure 31. The highest continuous current draw expected from the pump was 185 mA when the experiment is at 12 km altitude and was expected to decrease as we increase in altitude. While it appeared that the pump increased in current draw at around 6 km there was no plan to sample below 12 km therefore the highest current draw was taken from 12 km. As the pump had a peak current of 600 mA when it switches on, the mosfet and DC-DC power have been chosen to be able to withstand this demand.

Figure 30: KNF 850.1.2. KNDC B Miniature Diaphragm Pump.

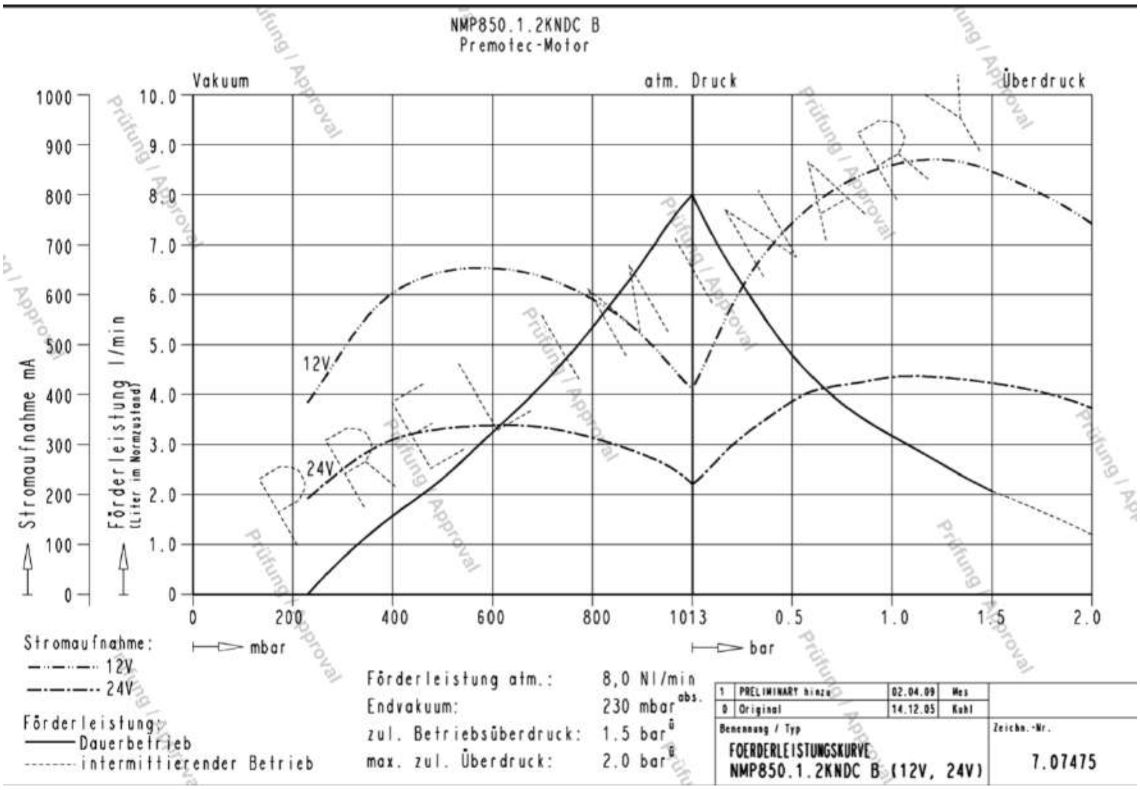


Figure 31: KNF 850.1.2. KNDC B Flow Rate and Current Draw to Pressure Graph.

4.5.3 Electromagnetically Controlled Valves

Filling the sampling bags was controlled by solenoid valves. The solenoid valves selected were model VDW23-5G-1-H-Q, seen in Figure 32, manufactured by SMC. These valves were normally closed through out the experiment with zero power consumption and opened, when given power, to fill up the sampling bags at specific altitudes. In addition one valve was on the CAC, in order to seal the coil at the end of the flight and another at the end of the AAC tubing, flushing valve, in order to flush the system. The valves selected for these are model VDW22UANXB, Figure 32. The CAC valve was opened shortly after take off and remained open the whole flight. This valve was closed shortly before landing. The flushing valve was opened before sampling in order to ensure the air in the tubes was from the correct altitude.

Figure 32: SMC Solenoid Valves, VDW22UANXB on the Left, VDW23-5G-1-H-Q on the Right.

The port size of the valves was 1/8" which is compatible with the gas analyzer. The coil inside can withstand temperatures from -20 to 110 $^{\circ}C$ which was suitable for flight operations at high altitudes. These valves can operate under a maximum pressure drop of 133 Pa. Valves from the same series were flown before to the stratosphere and provided successful results [5] however, the valves were tested at low temperature and pressure to check they still operate as intended. The test results can be seen in Test 4, Table 25 and Test 5, Table 26.

4.5.4 Switching Circuits

The valves, pump and heaters were not powered by the Arduino but they were still controlled by it. In order to allow this control a connection was made for each component to the Arduino with a switching circuit. This switching circuit used eleven MOSFETs, model IRLB8748PBF, Figure 33, to control which components were turned on at which time.

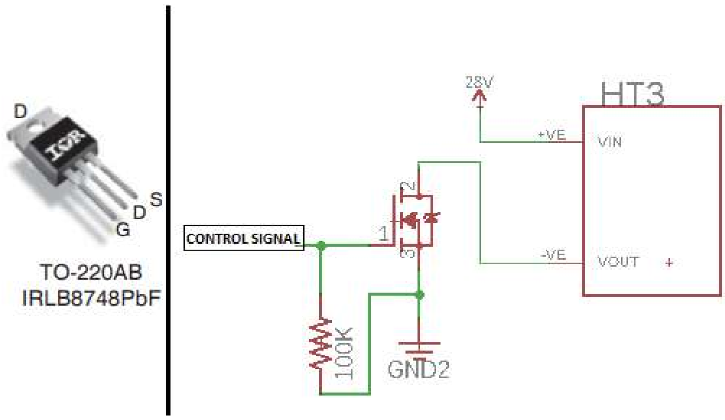


Figure 33: Figure Showing an Image of the 30V,78A,75W MOSFET, Model Number IRLB8748PBF on the Left and the Schematic for the Switching Circuit for One Heater on the Right.

4.5.5 Schematic

The schematics show all the components and how they are connected, the full schematics can be seen in Figure 34. There are four requirements for the the power distribution given below:

- $28.8\,V$ for the heaters.
- $28.8\,V \implies 24\,V$ for the pump and valves.
- $28.8\,V \implies 12\,V$ for the airflow sensor, static pressure sensor and Arduino due.
- $3.3\,V$ for the temperature and pressure sensors.

The voltage available from gondola power is 28.8 V, therefore the heaters were connected directly to the main power supply. For the rest of the components, two 24 V and two 12 V DC-DCs in parallel were used to make sure if one of them fails then the other can take over. The circuitry can be seen in Figure 35. All the valves and the pump were then powered through the 24 V DC-DCs. To step down the voltage from 28.8 V to 12 V to power the airflow sensor, static pressure sensor and the Arduino, two 12 V DC-DCs in parallel were used for redundancy purposes. Finally, to power the temperature and external pressure sensors, 3.3 V is required which is supplied by the Arduino board.

To meet the requirements of the pneumatic subsystem, a static pressure sensor was chosen to measure the pressure inside the tubes and bags. This analogue pressure sensor operated on 12 V so could share the same power line as the airflow sensor and Arduino.

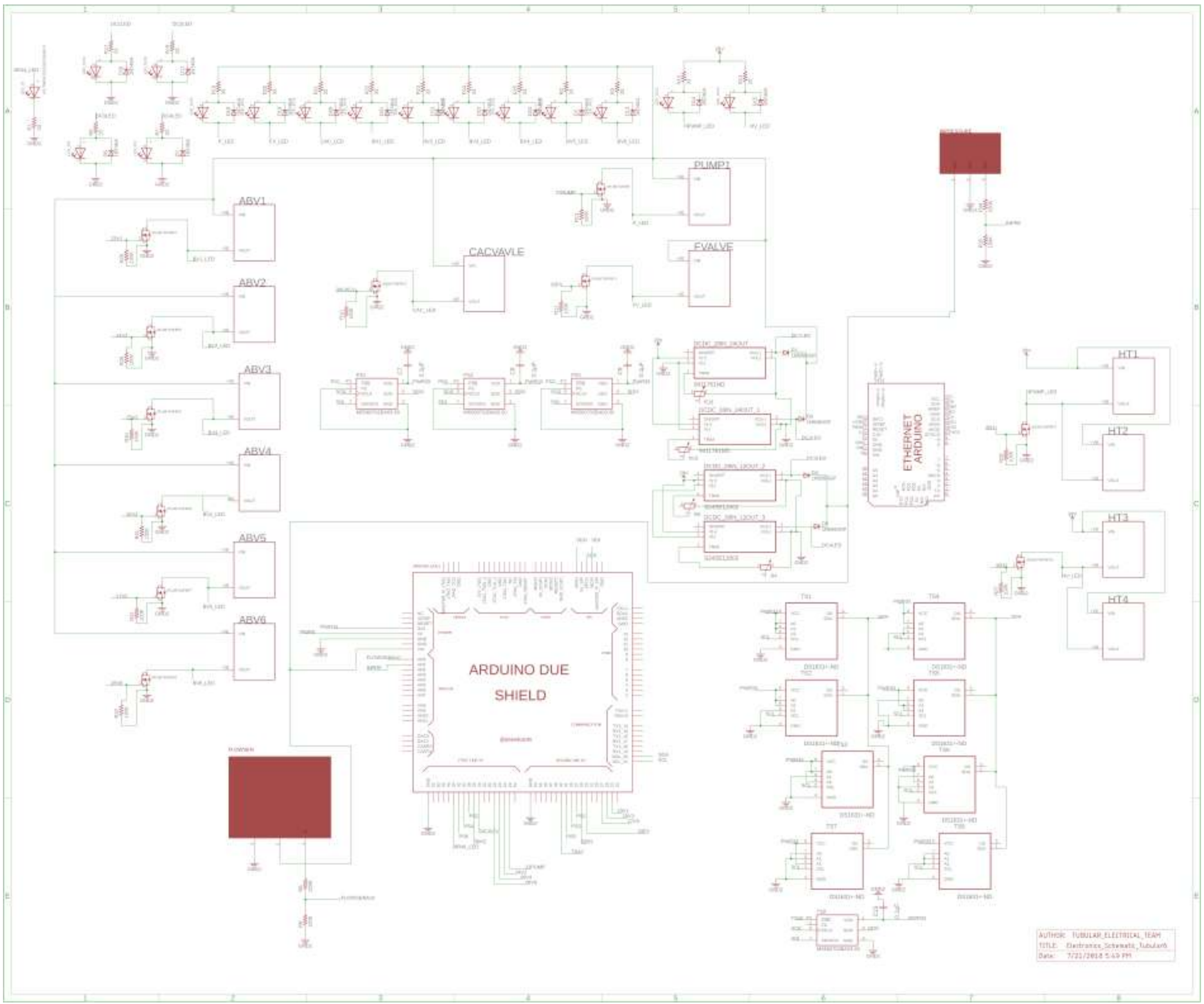


Figure 34: Schematic for All of the Electronics on Board TUBULAR. This can also be Found at https://rexusbexus.github.io/tubular/img/electrical-design-schematics.png

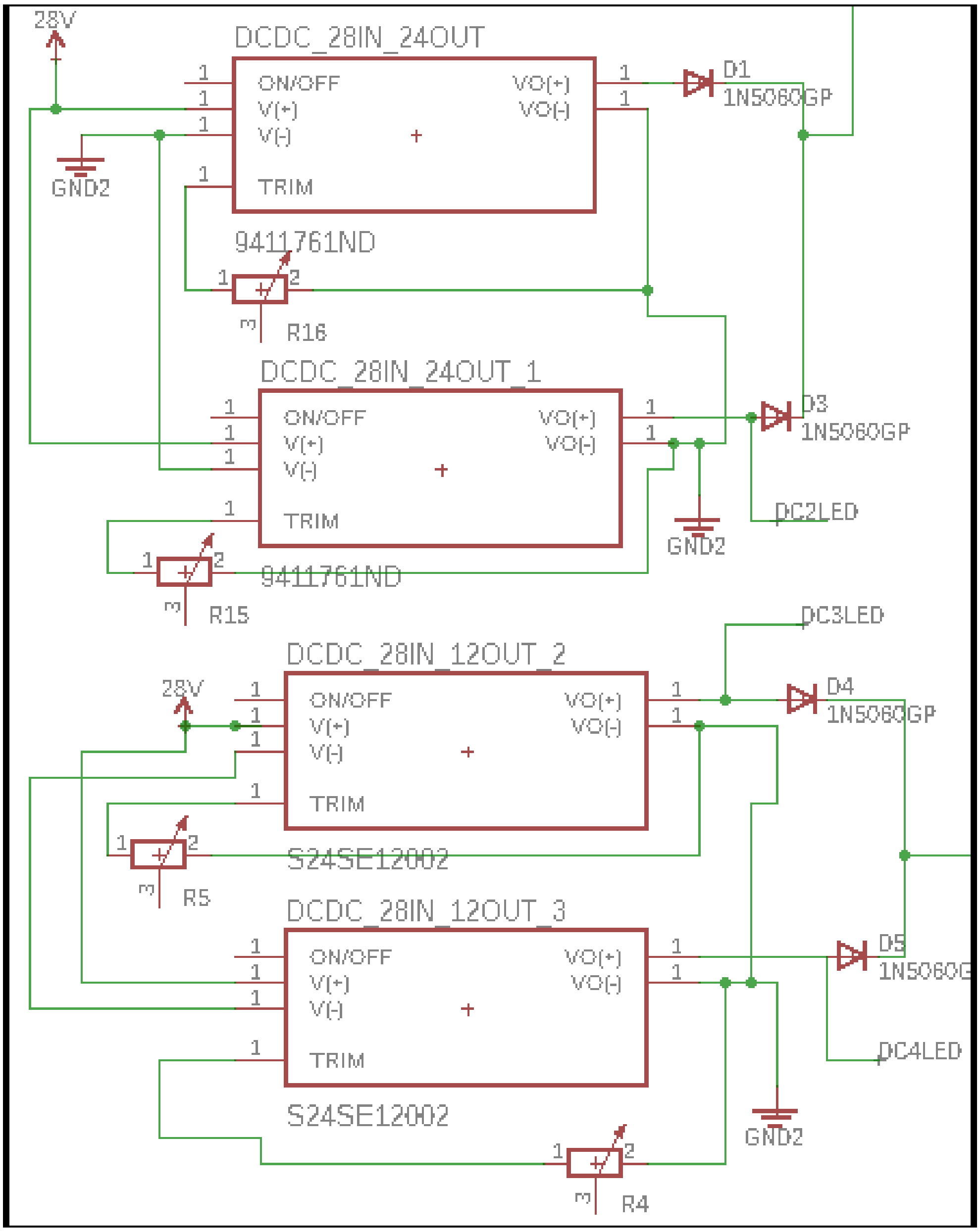


Figure 35: Schematic Showing the DC-DC Redundancy of Both 24 V and the 12 V DC-DC Converters.

4.5.6 PCB Layout

All electronic control circuits were gathered on a single PCB on level 3 of the Brain. The PCB contained the Arduino due, switching circuits, indication LEDs, a temperature sensor, the power system and all necessary connectors. The connectors were divided so that each connector's wires goes to the same level of the Brain to improve cable management. Due to the relocation of components there are some components on level 2, Static pressure sensor and the airflow sensor, which were connected to the level 1 connector. Although this did not produce major problems since both those components have separate connectors on the cable going down to level 1 and does not share any connections with any components on level 1. Thus you could still unplug each level separately since the wires to these two components could just be broken of from the cable loom at the appropriate point. To further improve cable management the shared pins for I2C and SPI were connected to a single pin on each respective D-SUB connector and split up on the respective level. The PCB's components layout can be seen in Figure 36

The PCB was made using Eagle software and fully sponsored by the Eurocircuits for manufacturing. The traces had a width designed to fit the IPC-2221 standards[14] with extra width added. The PCB layout with traces can be seen in in Appendix C.11. On the main PCB the traces were 1.4mm wide for the nets containing components that consumes higher amounts of current and the ones with lower current requirements had a trace width of 0.3mm. On the pressure sensor PCB all traces were 0.5mm wide.

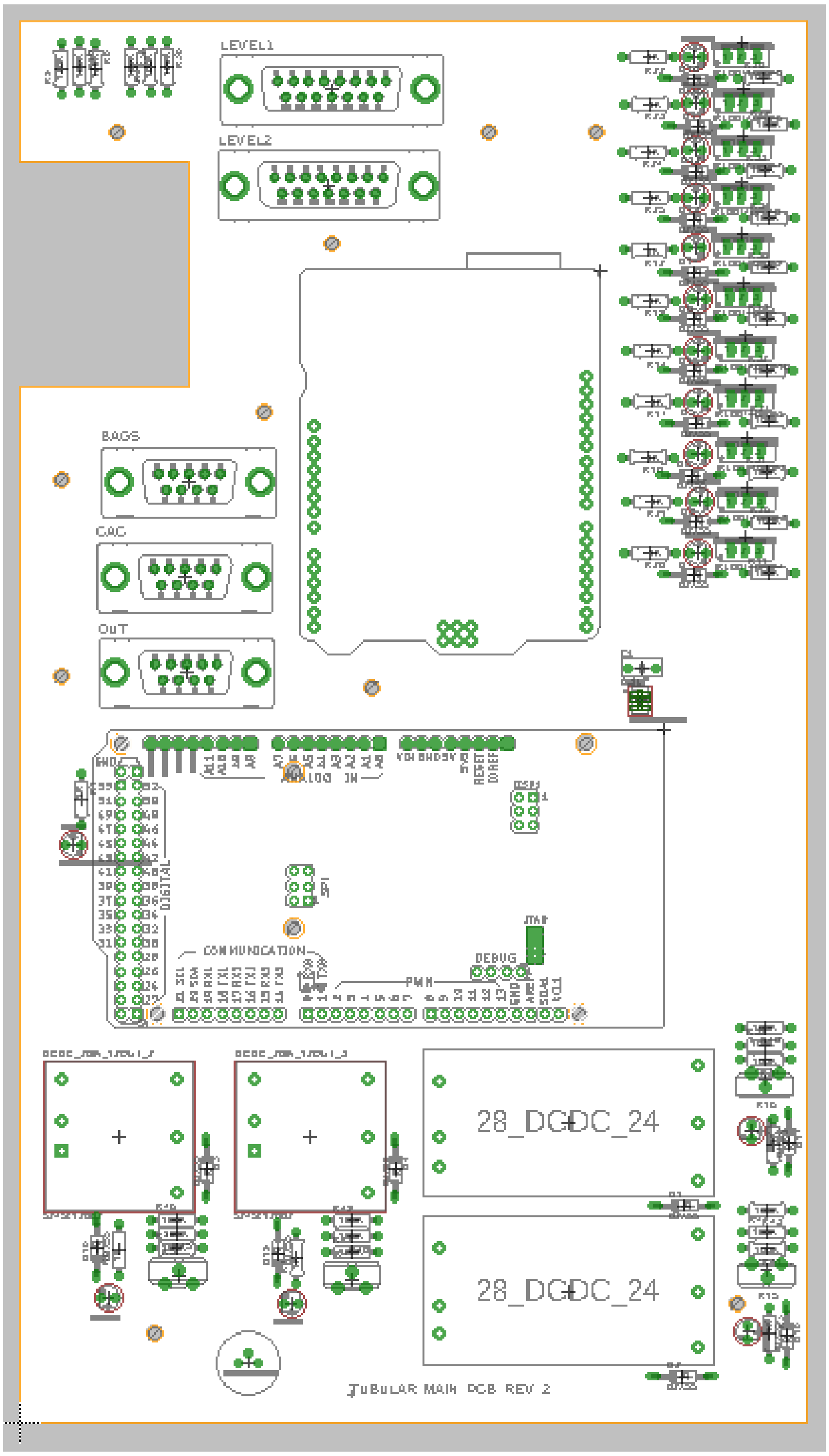


Figure 36: PCB Components Layout

4.6 Thermal Design

4.6.1 Thermal Environment

The experiment experienced a wide temperature range during the flight and it was able to continue operating despite these changes due to the incorporated thermal design. As seen in Figure 37, the coldest point of the flight was between 10 km and 15 km where the air temperature can drop to $-70°C$ outside. During the flight the coldest recorded temperature on the gondola was $-54°C$ during the Ascent and Descent. In addition, launching from Kiruna in late October meant the temperature on the ground could be as low as $-10°C$ but the temperature at the time for launch ended up being around $0°C$. As the component with the warmest lower limit operating temperature had to be kept at a minimum of $5°C$ (E3 in Table73), this required the heaters to be switched on while the experiment was still on the ground.

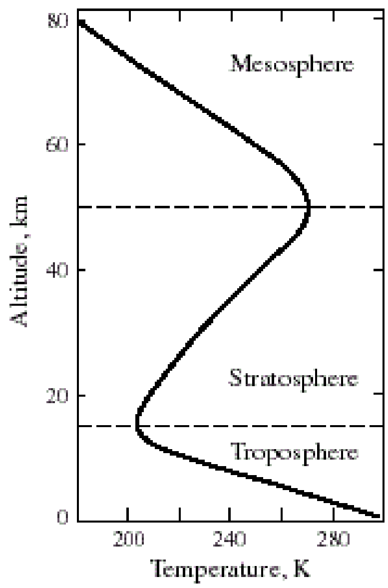


Figure 37: Diagram Showing the Temperature Profile of the Atmosphere [15].

4.6.2 The Critical Stages

The flight had the following critical stages:

- Launch pad
- Early ascent
- Sampling ascent
- Float
- Descent before sampling

- Sampling descent
- Shut down
- Landed, waiting for recovery

These stages were accounted for in further calculations and simulations.

4.6.3 Overall Design

To protect the components against the cold, a thermal control system was designed. Insulation and internal heating both came into play in keeping all the components functional throughout the duration of the flight. The two components with the most critical thermal ranges were the pump and the valve manifold system (E3 and E5 in Table 73). Thermal regulation elements were designed with the main focus having been on the AAC, however a thermal analysis of the CAC can be found in Appendix I under Section I.3.8 where in the CAC box the valve was identified as the critical component in terms of thermal regulation (refer to component E5 in Table 73). It had a current through it throughout the flight, therefore heating it self up.

The main protection against the cold environment in the stratosphere was a passive thermal design by means of insulating layers added to the walls of the experiment. It was comprised of two layers: one outer sheet of aluminum and a thicker sheet of Styrofoam. The main insulating factor was Styrofoam, which significantly reduced the heat exchange between the otherwise exposed experiment box, and also provided shock absorption when the gondola landed after separating from the balloon.

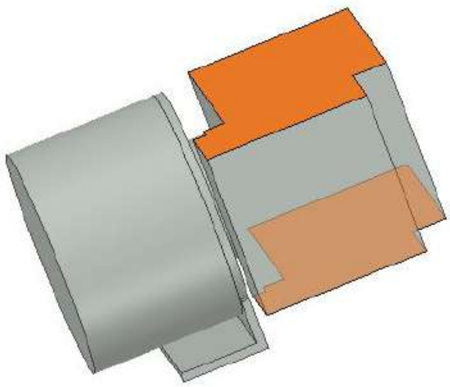


Figure 38: Highlight of the Heater On the Pump.

An active thermal control system consisting of four heaters was also implemented. Two heaters were placed as seen in Figure 38 and a single heater was placed on the flushing valve temperature and one heater was placed on the manifold. To control these heaters, two temperature sensors were also on board, one attached to the pump and the other attached to the manifold. If the reading from one of the temperature sensors was lower than the predefined threshold, then the heater turned on and warmed the component. If it was above the higher threshold the heater turned off.

Simulations in MATLAB (code can be found in Appendix J) were used to determine the average uniform heat inside the experiment. The ANSYS thermal modelling platform was used to the simulate the thermal conditions inside the Brain.

Table 18, below, covers the thermal ranges of the components crucial to the experiment flight from those listed in Section 4.3:

ID	**Components**	**Operating (°C)**		**Survivable (°C)**		**Expected (°C)**	
		Min.	Max.	Min.	Max.	Min.	Max.
E1	Arduino Due	-40	85	-60	150	-15.7	54.0
E2	Ethernet Shield	-40	85	-65	150	-15.7	54.0
E3	Miniature diaphragm air pump	5	40	-10	40	10	34.9
E4	Pressure Sensor	-40	85	-40	125	-15.7	54.0
E5	Sampling Valve (inlet and outlet 1/8”’ female)	-20	68	-20[3]	68[3]	-15	20
E6	Airflow sensor AWM43300V	-20	70	-20[3]	70[3]	-8.8	34.9
E7	Heater $(12.7 \times 50.8mm)$	-200	200	-200[3]	200[3]	-20	36
E9	Temperature Sensor	-55	125	-65	150	-19.7	43
E10	DCDC 24 V	-40	85	-55	125	-15.7	54.0
E12	Micro SD	-25	85	-200[3]	200[3]	-15.7	54.0
E16	MOSFET for current control	-55	175	-55	175	-15.7	54.0
E17	Diodes for DCDC converters	-65	175	-65[3]	175[3]	-15.7	54.0
E18	3.3V LED	-40	85	-40[3]	85[3]	-15.7	54.0
E28	3.3 Zener diode	-65	175	-65[3]	175[3]	-15.7	54.0
E32	Logic CAT5 E-link for inside box	-55	60	-55[3]	60[3]	-34	15
E34	Flushing valve (inlet and outlet 1/8”’ female)	-20	68	-20[3]	68	-7.4	25.8
E35	Valves manifold (outlet 1/8”’ female)	-10	50	-10[3]	50[3]	3	18
E58	PCB	-50	110	-50[3]	110[3]	-15.7	54.0
E59	Pressure Sensor PCB	-50	110	-50[3]	110[3]	-50	39

Table 18: Table of Component Temperature Ranges.

[3]If survivable temperatures were not given, operating temperatures were used as survivable limits.

A complete table of component temperature ranges, which includes static entities (such as wires and connectors) can be found in Appendix I.

4.6.4 Internal Temperature

An enclosed partition of the experiment model was reserved in the corner of the AAC section. This partition took the shape of a rectangular section and was to house all of the electronic components not required to be situated in specified locations throughout the experiment setting, such as the Arduino boards and some of the sensors.

The pump had the most critical temperature range as it was the only component in the experiment that could not operate below freezing temperatures. Failure of the pump meant failure of the entire AAC system. It's data sheet stated that it must always start above $5°C$, or the EPDM diaphragm may be too stiff to start. However, as this type of pump was used successfully on previous high altitude flights, [5], tests were conducted on the pump to find its true performance at lower temperatures and in a low vacuum environment. The AAC valves were also crucial to the experiment's function, as they enabled each and every sampling bag on board to be used. For this reason, while the valves could operate down to $-20°C$, it was desirable to be keep them above this limit whenever in use. The manifold valves in the brain had a minimum operating temperature of only $-10°C$, but simulations proved they would be kept above $0°C$.

As the most temperature-sensitive equipment was all housed within the Brain, it was important to know what heat would be lost through the different heat transfer mechanisms as this would affect the amount of time the heaters had to be active. This was addressed through calculations and simulations to find required insulation. All calculations concerning heat transfer can be found in Appendix I. As a worst-case scenario for heat distribution, it was assumed that *all* of the power dissipated through resistance in the electrical components would reach the marked boundaries of the experiment's walls.

Aluminum sheeting was used as the outer layer of insulation for the experiment and Styrofoam was the inner layer. Aluminum may have among the highest of thermal conductivities, but its arrangement around the Styrofoam, creating one large heat bridge with the inner layer, provided a useful thermoregulatory mechanism [23]. The high ratio between the absorptivity (0.3) and emissivity (0.09) of the material was used to its advantage [23]. Because the ratio for polished aluminum is higher than 1.0, the element would get hotter as it got exposed to the radiation from the sun and the power-dissipating components [16]. The low emissivity coefficient for the aluminum cover meant it would not get significantly hotter than the surrounding ambient temperature, but its increased temperature may have negated some of the heat being lost from the experiment's interior via some of the heat from the aluminum propagating into the experiment, reducing the net heat loss by a small amount. As conservation of power was imperative, the heaters were used sparingly, and instead methods like the use of aluminum for shielding were employed as passive heating. The aluminum layer was be 0.5 mm in thickness, while the Styrofoam layer beneath it span 20 to 30 mm in thickness. The Styrofoam, in contrast to the aluminum had a low thermal conductivity even when compared to similar polymer structures [23]. The Styrofoam handled the bulk of the thermal resistance in keeping the experiment from losing the heat it would have obtained prior to being moved to the launchpad. The aluminum came into play as the experiment rose into colder altitudes and encounters increased sun exposure. While the warmed aluminum had little impact on the experiment's heat loss, this also meant that the experiment's internal temperatures would be prevented from rising to the upper allowed operating limit of the experiment made possible because of the aluminum's low absorptivity of sunlight.

Another heat bridge that was needed was the fastening of the experiment to the gondola. The aluminum frame of the gondola would be colder than the experiment and with normal screws there would be a lot of heat transfer. In this case rubber bumper screws, suggested at CDR, were used to fasten the experiment to the gondola and reduced the heat transfer between the experiment and the gondola.

4.6.5 Calculations and Simulation Reports

The temperature ranges could vary for the different stages but the most critical moment was during the Ascent Phase. According to the thermal analysis, the heaters would not be required during float and descent. During the flight the heaters were still operating for some intervals during the Ascent and Float Phases. All simulation equations and their details can be seen in Appendix I.

An estimate of the temperature in the Brain at the sampling times during the Ascent Phase is visualized in Figure 39. The higher temperature was in the lower right corner where the pump is located. A cooler area exists around the middle of the left edge where no heaters are applied. The legend in the Figure shows the temperature in Celsius.

Figure 39: Cross Section of the Air in the Brain at the Time to Start Sample During Ascent.

In Figure 40 the average temperature of the pump with data from ANSYS is presented. One was simulated with no air in the Brain and the other has air with the same density as sea level. In between the vertical dotted line is when the experiment is above 15km. At 4h in the figure the experiment is launched. It can be seen that the pump should have an average temperature over 5 degrees during the flight.

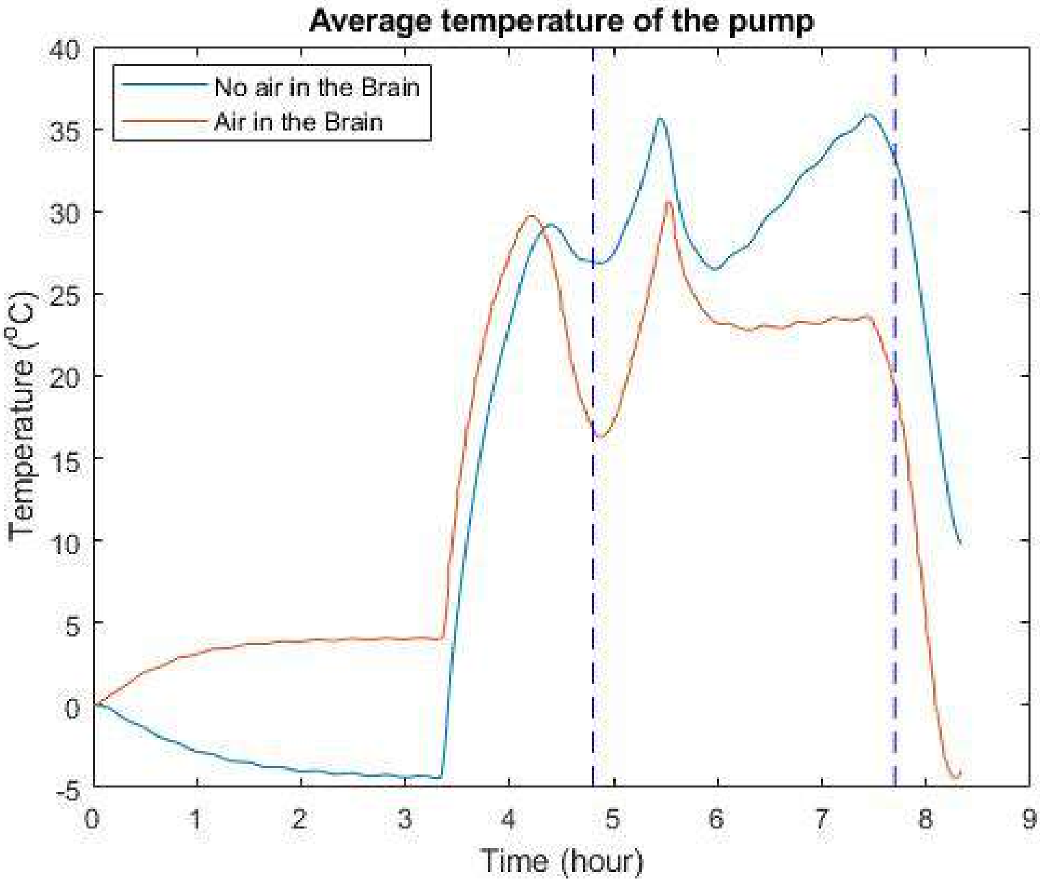


Figure 40: Temperature of the Pump Over a Simulated Flight.

The following two figures in Figure 41 were a visualization of the pump and the manifold at the time in which the AAC sampling begins during ascent.

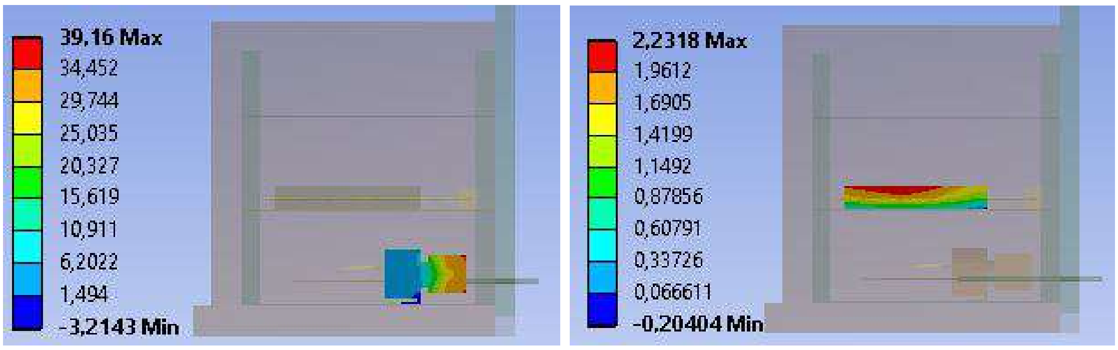


Figure 41: Pump and Manifold at Sampling Time During Descent With No Air in the Brain.

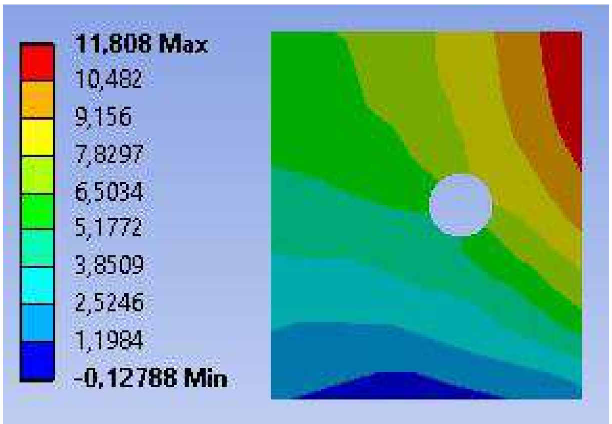


Figure 42: Flushing Valve Prior to Sampling Commencing With No Air in the Brain.

During a worst case simulation that is shown in Figure 41, the four heaters were used for 26.66 Wh in total together over the course of the simulation the figures are from. Only the pump heaters required more time if the outside were colder there was 80 Wh in the power budget table dedicated to thermal control (shown in Table 19). There was therefore an incentive to keep the pump heaters on for a longer time if needed.

Based on the calculations and thermal simulations, it was concluded that the thermal designed passive and active thermal control mechanisms detailed in this section would ensure that the AAC's pump and manifold were in their operating temperature during the entire flight flight. It has been shown that the CAC has a sufficiently adequate thermal design to operate throughout the whole flight.

Thermal testing (Test 5, section 5.3.13) showed that the heaters and the subsequent internal temperature responded as expected from simulations and work as required when heating the critical components. A full 4h test at $-50°C$ was done after the temperature sensor issue had been resolved and it concluded that the experiment would be able to operate thermal wise during the whole flight.

4.7 Power System

4.7.1 Power System Requirements

The Gondola provided a 28.8 V, 374 Wh or 13 Ah battery with a recommended maximum continuous current draw of 1.8 A . However, more typical values which were given were 196 Wh or 7 Ah [8].The experiment should have been able to run on (gondola) battery for more than two hours before launch during the countdown phase and for the entire flight duration, lasting approximately four hours. As a factor of safety, in case of unexpected delays, the experiment was able to run for an additional four hours. Therefore the experiment could be able to run on (gondala) power for a total of 10 hours. For this reason, all the calculations were done using a 10 hour total time [8].

ID	Component	Voltage [V]	Current [mA]	Power [W]	Total [Wh]
E1	Arduino Due	12	30	0.36	4
E3	Miniature Diaphragm air Pump	24	200	7.68	7.68
E4	Pressure Sensor	3.3	1.4	0.032	0.32
E5	Solenoid Valves	24	125	24	39
E56	Static Pressure Sensor	12	8	0.1	1
E6	Airflow Sensor	12	8.3	0.1	1
E7	Heaters	28	180	21	84
E54	12 V DC-DC converter	28.8	8 (1670 output)	0.1 (20 output)	1
E9	Temperature sensor	3.3	0.28	0.011	0.11
E10	24 V DC-DC converter	28.8	37 (2500 output)	2 (60 output)	11.69
-	**Total**	-	1100	38	181
-	**Available from gondola**	-	-	-	374

Table 19: Power Design Table.

The total power consumption 181 Wh, Table 19, was within the limits of the available power. Other calculations for the average, peak, and minimum power values were 24 W, 38 W, and 16 W respectively. In addition the different expected current consumption for the average, peak, and minimum values were 0.64 A, 1.1 A, and 0.22 A respectively.

The 24 V DC-DC converters had 2.5 A output current and 60 W output power with the efficiency of 93%. This fulfilled the peak requirements for both power and current. Moreover, the dissipated power and current across the DC-DCs were calculated as 12.69 Wh and 45 mA respectively and have been added to the total power budget.

4.8 Software Design

4.8.1 Purpose

The purpose of the software was to automate control of the valves so that they will be opened/closed at the target altitude. Moreover, the software stored housekeeping data from sensors, pump, and valves states to the on-board memory storage device. Logging sensor data was necessary in order to determine a vertical profile of the analyzed samples:

> In order to determine the vertical profiles of CO_2, CH_4, and CO from the analysis of sampled air, measurements of several atmospheric parameters were needed [...]. The two most important parameters were the ambient pressure and the mean coil temperature. These parameters were be recorded by the AirCore-HR (High Resolution) electronic data package. Mean coil temperature was obtained by taking the mean of three temperatures recorded by independent probes located at different positions along the AirCore-HR.[17]

Both the ambient pressure and the sampling container temperature were also essential for AAC sampling bags. The temperature data was collected by the sensors near the sampling bags.

The software shall also transmit data to the ground so that the team can monitor the conditions of the experiment in real time. Telecommand was also needed to overwrite pre-programmed sampling scheduled in case of automation failure or to mitigate unexpected changes in the flight path and reached altitudes. It was used to test the system, especially valves and heaters.

4.8.2 Design

(a) Process Overview
The software which ran on the Arduino read from the sensors through the analog, I2C, and SPI interfaces. The sensors provided temperature, pressure and airflow data. The acquired data was time-stamped and stored in the on-board SD card and transmitted via the E-Link System to the ground station. Then according to the pressure/altitude, the software controlled the valves which allowed the air to be pumped inside the bags. Figure 43 visually explain the process flow.

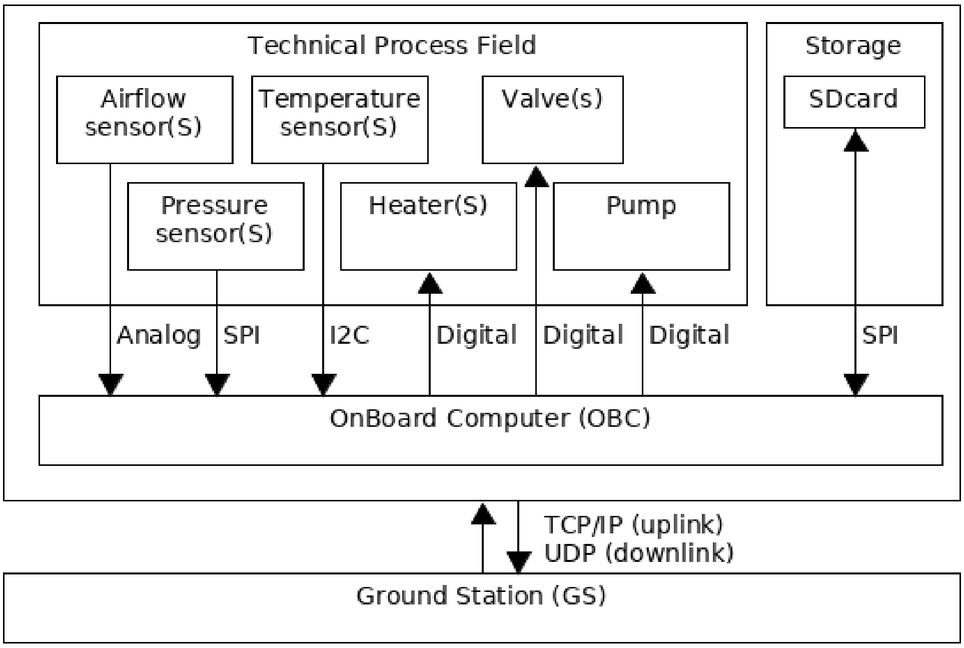


Figure 43: The Process Overview of the Experiment.

(b) General and Safety related concepts
The watchdog timer, which was an electronic countdown timer that causes an interrupt when it reaches 0, was used to avoid failure because of a possible freezing problem in the software. During normal operations, the software set flags when done with their task. When all the flags had been set the watchdog got reset. If any task fails to set the their flag before the watchdog elapses, the system resets. Telecommand was also be used as backup in case the automation fails or otherwise become unresponsive. Telemetry was utilized to transmit housekeeping data and the state of the valves to get confirmation of operation. Rigorous testing was performed during the development of the project and before the launch phase to insure that that the software was capable to control the experiment.

(c) Interfaces
Table 20 demonstrates how the components interacted with the onboard computer (OBC). Components that used SPI, shared MISO, MOSI, and CLK pins on the Arduino board. Each of them was also connected to general pins input output (GPIO) for slave select. Furthermore, components using I2C protocol, shared Serial Data pin (SDA) and Serial Clock pin (SCL).

Components interacting	Communication protocol	Interface
Pressure sensors-OBC	SPI	Arduino SPI and Digital Pins
Temperature sensors-OBC	I2C	Arduino I2C
Airflow sensor-OBC	Analog	Arduino analog pin
Heaters-OBC	Digital	GPIO pins
Air pump-OBC	Digital	GPIO pins
Valve-OBC	Digital	GPIO pins
OBC-microSD Storage	SPI	Arduino Ethernet shield
OBC - E-Link	Ethernet	Ethernet port

Table 20: Communication and Interface Protocols.

Every transmission to/from the ground utilized the E-link connection. The data packet which was used was an Ethernet Packet with a header containing the address of destination, followed by the data, and at the end there was a frame check sequence (FCS). The up-linked data packet had the same structure, with header followed by commands and ended with FCS.

The protocol that had been chosen was UDP for telemetry and TCP for telecommand. The UDP was used to prevent software getting stuck waiting for handshake from the ground if the connection was temporarily lost.

The telecommand contained the following services:

- Changing instrument modes
- Manually control valves, pump, and heaters
- Change sampling schedule

Furthermore, telemetry contained the services below:

- Data from temperature, pressure and airflow sensor
- Current instrument modes
- Instrument housekeeping data (valve, pump, and heater states)

(d) Data Acquisition and Storage
Data was stored on the SD memory card on the Arduino Ethernet Shield using the FAT16 and FAT32 file systems. To minimize data loss in the event of a reset, the same file was written only in a set amount of time before closing it and opened a new file. It was estimated that for the entire flight, all the sensors produced less than 5 MB of data. The sampling rate was fixed at 1 sampling per second.

The data was collected and presented as a matrix, where the first column was the time frame, the following columns were the sensors data. After the sensors data, there was also housekeeping data, that kept track of the valves, and heaters states. However, the size of the housekeeping data was not expected to surpass 20 bits per sampling.

Data was continuously down-linked two times per second and the total telemetry size was less than 4 MB for 10 hours of flight. The telecommand size was on the other hand varied based on how many subcommands were sent each time. If all of the subcommands were enabled, the total size was 128 bytes. Considering the telecommand was not sent more than once per second, the telecommand data rate was 126 bytes/sec.

(e) Process Flow
The process flow can be explained with the mode diagram in Figure 44. The software started with Standby Mode, in which the software got samples from all sensors. The on-board memory card contained the default sampling schedule parameters (when the sampling will start and stop), which was read by the software during initialization of the OBS. This allowed users to change the sampling schedule without changing the internal code. When the software received negative increment of pressure changes, it changed to Normal - Ascent mode, where the software triggered emptying of the CAC's coiled tube by opening the valves. Then, at certain altitudes, air sampling was conducted during Ascent Phase. During Float Phase, no sampling was conducted. The software went to Normal - Descent mode when it detected the increment of pressure was considerably big at which point the software sampled the air by opening the valves for each bag in their designated altitude. Considering that the gondola might not have smooth ascent/descent, the mode changes only happened if the changes exceeded a certain threshold. After analysis and testing, -20 hPa and 20 hPa were considered as the threshold. The experiment went to SAFE mode approximately 1200 m before the landing, and triggered all the valves to be closed. The manual mode was entered with a telecommand and left with another one. If no telecommand was received by the OBC within a certain amount of time it left manual mode and entered into standby mode.

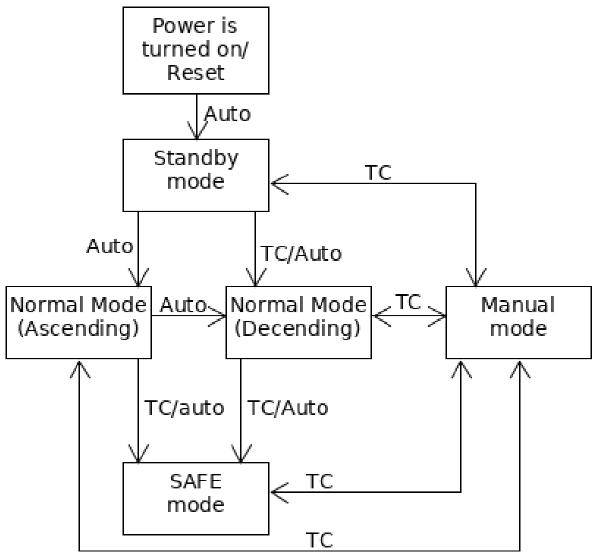


Figure 44: Process Diagram for the Modes.

In the sampling algorithm, it was necessary to keep track of the time because the bag could not be filled fully (it might burst). A simple library was used to keep track of the time from the start of the experiment.

(f) Modularization and Pseudo Code

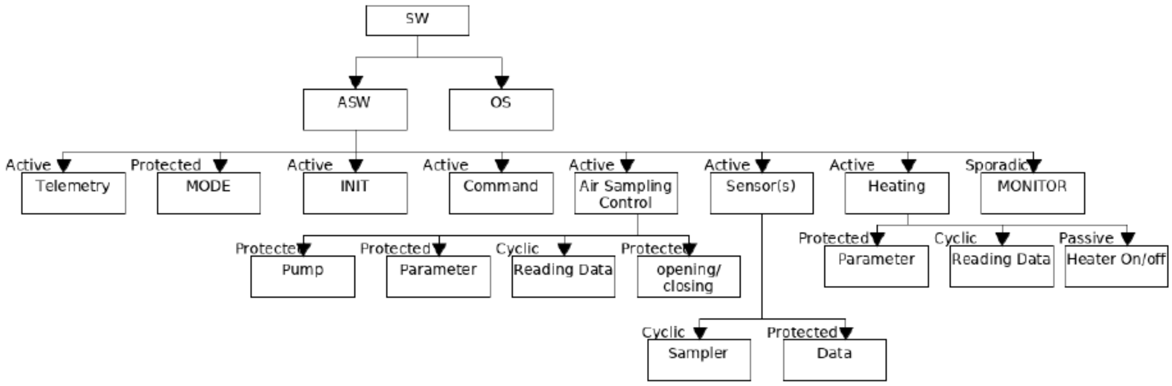


Figure 45: Onboard Software Design Tree.

The software design was produced by using object oriented approach. The functionality of the experiment was divided into several objects and their children. The design tree is shown in Figure 45.

The Telemetry object was responsible to format the sensor/housekeeping data, and to transmit it. MODE was responsible for controlling the five modes of software. INIT initialized the necessary software. COMMANDS read the telecommands and executed their commands. The AIR SAMPLING CONTROL object had the four children objects. The first child was responsible for controlling the pump. The second child contained the parameters for the valves and pump. The third child read the data from the sensors, a fourth child was responsible for manipulating the valves.

The SENSOR object had two children objects. One for sampling the sensors and another for recording and storing the housekeeping data. The HEATER object had three children objects. One for reading the temperature sensor data, another for deciding if the heaters should be turn on/off. And the third child for turning it on/off.

The MONITOR object utilized a watchdog timer that caused an interrupt when it reaches 0. The watchdog did not get fed directly from by the end of the different tasks. Instead the tasks set a flag, if all the flags were set the watchdog got reset and the countdown started from the beginning. If the watchdog timed out before all the flags were set the monitor object reset the board.

Each of the objects interacted with each others fulfilling mutually exclusive interaction. It meant that any shared variables could only be accessed by one object at time. This was important considering the program was fully automatic and to prevent unnecessary data lost. The objects interface diagrams and their sequence diagrams can be found in Appendix C.7 and C.10.

4.8.3 Implementation

The C/C++ programming language was used when programming the platform. Instead of Arduino IDE, PlatformIO IDE was used, other software was used if necessary. The software was functioning autonomously using a real-time operating system. FreeRTOS was chosen as the real-time operating system, which provided a feature to split functionality into several mutual exclusive tasks. These tasks were

- The Sampler task (periodic)
- The Reading task (periodic)
- heaterTask task (periodic)
- telecommand task (sporadic)

Several libraries that were used:

- FreeRTOS_ARM.h (FreeRTOS specially port for ARM microprocessor like Due)
- ArduinoSTL.h (allows standard C++ functionality)
- RTCDue.h (keeps track of the time from the software start)
- Necessary Arduino libraries.
- DS1631.h (self made library)
- MS5607.h (self made library)
- Sensors libraries.

4.9 Ground Support Equipment

The purpose of the ground station was to monitor in real-time the experiment and provide manual override capability in case the experiment failed functioning autonomously. The manual override was able to control all the valves, pump, and heaters. It also provided a service to change the sampling schedule while in flight.

One personal computer was used to connect to the E-Link through the Ethernet port. A GUI was created to display the sensors data and valves, pump states during the experiment. MATLAB GUIDE was used for the development.

The design of the ground station was responsible for receiving and transmitting data over the provided Ethernet connection. Using GUIDE to create a GUI and respective functions as a skeleton, the necessary functionality to receive, transmit and display were built accordingly. The functions were defined for each GUI element.

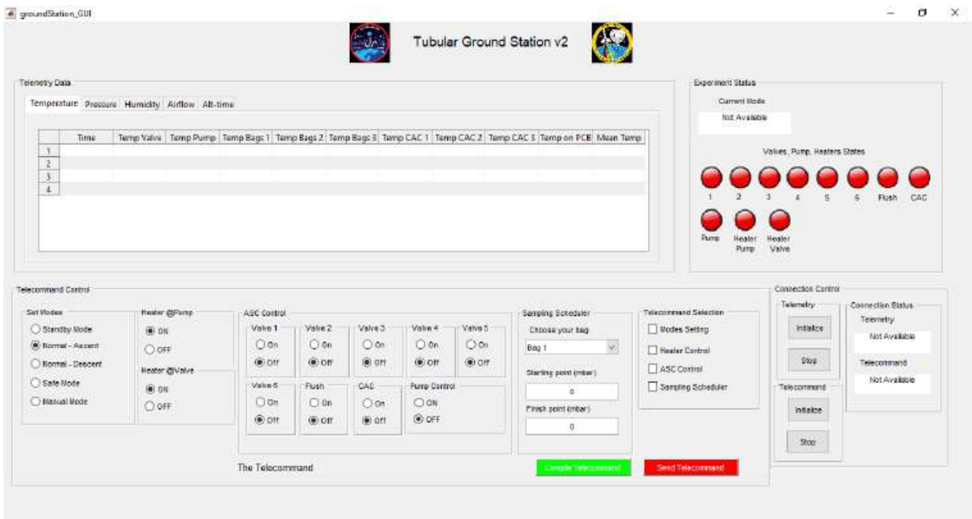


Figure 46: GUI Design for Ground Station Version 2.

Figure 46 shows the design of ground station GUI. Telemetry data was shown in several tables based on the data type. The data was recorded and stored on the computer. The experiment status panel represented the real-time status of the experiments, the red indicator changed to green if the pump or valves were open later on. On the bottom side, the telecommand control panel provided command generation for the experiment. On its right side, the connection control panel had full control of the connections.

5 Experiment Verification and Testing

5.1 Verification Matrix

The verification matrix was made following the standard of *ECSS-E-10-02A*. [21]. This section does not list obsolete requirements. For a complete list of requirements that include obsolete ones, refer to Appendix N.

There are four established verification methods:
A - Verification by analysis or similarity
I - Verification by inspection
R - Verification by review-of-design
T - Verification by testing

ID	Written requirement	Verification	Test number	Status
F.2	The experiment *shall* collect air samples by the CAC.	A, R	-	Pass
F.3	The experiment *shall* collect air samples by the AAC.	A, T	2, 16	Pass
F.9	The experiment *should* collect data on the air intake flow to the AAC.	A, T	24, 31, 32	Pass [4]
F.10	The experiment *shall* collect data on the air pressure.	A, T	24, 31, 32	Pass [4]
F.11	The experiment *shall* collect data on the temperature.	A, T	24, 31, 32	Pass [4]
P.12	The accuracy of the ambient pressure measurements *shall* be -1.5/+1.5 hPa for 25°C.	R	-	Pass
P.13	The accuracy of the temperature measurements *shall* be +3.5/-3°C(max) for condition of -55°C to 150°C.	R	-	Pass
P.23	The sampling rate of the temperature sensor *shall* be 1 Hz.	A,T	10	Pass
P.24	The temperature of the Pump *shall* be between 5°C and 40°C.	A, T	5	Pass
P.25	The minimum volume of air in the sampling bags for analysis *shall* be 0.18 L at ground level.	A, T	16, 17	Pass
P.26	The equivalent flow rate of the pump *shall* be between 8 to 3 L/min from ground level up to 24 km altitude.	T	18	Pass
P.27	The accuracy range of the sampling time, or the resolution, *shall* be less than 52.94 s, or 423.53 m.	T	16	Pass

[4]sensor libraries are available online and used by many users

P.28	The sampling rate of the pressure sensor *shall* be 1 Hz.	A,T	10	Pass
P.29	The sampling rate of the airflow sensor *shall* be 1 Hz.	A,T	10	Pass
P.30	The accuracy of the pressure measurements inside the tubing and sampling bags *shall* be -0.005/+0.005 bar for 25°C.	R	-	Pass
D.1	The experiment *shall* operate in the temperature profile of the BEXUS vehicle flight and launch.[8]	A, T	5	Pass
D.2	The experiment *shall* operate in the vibration profile of the BEXUS vehicle flight and launch.[8]	A, T	9	Pass
D.3	The experiment *shall* not have sharp edges or loose connections to the gondola that can harm the launch vehicle, other experiments, and people.	R, I	-	Pass
D.4	The experiment's communication system *shall* be compatible with the gondola's E-link system with the RJF21B connector over UDP for down-link and TCP for up-link.	A, T	8	Pass
D.5	The experiment's power supply *shall* have a 24v, 12v, 5v and 3.3v power output and be able to take 28.8v input through the Amphenol PT02E8-4P connector supplied from the gondola.	A	-	Pass
D.7	The total DC current draw *should* be below 1.8 A.	A, T	10, 19, 20, 29, 33	Pass
D.8	The total power consumption *should* be below 374 Wh.	A	-	Pass
D.16	The experiment *shall* be able to autonomously turn itself off just before landing.	R, T	7, 10, 31, 32	Pass
D.17	The experiment box *shall* be placed with at least one face exposed to the outside.	R, A	-	Pass
D.18	The experiment *shall* operate in the pressure profile of the BEXUS flight.[8]	A, T	4, 18, 30	Pass
D.19	The experiment *shall* operate in the vertical and horizontal acceleration profile of the BEXUS flight.[8]	A, T	9, 25, 27	Pass
D.21	The experiment *shall* be attached to the gondola's rails.	R	-	Pass
D.22	The telecommand data rate *shall* not be over 10 kb/s.	A, R	-	Pass

D.23	The air intake rate of the air pump *shall* be equivalent to a minimum of 3 L/min at 24 km altitude.	A, T	4, 18	Pass
D.24	The temperature of the Brain *shall* be between -10°C and 25°C.	A, T	5	Pass
D.26	The AAC air sampling *shall* filter out all water molecules before filling the sampling bags.	A, T	17	Pass
D.27	The total weight of the experiment *shall* be less than 28 kg.	R, T	3	Pass
D.28	The AAC box *shall* be able to fit at least 6 air sampling bags.	R	-	Pass
D.29	The CAC box *shall* take less than 3 minutes to be removed from the gondola without removing the whole experiment.	R, T	12	Pass
D.30	The AAC *shall* be re-usable for future balloon flights.	R, T	7, 16	Pass
D.31	The altitude from which a sampling bag will start sampling *shall* be programmable.	A,T	10, 14	Pass
D.32	The altitude from which a sampling bag will stop sampling *shall* be programmable.	A,T	10	Pass
O.13	The experiment *should* function automatically.	R, T	7, 8, 10	Pass
O.14	The experiment's air sampling mechanisms *shall* have a manual override.	R, T	8, 10	Pass
C.1	Constraints specified in the BEXUS User Manual.	I	-	Pass

Table 21: Verification Matrix.

5.2 Test Plan

5.2.1 Test Priority

As shown in Table 22, tests were split into three different levels of priority, low, medium and high. The priority given to each test was dependent on several factors including complexity, amount of external help required and time taken.

Priority Level	Test Number	Classification
High	4, 5, 7, 10, 17	• Requires the use of external facilities which must be booked in advance and could have limited availability. • If a re-test is required the wait time could be on the order of weeks or months. • Testing could potentially break a non-spare component with a long re-order time.
Medium	2, 8, 9, 12, 16, 18, 24, 27, 29, 30	• Requires internal cooperation or multiple parts of the experiment completed to a minimum standard. • If a re-test is required the wait time could be on the order of days. • Testing could potentially break a critical component that would require re-ordering or replacing.
Low	3, 13, 14, 15, 19, 20, 25, 28, 31, 32	• Can be performed by a single department. • If a re-test is required the wait time could be on the order of hours. • Have low or no risk of breaking components.

Table 22: Table Showing the Classification of the Tests.

5.2.2 Planned Tests

The planned tests were as follows:

1. ~~Valves test~~.[5]
2. Data collection test in Table 23.
3. Weight verification in Table 24.
4. Low pressure test in Table 25.
5. Thermal test in Table 26.

[5] Was combined with Tests 4, 5 and 24.

6. ~~Experiment assembly and disassembly test.~~[6]
7. Bench test in Table 27.
8. E-Link test in Table 28.
9. Vibration test in Table 29.
10. Software operation test in Table 30.
11. ~~Power systems test.~~[7]
12. Experiment removal test in Table 31.
13. ~~Ground station - OBC connection test~~ [7]
14. Ground station - OBC parameters reprogram test in Table 32
15. ~~Ground station invalid commands test~~[6]
16. Sampling test in Table 33.
17. Samples' condensation test in Table 34.
18. Pump low pressure test in Table 35.
19. PCB operations test in Table 36.
20. Switching circuit testing and verification in Table 37.
21. ~~Arduino sensor operation test.~~[8]
22. ~~Arduino, pump and valves operation test.~~[8]
23. ~~Pump thermal test.~~[9]
24. Software and electronics integration testing in Table 38.
25. Mechanical structural testing in Table 39.
26. ~~Insulating foam low pressure test.~~[10]
27. Shock test in Table 40.
28. Pump operation test in Table 41.
29. Pump current in low pressure test in Table 42.
30. Sampling bag bursting test in Table 43.
31. On-board software unit test in Table 44.
32. Software failure test in Table 45.
33. Electrical component test in Table 46

[6] Unnecessary test.
[7] Was combined with Test 10.
[8] Was combined with Test 24.
[9] Was combined with Test 5.
[10] Was combined with Test 4.

5.2.3 Test Descriptions

If a non-destructive test was not proceeding as expected *and* it was thought there was a risk to components it would have been aborted. If a test was aborted for this reason an investigation must have been completed to discover why it did not proceed as expected and the issue resolved before a re-test could occur.

Tests took place on the flight model due to budget and time restrictions which prevented a test model from being created. However, if a component was broken during testing spares were available. Tests 4 and 5 did not use the entire model due to size restrictions in the chambers. Instead only critical components were tested.

Test Number	2
Test Type	Software
Test Facility	LTU, Kiruna
Tested Item	Arduino, sensors, valves and pump
Test Level/ Procedure and Duration	Test procedure: Run software for full flight duration and ensure data collection proceeds as expected. Particularly watch for error handling and stack overflow. Test duration: 5 hours. Based on previous BEXUS flight durations.
Test Campaign Duration	2 days (1 day build-up, 1 day testing)
Test Campaign Date	August
Test Completed	YES

Table 23: Test 2: Data Collection Test Description.

Test Number	3
Test Type	Weight Verification
Test Facility	LTU, Kiruna
Tested Item	The entire experiment
Test Level/ Procedure and Duration	Test procedure: Use scales to measure the weight of the entire experiment. Test duration: 1 minute
Test Campaign Duration	1 day
Test Campaign Date	October
Test Completed	YES

Table 24: Test 3: Weight Verification Description.

Test Number	4
Test Type	Vacuum
Test Facility	IRF, Kiruna
Tested Item	Sampling System
Test Level/ Procedure and Duration	Test procedure: Take sampling system down to 5 hPa and verify all systems work. If the size of the vacuum chamber is restrictive testing just the pump with the airflow and pressure sensors, one valve and one bag will suffice. Ensure valves and pump still perform as expected by checking the flow rate with the airflow sensor and visually observing the bag inflating. In addition the insulating foam will be checked to ensure it does not deform when exposed to low pressures. Test duration: 5 hours
Test Campaign Duration	3 weeks
Test Campaign Date	18th July, 20th July, August, September
Test Completed	YES

Table 25: Test 4: Low Pressure Test Description.

Test Number	5
Test Type	Thermal
Test Facility	FMI, Finland, Esrange, Kiruna
Tested Item	The entire experiment
Test Level/ Procedure and Duration	Test procedure: Place experiment in thermal chamber and take the temperature down to at least $-40°C$ but preferably $-80°C$ and verify all systems still work. Make sure that the Brain stays between $-10°C$ and 25$°C$. Test duration: 5 hours
Test Campaign Duration	1 week
Test Campaign Date	3rd-7th September, 29th September, 5th October
Test Completed	YES

Table 26: Test 5: Thermal Test Description.

Test Number	7
Test Type	Verification
Test Facility	LTU, Kiruna
Tested Item	The entire experiment
Test Level/ Procedure and Duration	Test procedure: Assemble entire experiment and ensure all testing points and/or monitors are in place. Run through simulated countdown. Run through simulated launch and flight, include simulated e-link drop outs. Potentially run experiment for longer to simulate wait time before recovery. Test duration: 10 hours
Test Campaign Duration	2 days (1 day build-up, 1 day testing)
Test Campaign Date	September
Test Completed	YES

Table 27: Test 7: Bench Test Description.

Test Number	8
Test Type	Verification
Test Facility	Esrange Space Centre TBC
Tested Item	The entire experiment
Test Level/ Procedure and Duration	Test procedure: Assemble experiment and set up any desired monitoring sensors. Run through simulated countdown. Run through simulated launch and flight, include simulated E-link drop outs. Potentially run experiment for longer to simulate wait time before recovery. Test duration: 5 hours
Test Campaign Duration	2 days
Test Campaign Date	October (during launch campaign)
Test Completed	YES

Table 28: Test 8: E-link Test Description.

Test Number	9
Test Type	Vibration
Test Facility	IRF/LTU, Kiruna
Tested Item	Entire experiment
Test Level/ Procedure and Duration	Test procedure: Mount the experiment on the back of a car/trailer in the same way it will be mounted on the gondola and drive over a bumpy or rough terrain. Afterwards, check the experiment for functionality and structural integrity. Test duration: 2 hours
Test Campaign Duration	1 week
Test Campaign Date	3rd - 7th September
Test Completed	YES

Table 29: Test 9: Vibration Test Description.

Test Number	10
Test Type	Software and Electronics
Test Facility	LTU, Kiruna
Tested Item	Electronics and sampling systems
Test Level/ Procedure and Duration	Test procedure: First ensure communication between ground station and OBC work. Ensure software and electronics responds well to all possible commands for all phases of the flight. Check the electronic currents, voltages at the different stages. Ensure experiment can be shut down manually. Perform simulated flight using previous BEXUS flight data. Test duration: 10 hours
Test Campaign Duration	2 days (1 day build up, 1 day test)
Test Campaign Date	August
Test Completed	YES

Table 30: Test 10: Software and Electronics Operation Test Description.

Test Number	12
Test Type	Verification
Test Facility	LTU, Kiruna
Tested Item	Entire experiment
Test Level/ Procedure and Duration	Test procedure: Mount the experiment as it would be mounted in the gondola. Using only the instructions that will be given to the recovery team a volunteer from outside of the team will remove the CAC box. A timer will be run to check how long it takes, this time should not exceed three minutes. The procedure should be simple and fast and the instructions clear. Test duration: 5 minutes
Test Campaign Duration	1 hour
Test Campaign Date	September
Test Completed	YES

Table 31: Test 12: Experiment Removal Test Description.

Test Number	14
Test Type	Software
Test Facility	LTU, Kiruna
Tested Item	Ardunio, ground station
Test Level/ Procedure and Duration	Test procedure: Ensure ground station can reprogram some parameters on OBC. Perform parameter changes. Test duration: 15 minutes
Test Campaign Duration	1 day
Test Campaign Date	25th August
Test Completed	YES

Table 32: Test 14: Ground Station-OBC Parameters Reprogram Test Description.

Test Number	16
Test Type	Verification
Test Facility	LTU, Kiruna
Tested Item	Sampling System
Test Level/ Procedure and Duration	Test procedure: Once the sampling system has been connected, including the bags, lay or hang the system out on the bench. The valves will be opened and closed in series and the pump switched on and off using the Arduino to control them. The Arduino should be supplied simulated pressure sensor readings so that the system will run the sampling points as it would during flight. The bags will be monitored to check that they are inflating as expected. Airflow and static pressure readings that give the pressure from inside the bags will be used to verify that sampling is occurring properly. Test duration: 3 hours.
Test Campaign Duration	2 days (1 day build-up, 1 day testing)
Test Campaign Date	August
Test Completed	YES

Table 33: Test 16: Sampling System Verification.

Test Number	17
Test Type	Verification
Test Facility	FMI
Tested Item	Sampling bags
Test Level/ Procedure and Duration	Test procedure: All valves, bags and tubes had to be connected. Then the entire system was flushed the same way it will be for the flight. After flushing, the sampling bags were filled with a gas of known concentration. The bags were then left outside for 6, 14, 24 and 48 hours. In total 8 sampling bags were used with two bags for each time duration. After each time duration two bags were removed and analyzed using the Picarro analyzer. The second time the test was repeated 6 sampling bags were tested and left outside for 15, 24, and 48 hours. The concentration of gases found inside the bags were compared to the initial concentration of the air placed in the bags. If the concentration changes then the sampling bags must be retrieved and analyzed before that amount of time has elapsed for the samples to be preserved. Test duration: 3 days.
Test Campaign Duration	5 days
Test Campaign Date	7th-9th May AND 3rd-7th September
Test Completed	YES

Table 34: Test 17: Sampling Bags' Holding Times.

Test Number	18
Test Type	Vacuum
Test Facility	IRF, Kiruna
Tested Item	Pump
Test Level/ Procedure and Duration	Test procedure: Pump shall be placed in a low pressure testing chamber and a bag with a known volume attached to its output. The pump shall then be run at several different pressures that will be encountered during flight. The time taken to fill the bag will be recorded and the flow rate extrapolated. Test duration: 1 day
Test Campaign Duration	2 days (1 day build-up, 1 day testing)
Test Campaign Date	1st - 2nd May
Test Completed	YES

Table 35: Test 18: Pump Low Pressure Test.

Test Number	19
Test Type	Electronics
Test Facility	LTU, Kiruna
Tested Item	Electronics PCB
Test Level/ Procedure and Duration	Test procedure: As PCB board is soldered check using a multimeter for shorts. Check that the circuit operates as intended by checking the voltages and currents at test points using a multimeter. Test duration: 1 hour
Test Campaign Duration	Recurrent
Test Campaign Date	July
Test Completed	YES

Table 36: Test 19: PCB Board Operations Check.

Test Number	20
Test Type	Electronics
Test Facility	LTU, Kiruna
Tested Item	Valves, Arduino, Switching Circuit
Test Level/ Procedure and Duration	Test procedure: Beginning on a bread board the switching circuit will be set up connecting one end to a 3.3 V supply and another to a 24 V supply. It will be checked that turning the 3.3 V supply on and off also turns the valve/heater/pump on and off. The current draws during switching will also be monitored to check that they are in line with what the DC-DC/gondola power that can be provided. Once the circuit is working in this configuration the 3.3V supply will be switched for the Arduino and the 24 V supply to the DC-DC and the test repeated. When the circuit is working on bread board it can then be soldered onto the PCB. As it is soldered onto the PCB each switch should be checked. Finally once all switches are soldered onto the PCB a check should be made on the whole switching system that it turns on and off all components on command. Test duration: Recurrent
Test Campaign Duration	2 months
Test Campaign Date	July and August
Test Completed	YES

Table 37: Test 20: Switching Circuit Testing and Verification.

Test Number	24
Test Type	Verification and integration
Test Facility	LTU, Kiruna
Tested Item	All electronics, ground station and Arduino
Test Level/ Procedure and Duration	Test procedure: Once the electronics is at minimum in a breadboard state it will be tested with the software. This will begin with sensor checks. The Arduino will be connected to the sensors and performance checked. Once the switching circuits have been completed for the valves, pump, and heaters the software which controls how these components turn on and off will be tested. If any of the responses from the electronics are not what was expected from the input from the software then the electronic connections will be checked and the software refined and the test will repeat. These tests will begin on bread board electronics and continue as the electronics are fixed into their final positions. In addition as the software will continue to be developed until 15th September these tests will repeat to ensure that performance continues to be as expected. Test duration: Recurrent
Test Campaign Duration	Until 15th September
Test Campaign Date	Recurrent
Test Completed	YES

Table 38: Test 24: Software and Electronics Integration Testing.

Test Number	25
Test Type	Verification
Test Facility	LTU, Kiruna
Tested Item	Mechanical box structure
Test Level/ Procedure and Duration	Test procedure: The mechanical structure will be tested under different loads to ensure it can withstand the expected stresses and strains during flight regarding different g-loads. This test will consist in a non-destructive static stress test with progressive loads located at the top of the CAC and AAC boxes. Test duration: 2 days
Test Campaign Duration	1 weeks
Test Campaign Date	August
Test Completed	YES

Table 39: Test 25: Structural Test.

Test Number	27
Test Type	Mechanical
Test Facility	LTU, Kiruna
Tested Item	Mechanical interfaces
Test Level/ Procedure and Duration	Test procedure: The mechanical interfaces will be tested under different loads to ensure they can withstand the expected stresses and strains during flight. This is done by dropping the whole box from a certain height with a mattress or soft surface underneath it. Maximum height 1 m. Test duration: 2 hours
Test Campaign Duration	1 day
Test Campaign Date	20th September
Test Completed	YES

Table 40: Test 27: Shock Test.

Test Number	28
Test Type	Electrical
Test Facility	LTU, Kiruna
Tested Item	Pump
Test Level/ Procedure and Duration	Test procedure: The pump will be tested to check its current draw under normal, turn on, entrance covered and exit covered conditions. Test duration: 1 hour
Test Campaign Duration	1 day
Test Campaign Date	24th April
Test Completed	YES

Table 41: Test 28: Pump Operation Test.

Test Number	29
Test Type	Electrical
Test Facility	IRF, Kiruna
Tested Item	Pump
Test Level/ Procedure and Duration	Test procedure: The pump will be tested to check its current draw as the outside air pressure is changed. Test duration: 2 hours
Test Campaign Duration	1 day
Test Campaign Date	4th May
Test Completed	YES

Table 42: Test 29: Pump Current in Low Pressure Test.

Test Number	30
Test Type	Verification
Test Facility	IRF, Kiruna
Tested Item	Sampling Bags
Test Level/ Procedure and Duration	Continuously pump air into the sampling bags until the sampling bags burst. If the tested sampling bag does not burst after 3 minutes of continuous pumping, remove the sampling bag from the pressure chamber and leave at rest to check if it will burst within 48 hours. If bursting occurs in the chamber while the sampling bag is being pump then observe and characterize its impact to assess whether a similar bursting risks damaging the sampling bag's surrounding in the experimental setup. If the bursting occurs during the 48 hours rest period then observe and characterize the damage/rupture on the sampling bag to assess whether a similar bursting risks damaging the sampling bag's surrounding in the experimental setup. Test duration: 3 minutes to 48 hours.
Test Campaign Duration	3 days
Test Campaign Date	1st, 2nd and 4th May
Test Completed	YES

Table 43: Test 30: Sampling Bag Bursting Test Description.

Test Number	31
Test Type	Verification
Test Facility	LTU, Kiruna
Tested Item	On-board software
Test Level/ Procedure and Duration	Test procedure: Unit test cases are build to test the functionality of the software. Test duration: Not Applicable.
Test Campaign Duration	Until software freeze date.
Test Campaign Date	May-September
Test Completed	YES

Table 44: Test 31: On-board Software Unit Test Description.

Test Number	32
Test Type	Software
Test Facility	LTU, Kiruna
Tested Item	On-board software and Arduino
Test Level/ Procedure and Duration	Test procedure: Test failure possibilities in the software. Micro-controller re-sets during auto-mode. Communication loss at inconvenient moments such as when changing mode, when sending a command, when receiving data whilst sampling. Simulate loss of SD card during flight. Test duration: 1 hour
Test Campaign Duration	Recurrent
Test Campaign Date	July and August
Test Completed	YES

Table 45: Test 32: Software Failure Test

Test Number	33
Test Type	Electrical
Test Facility	LTU, Kiruna
Tested Item	Electrical Components
Test Level/ Procedure and Duration	Test procedure: Connect components on breadboard as part of the schematic and test them partwise. Check the resistances required Test duration: 3 hour
Test Campaign Duration	2 weeks
Test Campaign Date	21st-22nd July and 4th-5th August
Test Completed	YES

Table 46: Test 33: Electrical Component Testing.

5.3 Test Results

The results shown here provide the key information obtained from testing. A full report for each test can be found in Appendix O.

5.3.1 Test 28: Pump Operations

It was found that when the power supply was switched on the current went up to 600 mA for less than one second. It then settled to 250 mA. By covering the air intake, simulating air intake from a lower pressure, the current drops to 200 mA. By covering the air output, simulating pushing air into a higher pressure, the current rises to 400 mA.

Therefore the power for each of these conditions was 14.4 W at turn on, 6 W in normal use, 4.8 W when sucking from low pressure, 9.6 W when pushing to high pressure.

5.3.2 Test 18: Pump Low Pressure

The pump was tested at low pressure using a small vacuum chamber down to 10 hPa. Flow rates were recorded from 75 hPa, the expected highest sampling altitude.

The results can also be seen in Table 47 and Figure 47.

	Sampling Altitudes	Ambient Pressure	Actual Flow rate
Ascent Phase	18 km	75.0 hPa	∼3.78 L/min
	21 km	46.8 hPa	∼3.36 L/min
Descent Phase	17.5 km	81.2 hPa	∼3.77 L/min
	16 km	102.9 hPa	∼3.99 L/min
	14 km	141.0 hPa	∼4.18 L/min
	12 km	193.3 hPa	∼4.71 L/min

Table 47: Sampling Altitudes as well as the Corresponding Ambient Pressures According to the 1976 US Standard Atmosphere and the Normal Flow Rates at Each Altitude.

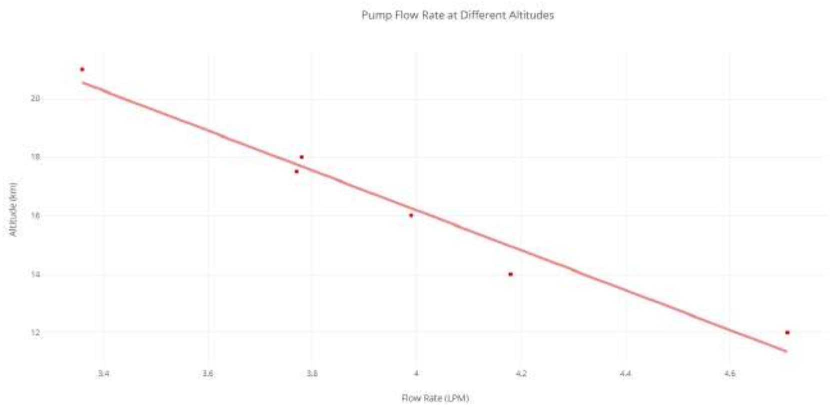


Figure 47: Obtained Pump Performance at Low Pressure.

5.3.3 Test 30: Sampling Bag Bursting

A sampling bag was placed in a small vacuum chamber connected to the pump and the pump was run for 3 minutes with a full bag to see how the bag reacted.

It was found that there are two potential failure modes. The first is a slow leakage caused by damage to the bag seal and the second is a rapid failure of the bag seal leading to total loss of the sample.

It was concluded that, as long as the bags are well secured to the valves at the bottom and through the metal ring at the top, bag bursting during flight would not cause damage to any other components on board. Even during the more energetic burst that occurs from continuous pumping the bag remained fixed to the valve connection and experienced no fragmentation. The consequences of a single bag burst would be limited to loss of data and a disturbance to audio frequencies.

5.3.4 Test 29: Pump Current under Low Pressure

In general it was found that decreasing the pressure, or increasing the altitude, lead to a decrease in pump current draw. The full results can be seen in Table 79.

Altitude (km)	**Pressure (hPa)**	**Into Bag Current (mA)**	**Into Seal Current (mA)**
20	57	140	138
18	68	150	141
16	100	161	146
12	190	185	175
9	300	-	200
6	500	-	242
0	1013	-	218

Table 48: Table Showing How the Current Draw of the Pump Changed With Outside Air Pressure for Two Different Conditions. The First Pumping Into a Sampling Bag and the Second Pumping Into a Sealed Tube.

From the table it can be seen that the current draw is higher during the bag filling than during the sealed case. As the experiment will sample between 11 km and 24 km it can be concluded that the highest current draw will occur during the 11 km altitude sample and can be expected to be around 200 mA.

5.3.5 Test 17: Sampling bags' holding times and samples'

The main objective of this test was to flush eight 1 L sampling bags with nitrogen, the same way it will be done for the flight. After the flushing was done, filled them with a dry gas and placed them outside for 6, 14, 24 and 48 hours. Then analyzed two sampling bags after each time duration and saw if the concentration of gases inside has changed.

The test was done twice as the first test did not give conclusive results.

The general outcome of this test the first time was that the team realized that the flushing of the sampling bags is a very delicate process. This test was also useful to decide that the flushing of the sampling bags should be done with dry gas instead of nitrogen in order to minimize the effects of the nitrogen diluting in the samples.

This test had to and was repeated, using the set-up described in Section 4, with some differences. This time 3L bags were flushed with dry gas and left outside for 15, 24, 48 hours. After the flushing was done, two bags for each time were filled with 0.5 L and 1L of dry gas and left outside. Then they were analyzed and checked if the sample concentrations were the same or close enough with the reference values of the filled dry gas.

The obtained results are shown in Figure 168. The blue points represent the sampling bags with the 0.5L sample, while the red points show the sampling bags with the 1L sample. Sampling Bag No1 with the sampling bag No4 were analyzed after 15 hours. The pair of sampling bags

No2 and No5 were analyzed after 24 hours and the last pair of sampling bags, No4 and No6 after 48 hours.

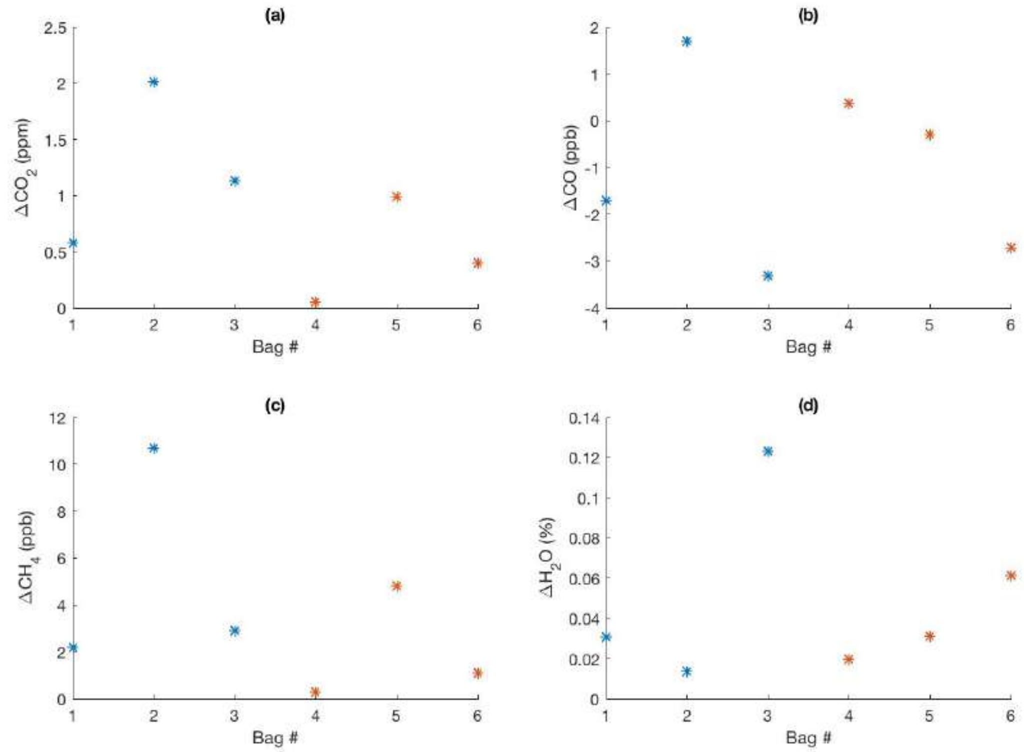


Figure 48: Obtained Variation in Concentration for (a) CO_2 in ppm, (b) CO in ppb, (c) CH_4 in ppb and (d) H_2O in $\%$.

The results were very good in general with the CO_2 concentration differences not higher than 2 ppm. The bags with the 0.5L sample gave bigger CO_2 concentration differences and higher humidity for all the tested times. For the bags that analyzed after 48 hours, the humidity was two times higher for the 0.5L sample compared to the 1L sample. If water goes through the walls of the bags at the same rate for both bags then it is normal that sampling bags with larger amounts of sampled air have lower humidity concentrations. Therefore, for better results, the air left in the sampling bags at sea level pressure must be the maximum possible.

Efficiency of the flushing procedure.

While testing the holding times of the sampling bags, some other relevant tests were performed. A sampling bag was flushed the way it will be flushed before flight, and then analyzed immediately. The Picarro readings were very close with the reference values, which means that the flushing procedure is sufficient. From the results obtained when flushing in May, it was also decided to use dry gas for flushing and not nitrogen which has now been confirmed to work better.

The humidity levels inside the AAC system were also tested and found to be acceptable.

Flushing over night.

In addition to the tests performed for the holding times, it was also tested if flushing a sampling bag the night before and sampling it the next day was affecting the samples. A sampling bag was flushed following the same procedure as before and left sealed over night. The next day it was sampled and left outside for almost four hours. Then it was analyzed and the results were compared with a sampling bag that was being flushed and then immediately sampled. The results were good enough with CO_2 concentrations being higher in the sampling bag which was flushed the night before. A reasonable result since the CO_2 concentration inside a room is higher than outside. Therefore, the team has decided that the flushing of the bags shall be done as late as possible moment before the flight.

5.3.6 Test 4: Low Pressure

Styrofoam

The same vacuum chamber was used as in Tests 18 and 29. The Styrofoam was measured on each side before it was placed in the chamber. It was then taken down to 5 hPa and held there for 75 minutes. It was then removed and the sides were measured again. It was found that there was no significant change in dimensions. The results can be seen in Table 49.

Side	Before (cm)	After (cm)
A	9.610	9.580
B	9.555	9.550
C	9.560	9.565
D	9.615	9.610
E	9.615	9.615
F	9.555	9.550
G	9.605	9.605
H	5.020	5.020
I	5.025	5.025
J	5.015	5.015
K	5.020	5.025

Table 49: Styrofoam Size Before and After Vacuum.

Airflow

After the first airflow in vacuum test failed due to datalogging errors the airflow test was repeated. In this repeated test all of the Brain was placed into the vacuum chamber and one bag attached. It was not possible to attach more than one bag due to space restrictions.

The flow rate seemed to be too low for the rate the bag was inflating in the chamber. It was concluded that the airflow rate displayed is the equivalent airflow at sea level.

Software

With the same set-up as the airflow low pressure testing the software was tested to verify if it was operating as intended and that the conditions for stopping sampling were working.

The software was found to be operating as intended and the stoppers were working.

Temperatures

As it is not possible to complete a thermal vacuum test in addition to the thermal testing temperatures were also monitored inside the vacuum chamber.

The temperature of the CAC flushing valve, pressure sensor, PCB, Pump and Manifold was also monitored with continuous use. After one hour and 48 minutes during the same test as the valve temperature the CAC flushing valve was found to reach 68°C and the pressure sensor was found to reach 39°C. After one hour and 24 minutes during the flow rate monitoring test where the sensors, pump, and one manifold valve were on continuously the PCB temperature sensor was at 43°C, the pump at 42°C and the manifold at 33°C. As the pump will never be on for more than a few minutes at a time there is not any concern that this temperature will ever be reached during flight.

5.3.7 Test 20: Switching Circuit Testing and Verification

The switching circuit has been continuously tested from breadboard to PCB and verified to work at each different step. All valves, heaters and pump can be controlled both manually and automatically by the Arduino. For further details on this test see Appendix O.5.

5.3.8 Test 32: Software Failure

it was found that losing the SD card does not interrupt ground station data, it just means no data will be written to the SD card. However, if you reconnect the SD after removing it will not connect back to the SD card and it as if the SD card has been permanently lost.

The second failure test is how the software handles unexpected reset. The most concerning problem is which bag that will be sampled after the reset. It has been tested that the software could read the current sampling status from SD card and continue where it left off.

5.3.9 Test 31: Unit Test

Unit test was used to test several software non-hardware dependent functionality e.g. translating telecommand, storing measurements data to buffer. The functions were tested for several expected cases and a few bugs were discovered and fixed.

5.3.10 Test 10: Software and Electronics Operation

OBS transmits data to ground station continuously. If connection is lost and later re-established the ground station will continue to receive data from the onboard computer. To send a telecommand after a drop in connection requires a restart to the TCP connection.

5.3.11 Test 14: Ground Station-OBC Parameters Reprogram Test

After the scheduler, a command to change the sampling parameters, is implemented, the scheduler was tested and can change the sampling schedule from ascent to descent. The previous parameters were 56.8 and 36.8. They were successfully changed to 30 and 70. However, the user needs to be careful and has to do the correct calculation for the new parameters.

5.3.12 Test 24: Software and Electronics Integration

The different type of sensors were integrated one at time with the Arduino. The result was all the sensors working without interfering with each other.

5.3.13 Test 5: Thermal Test

A AAC test box out of Styrofoam were put into a freezer at Esrange. Only the bag area were reduced in order to fit. The test were on for 4h and 40min. For 3h 30min the temperature were $-50°C$. During that span it were tested if the heating system worked between the thresholds, flush, sample and try run the pump and let it fall bellow zero while operating. From Figure 49 it can be seen that the pump (pink) and the valve (black) is heating and in their thresholds. It were concluded that everything worked as it should. After 3h 30min the freezer were slowly put to go down to $-60°C$ to try the experiments heating system more.

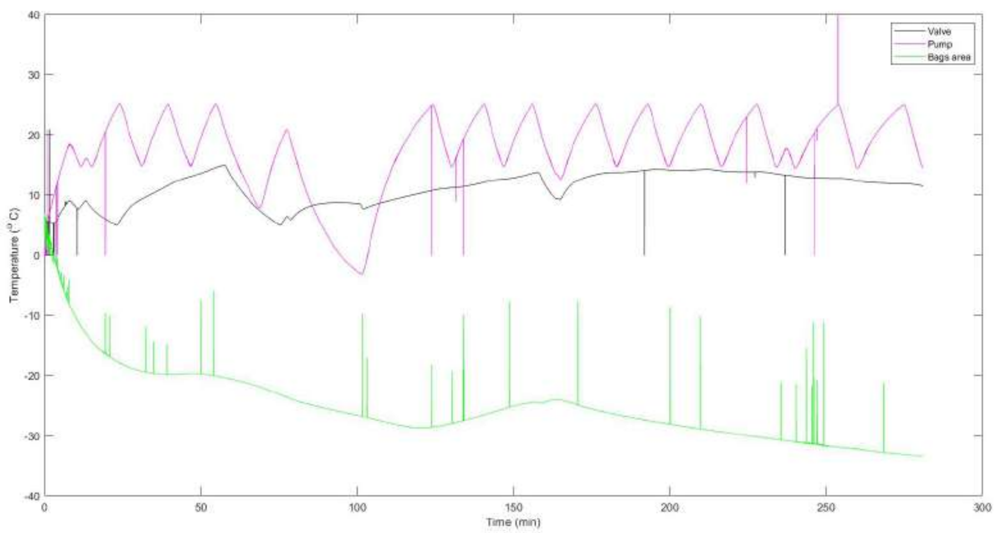


Figure 49: Thermal Chamber Test.

5.3.14 Test 27: Shock test

The entire pneumatic system and electrical system was mounted in the AAC box along with the walls and Styrofoam attached. It was then dropped from a height of approximately one meter three times. Nothing came loose or was damaged after this drop test. All electronics were verified to still work.

5.3.15 Test 9: Vibration test

The entire experiment was placed in the tailgate of a car, while the test was carried out on a 18 km long rough terrain. An emergency brake was also implemented during the test. The experiment's functionality and structural integrity were capable of handling the vibrations and the stopping force. No damages or issues were detected after this test.

5.3.16 Test 25: Structure test

A team member was placed on top of each box's structure. Both the CAC and AAC box was able to fully support the member's weight without showing any instability or deflections. No damages or issues were detected after this test.

5.3.17 Test 33: Electrical Component Testing

The components were tested separately, one by one to double check and determine their power consumption and their functionality. Some tests were also run to determine specific resistances on voltage bridges and pull down resistors for LEDs running at different voltages. These tests gave further insight to the PCB design and the power design. The test results were according to expectations and the design and assembly could continue as planned. There were also some test run for the PCB, which showed that some connections were not done in the way that was planned due to design issues. Theses were solved by adding wires to the PCB instead of redesigning the PCB and order a new one due to time and budget limitations. For further details on these tests see Section O.5.

5.3.18 Test 12: Removal test

For a non team member to perform the removal of the CAC box based on the given instructions, it took that person 6 min and 25 sec. This time is expected to be lower for the recovery team as the items to be unscrewed were not yet clearly marked. One problem that occurred during this test was that the person had problems to distinguishing the CAC from the AAC box. To resolve this the boxes now have clear labels on them.

5.3.19 Test 2: Data collection test

The full software was run in auto mode to check everything operated as expected over a full test flight. At the end of the simulated flight the experiment was to shutdown automatically. This was tested both on the bench and in the vacuum chamber. In the vacuum chamber tests, see Section 5.3.6, the bench test, see Appendix O.5.8 and the thermal test, see Appendix O.4.3 data collection was also monitored. It was found that the physical samples were being collected properly and all the sensors were returning expected data.

5.3.20 Test 7: Bench test

The experiment was run for 5 hours simulating 1 hour on ground, 1.5 hours in ascent, 2 hours in float and 0.5 hours in descent. The experiment was found to be operating as intended at all points. Additionally the temperature sensors have been tested at ambient conditions for over 6 hours and the pressure sensors for over 8 hours. No problems were found with the temperature sensors or pressure sensors on the bench.

5.3.21 Test 16: Sampling test

The system was tested while already mounted as this test was pushed back due to the late arrival of the static pressure sensor.

The Arduino successfully controlled all valves and the pump and through the static pressure and airflow sensor readings alone it could be confirmed if a bag was sampling.

6 Launch Campaign Preparations

6.1 Input for the Campaign / Flight Requirements Plans

The TUBULAR experiment consisted of two boxes with one air sampling system inside each of them. It was positioned with at least one side exposed to the outside.

6.1.1 Dimensions and Mass

The data shown in Table 50 below was based on the design presented in Section 4.4.

	CAC	AAC	TOTAL
Experiment mass [kg]	11.95	12.21	24.16
Experiment dimensions [m]	$0.23\ x\ 0.5\ x\ 0.5$	$0.5\ x\ 0.5\ x\ 0.4$	$0.73\ x\ 0.5\ x\ 0.5$
Experiment footprint area [m^2]	0.115	0.25	0.365
Experiment volume [m^3]	0.0575	0.1	0.1575
Experiment COG position	$X = 23.51\ cm$ $Y = 10\ cm$ $Z = 22.57\ cm$	$X = 29.04\ cm$ $Y = 16.63\ cm$ $Z = 16.2\ cm$	$X = 26.31\ cm$ $Y = 24.99\ cm$ $Z = 19.35\ cm$

Table 50: Experiment Summary Table.

6.1.2 Safety Risks

Table 51 contains the risks of all stages of the whole campaign and project.

Risk	**Key Characteristics**	**Mitigation**
~~Flammable substances~~	~~Styrofoam Brand Foam is oil based and is highly flammable~~[11]	~~Extensive testing will be performed to make sure there is no heat/fire source~~
Sharp or cutting edges	Edges along the experiment	File down edges and cover them with tape
Chemical substances	Chemicals could be exposed after a hard landing	Magnesium Perchlorate filter mechanism is sealed and has been used before without any problem. In case of exposure after a hard impact, use protective goggles and gloves to avoid contact with the eyes and skin. The small quantities used for the experiment will not be a threat for the environment. Magnesium Perchlorate alone is not flammable but may cause or intensify fire in case of contact with combustible material. Therefore, the filter is made of stainless steel, which has high durability.

[11] Styrofoam has been found to only pose a flammable hazard when heated to at least 346°C.[2]

Pressure Vessels	Compressed fluid containers can pose a risk of exploding if damaged	Pressurised gas will be used to flush the system before flight and to calibrate the sensors before analysing our samples after landing. NO pressurised vessels will fly. Three gas cylinders will be brought to Esrange by FMI. The cylinders will contain compressed dry air: Flush gas for the bag sampler: 20L at 140 bar Calibration gas for Picarro: 14L at 130 bar Flush/fill gas for AirCore: 26.8L at 110 bar (there will be 13 ppm CO in the cylinder)

Table 51: Experiment Safety Risks.

6.1.3 Electrical Interfaces

Please refer to Table 52 for details on the electrical interfaces with the gondola.

BEXUS Electrical Interfaces		
E-link Interface: Yes		
	Number of E-link interfaces	1
	Data rate - Downlink	1.58 kbps
	Data rate - Uplink	1.08 kbps
	Interface type (RS232, Ethernet)	Ethernet
Power system: Gondola power required? Yes		
	Peak power (or current) consumption:	38 W
	Average power (or current consumption)	24 W
Power system: Experiment includes batteries? No		

Table 52: Electrical Interface Table.

6.1.4 Launch Site Requirements

The experiment needed some preparations before the flight. For that reason, the team needed a room with a big table to place the Picarro analyzer, with some extra space for all the interfaces between the analyzer and the CAC system, as well as the AAC system. A laptop PC was used to monitor the experiment. Therefore, a desk and a chair were needed for this station. A total of 16 chairs need to be rented: 13 chairs for all members of the TUBULAR Team and an additional three for visiting collaborators from FMI. One power outlet and one Ethernet cable for E-link connection were also essential for the laptop PC.

6.1.5 Flight Requirements

Floating altitude was desired to be as high as possible in order to sample air from the stratosphere both in ascent and Decent Phase. The duration of the Float Phase was not relevant for the experiment performance.

No conditions for visibility were required for this experiment.

With respect to a swift recovery and transport for fast data analysis, a launch time in the early morning hours was favorable.

6.1.6 Accommodation Requirements

The experiment involved two rectangular boxes inside the gondola environment. The only requirement was to allocate the box with at least one face exposed to the outside. The latter also facilitated the fast experiment recovery for the later analysis of the collected samples. The design allowed full adaptability regarding the interface with the gondola's rails, for more details see Section 4.4. The current location of the experiment in Figure 50 is the one arranged with REXUS/BEXUS Coordinators during the Training Week in Esrange.

Figure 50: Example of Experiment Box Accommodation Inside the Gondola.

6.2 Preparation and Test Activities at Esrange

The ground station laptop PC was put in place and set up so it was operational. The communication through E-link with the experiment was tested. The air sampling schedule on the SD card was checked before flight.

In the preparation phase magnesium filters were prepared. These were short (7 cm) lengths of stainless steel tubing that were filled with 2 mg of fresh magnesium perchlorate powder [6]. One was attached to the inlet of the CAC tubing, to ensure that no moisture entered the tubing during testing or sampling. The magnesium perchlorate powder was loosely packed to make sure that the air flow was not blocked. Stone wool was placed at both ends of the tube to prevent the powder escaping from the filter.

The same set-up was used for the AAC. As stratospheric air is dry the risk of moisture entering the system during sampling was very low, however, the team decided to use one to reduce the risk of condensation in the samples after landing.

A few days before the flight while in Finland, the CAC was left inside an oven at 110 °C for 5 hours. At the same time, nitrogen was running through the CAC at a flow rate of 110 ml/min. This was necessary, in order to remove humidity sufficiently through evaporation. Due to the high temperature of the oven and having nitrogen running through the system, it was made sure to remove the humidity from the coil.

Two days before the flight, the CAC went through some preparations. At 19:44 on Sunday 14 of October, the flushing of the coiled tube with fill gas started. A fill gas is air with a spike of a known gas, for example CO. During the flushing process the coiled tube, solenoid valve, the exit tube as well as the magnesium perchlorate filter were flushed separately. In the flushing process the quick connectors at outlet and inlet were connected to the fill gas bottle and Picarro analyzer respectively. The fill gas with a flow rate of 2 L/min was then flown through the coiled tube all the way to the Picarro for 10 minutes. Then, it was left flushing over night at a flow rate of 40.8 ml/min to ensure unknown gases inside the tube would be removed.

After approximately 11 hours, the flushing of the CAC was over at 07:03 on Monday 15 of October. When the flushing procedure was over, Picarro was disconnected while the fill gas remained connected in order to over-pressure the CAC. This ensured that when the other parts were connected ambient air would not enter the system, as the fill gas would be exiting. Leaving the CAC over-pressured also ensured that if the quick connectors were leaking it would be fill gas leaking our and not ambient air leaking in. This was important as there were two days in between flushing and flight. Meanwhile on other hand the solenoid valve and the exit tube were flushed manually for approximately 5 minutes at a flow rate of 2L/min. As a last step, the outlet and inlet were sealed while the gas was still running through the CAC and therefore the CAC was filled and over-pressured. Thereafter it was attached to the remaining components such as the magnesium perchlorate filter, solenoid valve and exit tube. At this stage the CAC was ready for the flight.

A pre-launch checklist in Appendix D.1, was made to assure that the flight preparations will be done thoroughly. This includes a step by step flushing procedure.

For the AAC system, the manifold was cleaned by flushing it with a dry gas as soon as all the pre-flight testing was done. The dry gas is extracted from the fill gas and has slightly different concentrations from the fill gas. The dry gas bottle, the vacuum pump and the AAC system, were all connected as a system to the central valve. The pump and the valves of the AAC system were cleaned by this procedure. The night of the flight, Tuesday 16 of October at 23:00, the flushing of the AAC started. The plugs from the inlet and outlet tubes of the AAC were unscrewed and a male thread quick connector was screwed in to the inlet tube. The dry gas, vacuum pump, and central valve system were then connected to the inlet tube. Flushing started when the central valve was open to dry gas, and dry gas started flowing into the AAC manifold while the flushing valve was open with the rest of the valves closed. The flow rate was at 2L/min and the flushing procedure was going on for approximately 15 minutes. When the central valve was closed, and dry gas stopped flowing into the AAC, the flushing valve was closed. The dry gas bottle, the vacuum pump, and the central valve system were disconnected from the inlet tube. The plug was screwed in to the inlet tube.

In a second phase, using the AAC valves this time, the bags and consequently the tubes between the bags and the manifold, were flushed, again after the pre-flight testing was done. Only one bag was flushed at a time, using the central valve, the flushing valve, and the solenoid valve that matched the bag to control which bag was being flushed. The flushing had to be done three times for each bag to ensure the bags were properly cleaned. It was also important to flush the manifold again, between the flushing of each bag. The dry gas, the vacuum pump, and the central valve system were connected to the outlet tube, while the inlet tube was sealed. Next, the bags manual valves were opened. The flushing valve was kept open during the whole procedure. Only one solenoid valve that matched the bag which was being flushed was opened at a time.

Flushing started when the central valve was open to dry gas, and dry gas started flowing through the AAC manifold, tubes, into the bag. The flow rate was set at 2 L/min. It took 1.5 minutes to fill each bag with 3L of dry gas. Then, the central valve was turned open to the vacuum allowing the bag to empty, for approximately 4.5 minutes. This procedure was repeated for all six bags. After the flushing of one bag was completed, the dry gas, vacuum pump, and central valve system was disconnected from the outlet tube and connected to the inlet tube, allowing the manifold to be flushed, before flushing the next bag, as described above. Then the dry gas, vacuum pump, and central valve system were connected to the outlet tube again, and the next bag was flushed. The whole flushing procedure took approximately 3 hours. After the end of the flushing, when the bags were empty again, the flushing valve was closed. The dry gas, vacuum pump, and central valve system was disconnected from the outlet tube and the plug was screwed in. At this point, the AAC was ready for flight.

The pre-launch checklist in Appendix D.1 was again made sure that all the steps were done correctly and in the right order.

In a laboratory phase, tests under monitored conditions were done to evaluate the overall consistency of the CAC and the AAC. In particular, the CAC and the AAC were tested for leaks at the junctions and at the valves.

Furthermore, the team decided to clean the rest of the experiment's components, such as the Brain, as well as the structure. Doing so, any unwanted particles released during the experiment's construction, was removed avoiding these particles to enter the pneumatic system and thus contaminating the collected samples.

The system was cleaned manually with a dust cloth, using gloves and IPA, given that this cleaning procedure is not of high need as the cleaning of the coil or the bags. Considering that the building of the experiment took place in a lab, which was a clean environment, this action was done once before the flight. This procedure was done just after EAR.

6.3 Timeline for Countdown and Flight

Table 53 was the estimated timeline during countdown and flight.

The desired altitudes in which air samples were to be collected with the sampling bags was associated with specific air pressure values. Thus, the valve operations to sample air during the balloon Ascent and Descent Phases were to be triggered by readings from the ambient pressure sensor. The time values presented in Table 53 merely served as an indicative estimate of when the sampling will take place as sampling was not programmed based on flight time.

Time	Altitude	Events
T-1/2DAYS	0	Start flushing the CAC system overnight for 8H
T-7H	0	Start flushing the AAC system for 3H
T-3H	0	Experiment is switched on external power
T-3H	0	Experiment goes to Standby mode
T-1H	0	Experiment switches to internal power
T=0	0	Lift-off
T+1s	∼5 meter	Experiment goes to Normal - Ascent mode
T+15 min	1 km	Experiment starts to empty the CAC's tube
T+∼1H	∼18 km	Take air samples with AAC until ∼24 km
T+∼1.5H	∼25 km	Float Phase
T+∼2.5H	∼25 km	Cut-off
T+∼2.6H	∼25 km	Experiment goes to Normal - Descent mode
T+∼2.75H	∼20 km	Parachute is deployed
T+∼2.8H	∼19 km	Take air samples with AAC and CAC until 10 km above ground
T+3.5H	∼10 km	Experiment goes to SAFE mode (all valves are closed)

Table 53: Countdown and Flight Estimated Timeline.

Table 54 shows the actual timeline which occurred during flight. The in-flight pump startup failure that occurred is shown together with the relevant actions taken during the in flight analysis of what the problem might have been. The procedure of differential pressure difference is also shown. After attempting to start the pump several times the team recognised already that a likely cause of failure was related to the pump getting enough current, therefore several different procedures were attempted to start the pump. The first was attempting to turn the pump on when everything other than the Arduino was switched off. The second was heating the pump up until the temperature readings showed that the pump was near the top of its operating range and then attempting to turn it on, still with all other components except the Arduino turned off. Neither of these attempts worked. A third idea was to try and start it by creating a pressure difference during the descent, however this was not attempted as it risked the CAC sample. Instead during descent the valves were opened to attempt passive sampling of the bags. However due to the lack of pressure difference between the bag and the ambient pressure this had a low probability of success.

Time	Altitude	Event
T-03:54	0	Go to manual mode for 6 seconds then back to standby
T-03:07	0	Restart Ground Station
T-03:02	0	Groundstation Back Online and reciving data
T-00:00	0	Liftoff and automatic Accent mode
T+00:31	10.1-10.3 km	Pump heater on 12 minutes
T+00:58	18.8-19.1 km	First flushing was suposed to start, instead the Arduino resets and resulting in CAC valve closing
T+00:58	18.8-19.1 km	Enter Manual Mode
T+01:01	19.7-20 km	Flushing Valve opens for 20 seconds
T+01:05	20.9-21.2 km	CAC Valve Reopened
T+01:06	21.2-21.6 km	Pump Heater is on for 6 minutes
T+01:11	22.8-23.1 km	Board Resets Due to attempting to start pump
T+01:12	23.1-23.5 km	Pump Heater is on for 4 minutes
T+01:17	24.4-24.5 km	Board resets due to attempt to start pump and open flushing Valve
T+01:20	24.4-24.4 km	Flush Valve and Valve 1 is turned on to check if it would induce an error
T+01:21	24.4-24.5 km	Float Phase Entered
T+01:32	24.5-24.5 km	Change scheduler to 1 - 2 mbar for all bags as an atempt to make sure the system would not attempt to automaticaly sample
T+01:36	24.4-24.4 km	Pump and Valve Heater on
T+02:10	24.3-24.4 km	Pump and Valve Heater off
T+02:10	24.3-24.4 km	Attempt to start Pump, fails and resets board
T+02:12	24.3-24.3 km	CAC Valve opens and prepare for decent
T+02:55	24.1-24.1 km	Decent Phase Entered
T+03:04	14.9-14.1 km	Valve 2 is opened in an attempt to fill bags with ambient pressure difference
T+03:09	11.0-10.4 km	Valve 2 is closed
T+03:10	10.4-9.8 km	Valve 3 is opened in an attempt to fill bags with ambient pressure difference
T+03:14	7.9-7.3 km	Valve 3 i closed
T+03:15	7.3-6.7 km	Valve 4 i opened in an attempt to fill bags with ambient pressure difference
T+03:16	6.7-6.2 km	Valve 4 is closed
T+03:16	6.7-6.2 km	Accidental closing of CAC valve to early
T+03:17	6.2-5.7 km	CAC Valve accidentally reopens for 1 second.

Table 54: TUBULAR BEXUS 26 Launch Timeline

6.4 Post Flight Activities

6.4.1 CAC Recovery

It was important that the CAC was recovered as quickly as possible. The experiment had been designed so that the recovery team could easily remove the AirCore in the CAC box from the gondola without having to remove the entire experiment. This was to facilitate possible transportation back to Esrange via helicopter.

This quick recovery was important to minimize the length of time in which mixing of the gas occured in the collected CAC sample. The sample should be analyzed within five to six hours after the experiment lands. At PDR it was discussed that the CAC box could be brought back to Esrange on the helicopter instead of the truck. This situation was preferable for TUBULAR Team.

The FMI team arrived at Esrange on the 12th of October with all the necessary equipment for pre-flight flushing and post-flight analysis. Having the FMI team at Esrange gave additional time for them to install and calibrate their lab equipment and also allowed them to proceed faster with the analysis process as soon as the CAC was returned to Esrange.

Detailed instructions were provided on how to remove the CAC box. In addition, instructions were provided to ensure that the system was completely shut down and the valves secured. Shutdown was automated, however, a manual shutdown mechanism was included should the automation fail.

6.4.2 Recovery Checklist

FAST RECOVERY OF CAC

- Check no damage exists to outer structure and no white paste seen in inlet tubes, this confirms no leak and chemicals are SAFE.
- Screw on the three metal plugs provided to the inlet and outlet tubes.
- Unplug the gondola power cord from the AAC box. Circled with RED paint.
- Unplug the E-Link connection from the AAC box. Circled with RED paint.
- Unplug the D-Sub connector from the CAC Box. Circled with RED paint.
- Unscrew 6 screws in the outside face of the experiment. Painted in RED.
- Unscrew 6 screws in the inside face of the experiment. Painted in RED.
- Unscrew 2 gondola attachment points from the CAC
- Remove the CAC Box from the gondola. Handles located at the top of the box.

The regular recovery of the AAC and the non nominal recovery of the experiment is listed in Section D.3 of Appendix D.

6.4.3 Analysis Preparation

In order to efficiently remove ambient air moisture from the analyzer, a calibration gas had to run through the Picarro analyzer, after the gondola cut-off phase until the CAC analysis. The reason this was done was because it was necessary that the readings of the calibrating gas stabilized before starting the analysis and the presence of moisture would have made this stabilization slower. Having the analyzer running for a few hours before the CAC recovery, saved precious time as it made it possible to start the analysis as soon as the CAC was recovered.

7 Data Analysis and Results

7.1 Data Analysis Plan

7.1.1 Picarro G2401

The analyzer that was used is the model Picarro G2401. It uses near-infrared Cavity Ring Down Spectroscopy (CRDS) technology and is capable of measuring four atmospheric trace gases simultaneously and continuously (CO, CO_2, CH_4, H_2O).

The CRDS technique's basic principle is shown in Figure 51. Light from a semiconductor diode laser is used. There is an optical cavity filled with the gas that has to be analyzed and the aim is to determine the decay time of the diode laser light. As it can be seen in Figure 51, the sample gas is introduced in a cavity with three high-reflectivity mirrors. When the laser is shut off, the light that was circulating in the cavity decays with a characteristic time which is measured. If the wavelength of the injected light does not match any absorption feature of any gas in the cavity, the decay time is dominated by mirror loss and it is very long. On the other side, when the wavelength of the injected light is resonant with an absorption feature of a species in the cavity, the decay time is short and decreases as the reciprocal of the species concentration.

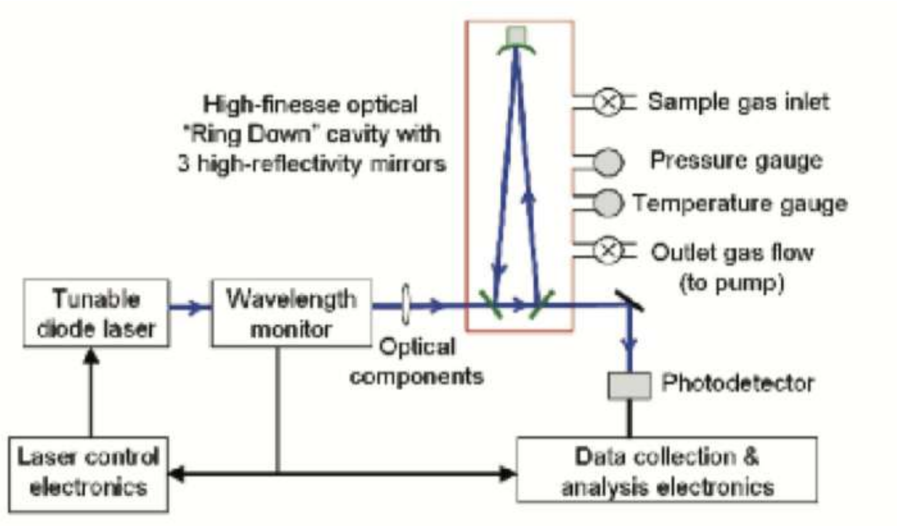


Figure 51: Schematics of CRDS Analyzer Showing Optical Cavity and Sample Gas Flow [19].

Figure 52 shows the back of the analyzer with gas supply, electrical and computer connections. The analyzer can be configured to deliver data in different formats: digital or analogue. When the main power is turned on the analyzer automatically starts, including the Graphical User Interface (GUI).

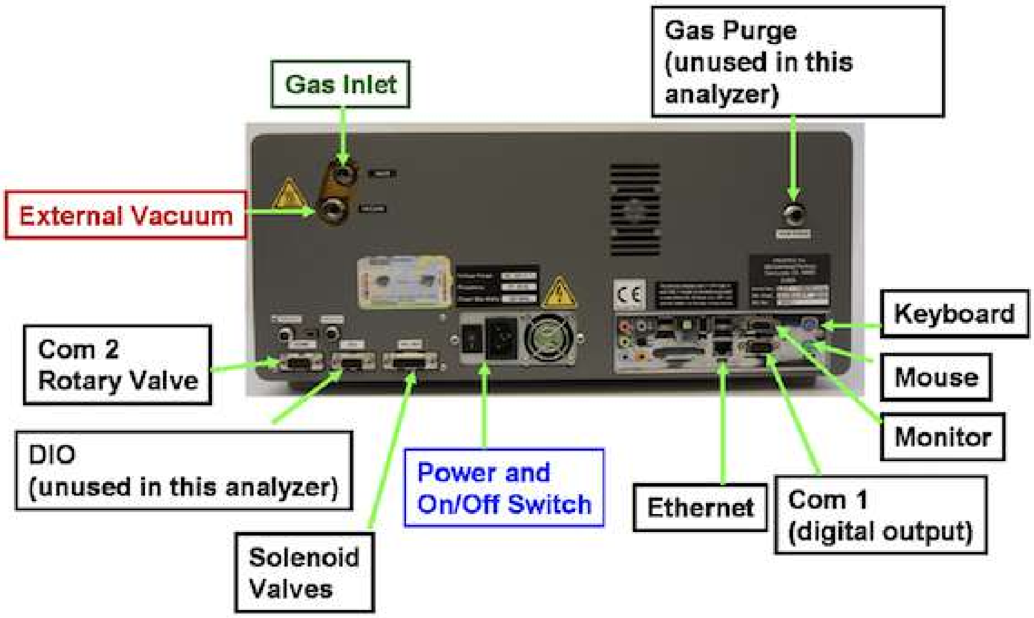


Figure 52: Back of Picarro G2401 Analyzer Showing Gas Supply, Electrical and Computer Connections [12].

Before the Picarro analyzer was ready for analysis, it was necessary to run a calibrating gas through it in order to remove moisture inside and to have stable measurements to compare with. Figure 53 shows the Picarro set up in Esrange. A three way valve controlled which was the gas flowing into the analyzer. The tube labelled as "AIRCORE" was the one to be connected to the sample, either sampling bags or CAC. The tube labelled as "PICARRO" was the one that was going to the Picarro's inlet and the third tube, without a label, was connected to the calibrating gas bottle.This set up allowed easy changing between the samples, dry gas and fill gas with the calibrating gas without getting moisture inside.

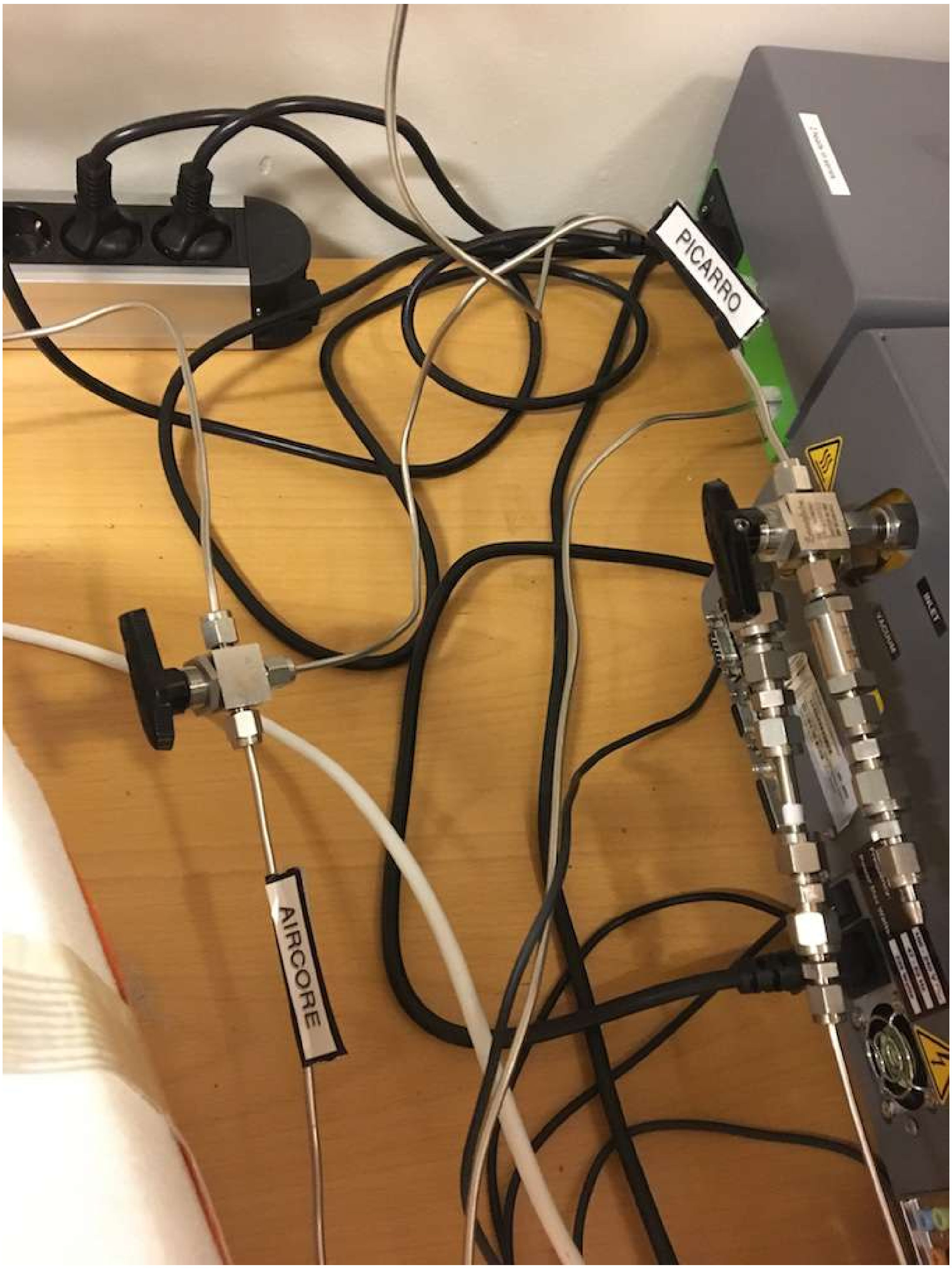


Figure 53: Picarro Set-up Connections at FMI in Sodankylä.

Figure 54 shows the Picarro GUI during analysis. From top to bottom: CO_2 ppm, CO ppm, CH_4 ppm and cavity pressure. These options could be changed during analysis as it only means that those were the ones being displayed. Figure 54 was taken minutes after a change between calibrating gas-sample had been done so a change in the concentrations of CO_2 and

CH_4 can be easily appreciated. The Picarro analyzer did not only give information about the displayed parameters, all the data was saved in a .dat file to be analyzed afterwards. The most relevant logged parameters were time, date, ambient pressure, cavity pressure, cavity temperature, CO concentration, CO_2, CH_4 and H_2O normal and dry concentration.

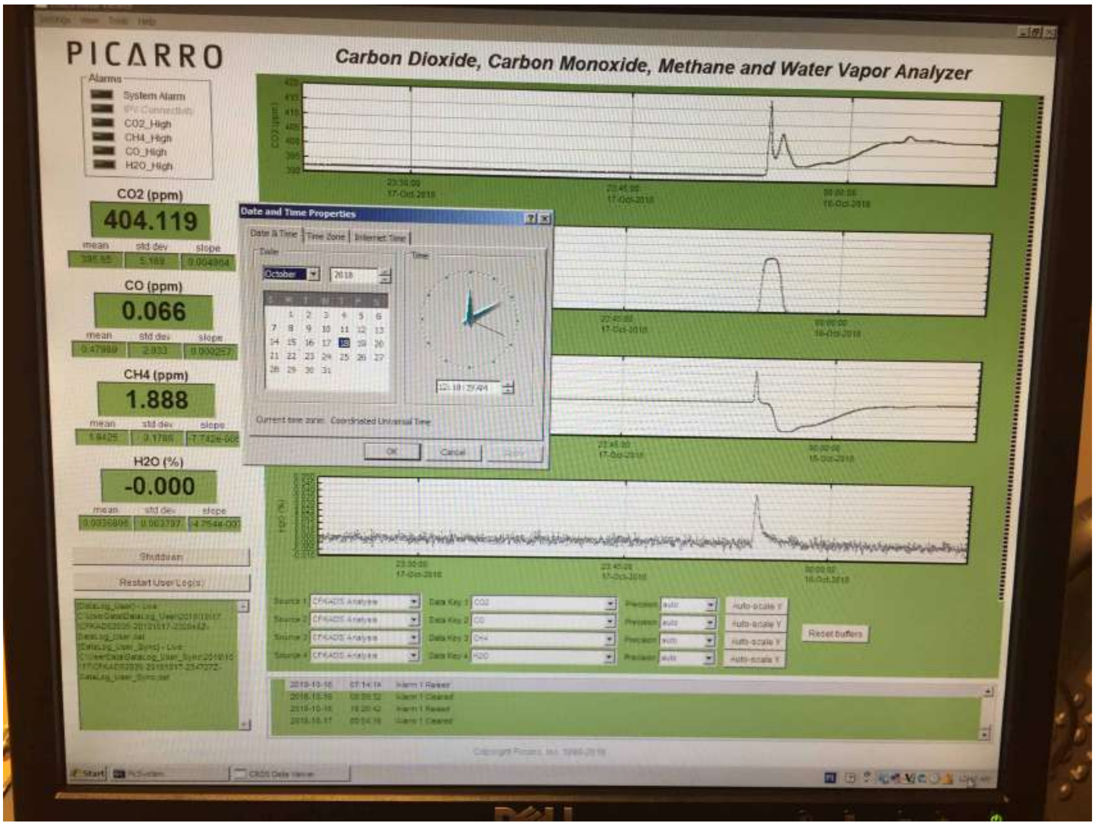


Figure 54: Picarro Graphical User Interface. From Top to Bottom: CO_2 ppm, CO ppm, CH_4 ppm and Cavity Pressure.

7.1.2 Analysis Strategy

Approximately one month after the CAC analysis, the Picarro raw data files were available and the analysis could start. Figure 55 shows some of the Picarro's raw data.

CFKADS2035201810172328482DataLogUser1				
CO	CO2	CO2_dry	CH4	CH4_dry
Number	Number	Number	Number	Number
CO	CO2	CO2_dry	CH4	CH4_dry
1.0668108552E-001	3.9232393059E+002	3.9234542897E+002	1.9111106539E+000	1.9111963531E+000
1.0668085833E-001	3.9233145046E+002	3.9234542897E+002	1.9111106539E+000	1.9111963531E+000
1.0668085833E-001	3.9233145046E+002	3.9235294926E+002	1.9113822791E+000	1.9111963531E+000
1.0846750207E-001	3.9233145046E+002	3.9235294926E+002	1.9113822791E+000	1.9111963531E+000
1.0846750207E-001	3.9233145046E+002	3.9235312283E+002	1.9113822791E+000	1.9114686825E+000
1.0846762246E-001	3.9238323175E+002	3.9235312283E+002	1.9113822791E+000	1.9114686825E+000
1.0846762246E-001	3.9238323175E+002	3.9240490697E+002	1.9105981028E+000	1.9114686825E+000
1.1078946854E-001	3.9238323175E+002	3.9240490697E+002	1.9105981028E+000	1.9114686825E+000
1.1078946854E-001	3.9238323175E+002	3.9240074062E+002	1.9105981028E+000	1.9106678693E+000
1.1078963464E-001	3.9233884933E+002	3.9240074062E+002	1.9105981028E+000	1.9106678693E+000
1.1078963464E-001	3.9233884933E+002	3.9235635621E+002	1.9111390502E+000	1.9106678693E+000
1.2649280980E-001	3.9233884933E+002	3.9235635621E+002	1.9111390502E+000	1.9106678693E+000
1.2649280980E-001	3.9233884933E+002	3.9237185175E+002	1.9111390502E+000	1.9112706050E+000
1.2649258215E-001	3.9235905346E+002	3.9237185175E+002	1.9111390502E+000	1.9112706050E+000
1.2649258215E-001	3.9235905346E+002	3.9239205758E+002	1.9108788424E+000	1.9112706050E+000
1.4323594142E-001	3.9235905346E+002	3.9239205758E+002	1.9108788424E+000	1.9112706050E+000
1.4323594142E-001	3.9235905346E+002	3.9239247037E+002	1.9108788424E+000	1.9110120245E+000
1.4323610030E-001	3.9233578536E+002	3.9239247037E+002	1.9108788424E+000	1.9110120245E+000
1.4323610030E-001	3.9233578536E+002	3.9236920029E+002	1.9110391280E+000	1.9110120245E+000
1.0989252839E-001	3.9233578536E+002	3.9236920029E+002	1.9110391280E+000	1.9110120245E+000
1.0989252839E-001	3.9233578536E+002	3.9236153799E+002	1.9110391280E+000	1.9111417790E+000
1.0989265428E-001	3.9231229559E+002	3.9236153799E+002	1.9110391280E+000	1.9111417790E+000
1.0989265428E-001	3.9231229559E+002	3.9233804669E+002	1.9112500556E+000	1.9111417790E+000
1.3978866978E-001	3.9231229559E+002	3.9233804669E+002	1.9112500556E+000	1.9111417790E+000
1.3978866978E-001	3.9231229559E+002	3.9233963904E+002	1.9112500556E+000	1.9113590662E+000
1.3978845621E-001	3.9232824490E+002	3.9233963904E+002	1.9112500556E+000	1.9113590662E+000
1.3978845621E-001	3.9232824490E+002	3.9235558946E+002	1.9106302135E+000	1.9113590662E+000
1.0928947942E-001	3.9232824490E+002	3.9235558946E+002	1.9106302135E+000	1.9113590662E+000
1.0928947942E-001	3.9232824490E+002	3.9234849692E+002	1.9106302135E+000	1.9107109231E+000
1.0928944145E-001	3.9235474099E+002	3.9234849692E+002	1.9106302135E+000	1.9107109231E+000
1.0928944145E-001	3.9235474099E+002	3.9237499437E+002	1.9107600927E+000	1.9107109231E+000

Figure 55: Picarro Raw Data Showing the Concentrations of CO, CO_2, and CH_4 all in ppm.

For the analysis purposes, the program MATLAB was used. Several steps were required to accurately place the Picarro measurements on a vertical scale in order to retrieve the vertical profiles. The dry mole fractions of CO_2 and CH_4 provided by the Picarro were used. The reason behind that was because they were automatically corrected by the instrument for a combined effect of dilution and line broadening caused by water vapor.

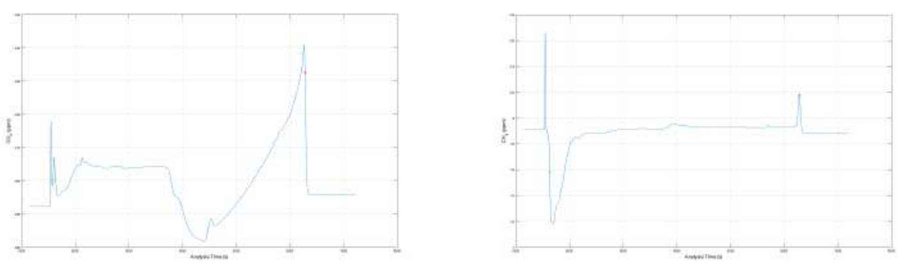


Figure 56: Picarro Analysis of the CAC sample from the BEXUS 26 flight. Left: CO_2 Mixing Ratios as a Function of the Analysis Time in Seconds; Right: CH_4 Mixing Ratios as a Function of the Analysis Time in Seconds.

Figure 56 shows an example of CO2 and CH4 mixing ratios measured by the Picarro instrument during the BEXUS 26 campaign. In order to extract the measurements corresponding to the sampled air, the top and the bottom of the profiles needed to be defined. The top of the CAC sample was considered to be at midpoint of the transition in concentration between the push gas and the remaining fill gas. This point is marked with a green star in Figure 56. The bottom of the profile was defined at midpoint on the transition of concentration between push gas and sampled air. It is marked with a red star in Figure 56.

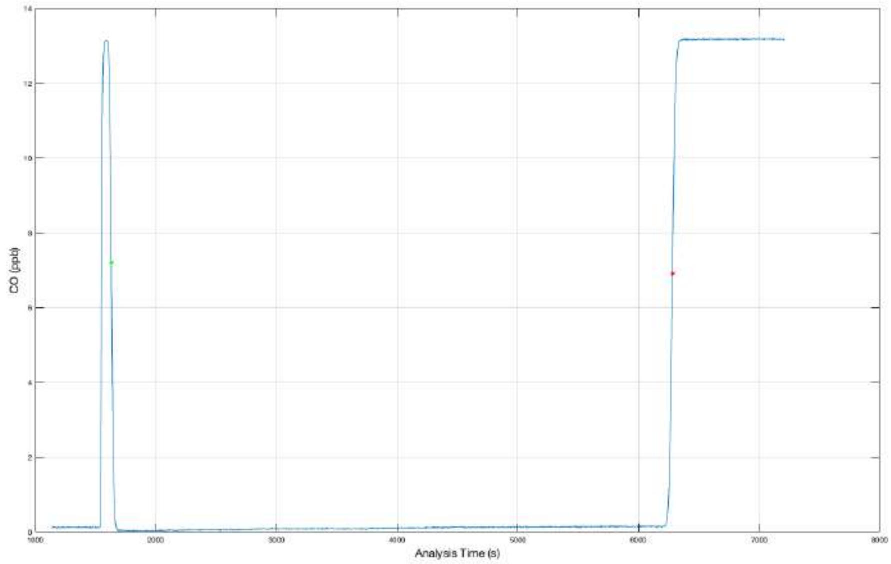


Figure 57: CO Mixing Ratios as a Function of the Analysis Time in Seconds.

The beginning and end of the sample analysis was detected due to changes in concentrations, at the beginning between calibrating gas/sample, and at the end, between sample/fill gas. The remaining fill gas in the coil had high concentration of CO, while the stratosphere had considerably lower CO concentrations. Figure 57 , was used to define the sample. Again, the top of the profile is marked with a green star and the bottom of the profile with a red star.

It is assumed that the air entering the tube equilibrates the sample with ambient pressure and adjusts very quickly with the mean coil temperature. As the characteristics of the CAC (length, diameter) do not change, ambient pressure and mean coil temperature are the two main factors that regulate the number of moles in the CAC. Using the ideal gas law, it is possible to calculate the number of moles captured in the tube all along the trajectory.

$$PV = nRT <=> n = \frac{PV}{RT} \tag{1}$$

where P was the ambient pressure, V was the inner volume of the CAC, n the fraction of moles, R was the universal gas constant in J K^{-1} mol^{-1} and T the ambient temperature in Kelvin, [17]. A constant unit of pressure in the atmosphere was represented by a unit of length in the CAC tube, due to the method that the CAC sampled the ambient air. With measured time series of pressure (Pi) and temperature (Ti), it was possible to relate the number of air moles in the tube (ni) to the atmospheric pressure at any given time during the flight:

$$n_i = \frac{P_i V}{R T_i}, \tag{2}$$

and this number was maximum when the CAC reached the surface,

$$n_{max} = \frac{P_s V}{R T_s}, \tag{3}$$

where P_s and T_s corresponded to the surface pressure and to the temperature of the CAC when landed at the surface.

The flow rate during the analysis was kept constant at 40.8 cm^3/min, which ensured that the number of moles that went through the analyzer increased linearly with time. So, the number of moles at any time during the analysis was

$$n_i = n^{max} \frac{t_i}{\Delta t} \tag{4}$$

where Δt was the total time duration of the analysis between the top and bottom of the CAC sample.

At the next step, Equations 2, and 4 were used to associate every pressure point with every Picarro measurement of the sample to retrieve the vertical profiles. In order to do that, it was important that the data points of the sample from the Picarro, matched the data points for pressure and temperature from the ground station. This was not the case, because the Picarro data had by far more. For that reason, the ground station data for pressure and temperature were interpolated to match the ones from the Picarro.

Finally, the CO, CO_2, and CH_4 vertical profiles were plotted against the pressure. The resulted vertical profiles as well as discussion of the results can be seen in Section 7.3.6.

The AAC sampling system was planned to be analyzed, in the same manner as the CAC, using the same Picarro gas analyzer. In the same way as for the CAC, the calibrating gas would needed to be flowing through the analyzer until the moisture was minimum and the readings in concentrations were stable. Then a sampling bag system would have been connected to the analyzer and a dry gas bottle, in a similar way as it was done in Test 17. The tubes connecting the sampling bags would have been flushed with dry gas and when the concentrations given by the Picarro analyzer were stable, the air inside the sampling bags would go through the analyzer followed again by dry gas.

Watching at the Picarro GUI, it was easily recognizable when a sampling bag was being analyzed due to the difference in concentrations between its air and the dry gas. Again, as for the CAC, equations 1 and 4 were going to be used to relate a specific pressure point with every Picarro measurement of the sample.

The basic working principle used by the chromatographer to obtain the concentrations was as follows:

- Have calibrating gas - sample - calibrating gas flowing through the analyzer. (It could also be the case: calibrating gas - dry gas - sample - dry gas - calibrating gas but the principle was the same).

- Identify in the GUI readings the different gases easily seen by sudden variations in the concentrations.
- Compare the calibrating gas reading with the known real value. Do this before and after the sample. This difference corresponds to the drift given by the Picarro.
- Interpolate the values of drift from before and after the sample to obtain the drift during the sample.
- Correct the readings given by the Picarro analyzer due to drift and that is the real concentration value.

NOTE: A calibrating gas was a gas that has been flowing through the Picarro analyzer multiple times and its concentration were known with accuracy. A calibrating gas had to flow before and after the samples in order to compare the readings given by the analyzer with the real value and obtain a corrected value for the samples.

7.2 Launch Campaign

7.2.1 Flight preparation activities during launch campaign

The scientific and pneumatic flight preparations can be found in Section 6.2.

On the first day of the campaign the experiment boxes were mounted into the gondola for the first time to check where the gondola fixation points should be. Once this was checked the box was dismounted again for final preparations. Styrofoam was fixed onto the bottom of the gondola to act as extra support for the boxes. It was fixed with the same double sided tape as was used to fix the Styrofoam to the walls of the experiment boxes.

Once the CAC box was fully integrated with the AirCore it was discovered that one temperature sensor required re soldering.

During preparations for the E-link test it was discovered that the The Amphenol RJF21B connector was built in the incorrect configuration and it had to be dismantled and rebuilt before E-link testing could be completed.

During the Flight Compatibility Test (FCT) it was discovered that the experiment was sensitive to the Radio Frequencies (RF) emitted from the VHF radios used. If the VHF radios were used within a 10-15m radius of the experiment box errors would appear in the sensor data. In the most extreme case this caused a complete failure of the software and no more data was received until a power cycle was completed. Following this discovery a radio silence area was set around the experiment to prevent these errors from occurring again. It is thought that this phenomenon was caused by two factors, the first being that the boxes housing the experiment have very large surface areas which are completed covered in aluminum and are grounding the electronics. Therefore when the experiment was on if RF interfered with the floating ground point in the boxes surface this can affect the grounding voltage. The second factor was the fact that the I2C connection was spread across very long wires making them more susceptible to interference. This also gave some background to the sensor issues experienced during thermal testing.

Just before mounting the box onto the gondola for the final time all sides of the box were taped with kapton tap to cover any small gaps in between the walls and the structural bars.

7.2.2 Flight performance

The flight began nominally with data being down linked as expected. There were some communication losses before takeoff but these were to be expected from the gondola antenna being too close to the ground.

Thermal systems were observed from the ground station to be operating nominally.

After takeoff the software successfully entered ascent mode and the CAC successfully opened. Thermal control continued nominally.

At the first sampling point for the AAC subsystem the software operated as it should attempting to turn on the pump however the pump failed to switch on and caused a full reset of the board. After the board reset the software could correctly re-identify the mode and reopen the CAC valve. However manual control was taken in an attempt the remedy the pump. Unfortunately all attempts to start the pump were unsuccessful during ascent and float phases.

During the descent phase in order to preserve the samples in the CAC no further attempts were made to start the pump as if the CAC valve closed and reopened it would compromise the samples within it.

From takeoff until the landing there were no sensor errors as had been observed during testing. It is thought that the sensor errors during testing may have been due to RF from mobile phones and other on ground emitters. This would explain why there were errors on ground but not during flight.

Upon recovery it was noted that all mechanical systems operated nominally.

7.2.3 Recovery

The recovery checklist, in Section 6.4.2, was given to the recovery team to collect the CAC. Due to low cloud cover it was not possible to make a recovery by helicopter. Instead the recovery team drove out to the landing site before hiking through several kilometers of forest. They found the gondola had landed onto the air inlet and outlet tubes however no damage was observed. It is thought that the gondola came down slowly due to the trees and tilted at the last moment. Dirt and forest debris was inside all three tubes.

The CAC was then returned to Esrange at around 1am the same night. It was immediately hooked up to the analyzers which were previously prepared.

The AAC returned the following night at around 2am and was also immediately investigated to see if any samples had been collected.

Both systems were returned before the gases inside the tubes and bags would have been too mixed. The TUBULAR Team is very grateful to all who made this recovery happen so fast given the conditions.

7.2.4 Post flight activities

The CAC system was recovered and brought back to Esrange approximately 13 hours after the gondola landed, and was immediately hooked up to the gas analyzer. The CAC analysis system can be seen in Figure 58.

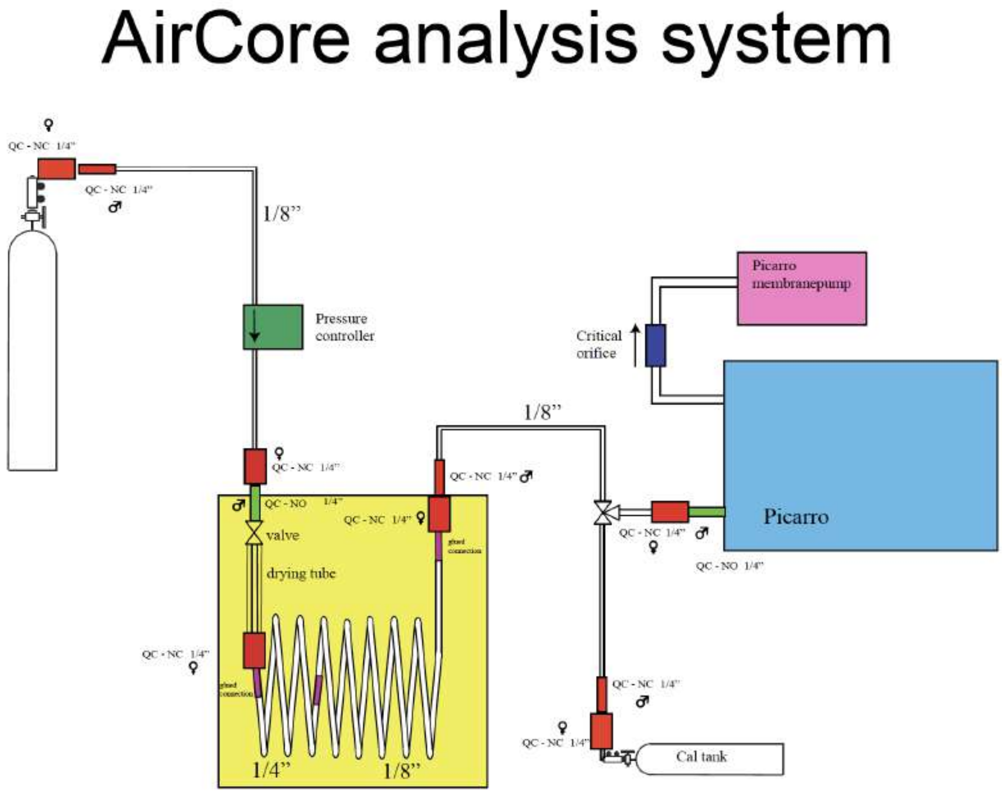


Figure 58: Schematics of CAC Analysis System [10].

For the analysis purposes, parts 10 to 17, shown in Figure 22 were removed. The magnesium perchlorate filter was also removed and wrapped in plastic foil for sealing reasons, and was taken by the FMI people. The fill gas was connected to the quick connector body (9), seen in Figure 22, and since the CAC valve closed at 6 km of altitude, one would expect a pressure decrease. In that case it would be necessary to fill the coil with fill gas, and bring it to ambient pressure, before connecting it to the analyzer. But no pressure change was seen. This could only mean two things: either there was a leak and ambient air entered the coil or the CAC valve never worked and the fill gas from the flushing procedure was still there. Next, the Picarro analyzer was connected to the quick connector body (1) as seen in Figure 22. As it has been mentioned in Section 7.1, during the flight, calibrating gas was flowing through the Picarro G2401. As soon as the values measured with the continuous analyzer were stabilized to the expected values for the calibration gas, the analysis of the air captured in the coil could start. As soon as this connection was done, both CAC ends were opened simultaneously, and the valve shown in Figure 53 was switched from calibrating gas to "AIRCORE" position. Few moments later, Picarro read the sample and the first readings showed up in the screen, seen in Figure 59. The air was pulled from one end into the continuous analyzer and low-concentration fill gas was pulled through the other end. The top of the profile with the remaining fill gas was pulled first into the analyzer.

The fill gas was a high-concentration standard in order to have a noticeable difference between the remained fill gas in the coil and the stratospheric air sample at the top of the profile. The low-concentration calibration standard was chosen to be used as push gas to have a noticeable difference of the mixing ratios compared with the expected values of CO_2 and CH_4 at the surface.

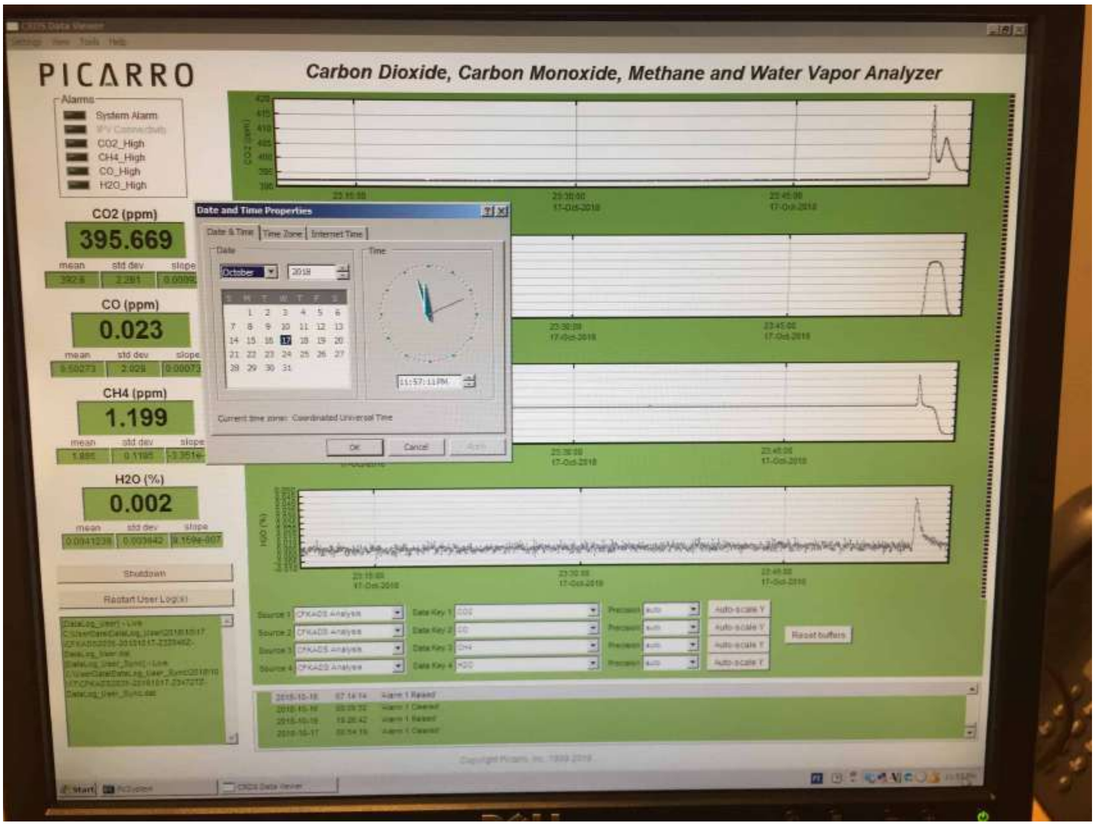


Figure 59: First Readings of the CAC. From top to bottom: CO_2 ppm, CO ppm, CH_4 ppm and cavity pressure.

As seen in Figure 59 there was a sudden increase in the concentrations and this was the fill gas that had remained, as expected, in the coil. After a while, there was a sudden decrease in the concentrations, and that was the start of the actual sample. The whole CAC profile can be seen in Figure 60

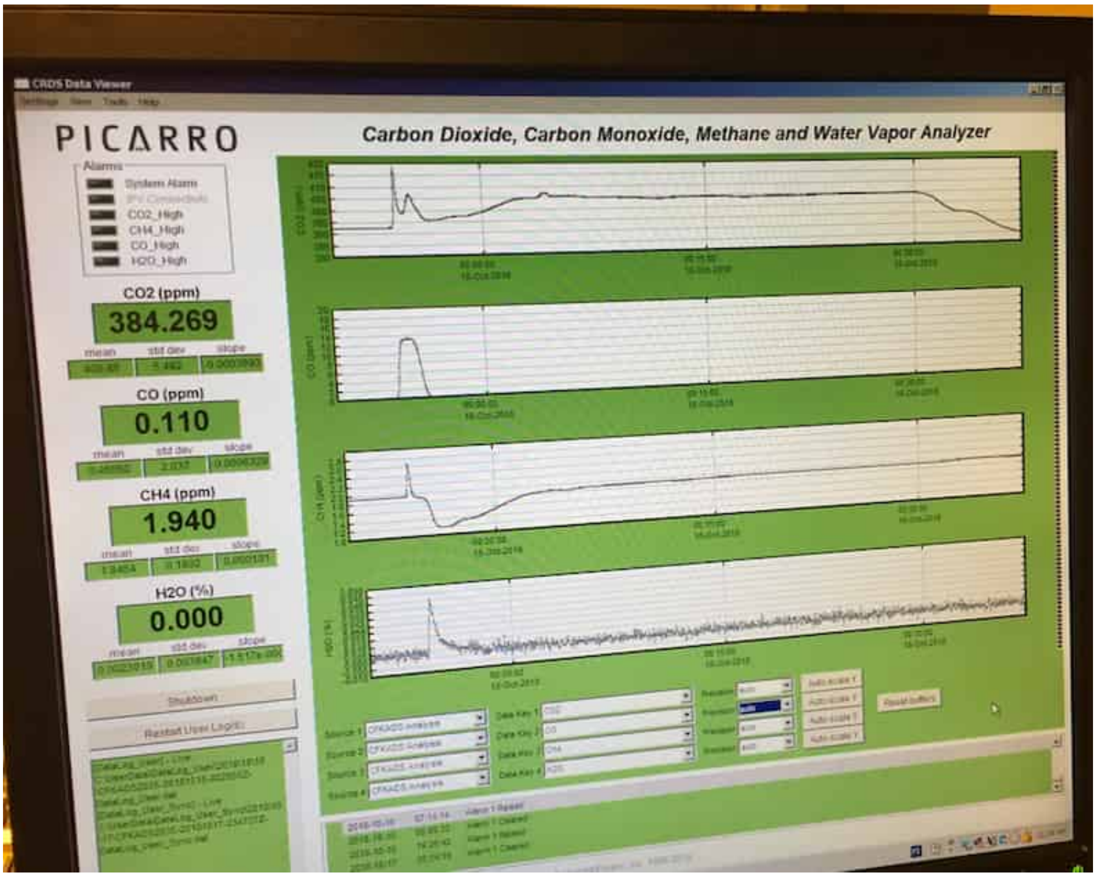


Figure 60: CAC Complete Profile after the Analysis was Completed. From top to bottom: CO_2 ppm, CO ppm, CH_4 ppm and cavity pressure.

The slight increase in the CO_2 and CH_4 concentrations in Figure 60 flagged the beginning of the tropospheric part of the sample. After approximately 40 minutes the CAC sample was almost finished and it could be confirmed that the CAC valve was leaking, letting ambient air enter the coil. Even though air from the ground entered the coil, the humidity levels were kept low, because of the magnesium perchlorate filter.

The CAC system managed to sample the stratosphere and the troposphere down to 6 km of altitude. The lower parts of the profile represent ambient air that went inside the coil through the valve. The analysis of the results can be seen in Section 7.3.6.

After the analysis was completed, the stratospheric part of the sample was saved into a sampler, composed of fifteen smaller tubes as seen in Figure 61. All the valves were open when the sample was introduced. Once the stratospheric part of the sample was in the sampler, all the valves were closed at the same time, separating the samples for different altitudes and preventing further molecular diffusion. This part of the sample, will be further analyzed for isotopes and other atmospheric gases.

Figure 61: CAC Sampler with 15 Different Stages.

For the AAC unfortunately due to the pump failure no data was collected. A post flight failure analysis was carried out on the pump and this can be seen in Section 7.4.

Data received by the ground station was also analyzed to find the pressure and temperature profiles during the flight. This was completed on MATLAB and was shown during the post flight briefing at campaign.

7.3 Results

The results gained from the TUBULAR flight can be broken down into the various subsystems as follows

7.3.1 Mechanical Subsystem Performance

Structural Performance

The frame structure and the aluminum walls withstood all the flight phases providing the required protection to all the components inside both boxes.

Regarding the frame, the most critical load that it had to face was during landing. The gondola landed on the side where the boxes where allocated, thus they experienced a high load. Thanks to the use of bumpers as anchors of the boxes to the gondola rails and the styrofoam as a sitting surface, the force was damped, see Figures 62 and 63. Consequently the boxes did not move from its original place.

Figure 62: Position of the bumpers after landing.

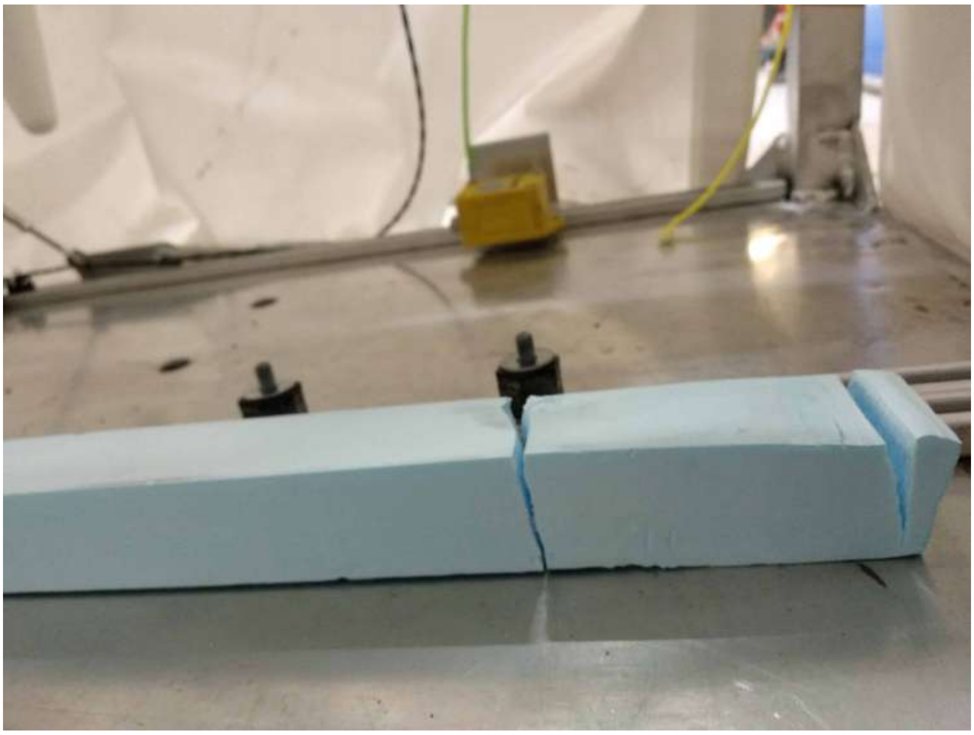


Figure 63: Sytrofoam below the boxes after landing.

The walls did not suffer any remarkable damage apart from the dirt that stuck to them as a cause of the sideways landing and some scratches from trees during landing.

Pneumatic circuit Performance

The experiment had two separate pneumatic circuits, on each box.

The air sampling with the CAC system was nominal. The valve opened and closed upon both automated and manual commands. This allowed to empty the 300-meter coiled tube during ascent and filling with stratospheric air during the descent phase.

On the other hand, the large pneumatic system of the AAC system experienced a failure in the pump which lead to the failure of the this alternative sampling system. Although the bags could not be filled with stratospheric air for later analysis, data of both airflow and pressure sensor was received as expected and all the valves worked nominally (manifold and flushing).

The failure analysis of the pump can be found in Section 7.4.

7.3.2 Electrical Subsystem Performance

Throughout the flight, none of the previous sensor dropouts that had been experienced were seen. This is thought to be due to the absence of larger electromagnetic interference's.

All other electrical parts worked as intended.

For details on the full failure analysis of the pump see Section 7.4.

7.3.3 Software Subsystem Performance

The software managed to control the experiment through the majority of the phases of the mission. The software worked even with frequent telemetry connection cutoff before the takeoff, during take-off it switched to Ascent mode successfully. When the failure with the pump occurred it successfully reset and put itself in the correct mode. Since sampling caused a reset it was decided that the software would be kept in Manual mode for the remainder of the flight.

An unforeseen behavior was observed during descent when the choice was made to change the mode from Manual mode to Normal-Descent mode. Directly after this change a loss of communication happened before it reestablished itself a few seconds later, with all valves closed and the experiment in Standby mode. This is was indicative of a reset. Why it reset itself was most likely brought on by the fact the experiment passed several sampling points in Manual mode. Manual mode was thought to only be used for a short while and not to skip a sampling point. Incapable of taking a sample in Manual mode it is believed that the ASC performed a sampling when the software had the authority to do so, in which the pump was involved and therefor a reset happened. After the reset the software successfully went into Normal-Descent mode without taking a sample using the AAC. The choice was the made to take it into Safe mode which closed every valve successfully.

During the flight the only intermission of telemetry was during the reboot of the software after a reset. A permanent loss of telemetry happened at a low altitude due to limitations with line-of-sight. The on board software continued to record sensor data for several hours after landing.

7.3.4 Thermal Subsystem Performance

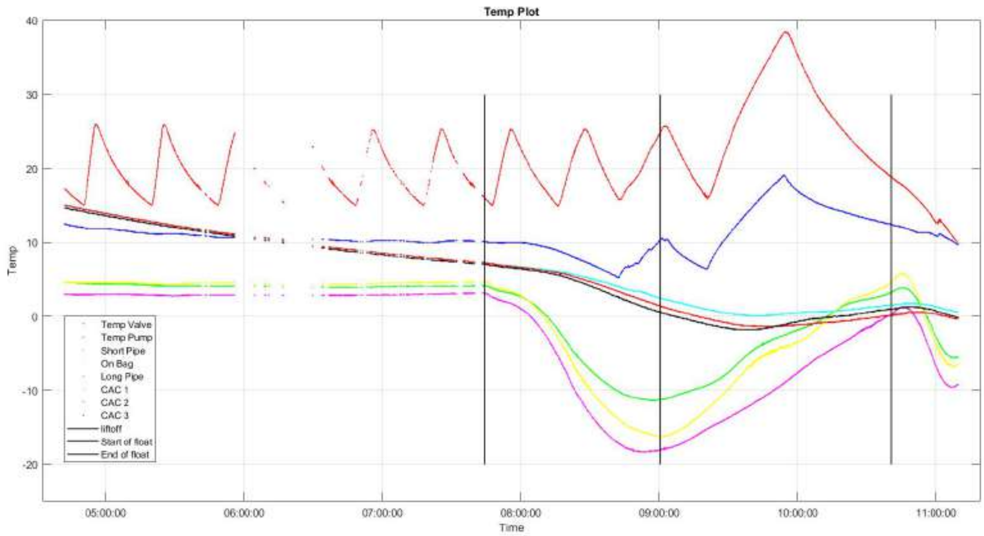


Figure 64: The Temperature for the Different Sensors During Whole Fight.

The thermal result for the flight are as seen in Figure 64. Both the critical components did not go lower than the operating threshold. The heaters operated as expected and kept the pump and manifold in their respective threshold limits. During the float phase a test were done to see if the pump issue were thermal related. The pump were then heated up to the upper limit and tried to start but did not work. It could then be concluded that the issue with pump during the flight were not thermal related. The simulations estimated the heaters would use 26.66Wh and during flight (calculated from Figure 64) 27.667Wh were used so the simulations were a good estimation.

7.3.5 Past Results

After the analysis of the samples, the expected results were the vertical profiles of CO, CO_2, and CH_4. The profiles presented a similar pattern to that of Figure 65 which was found in an experiment by Karion et al (AirCore: An Innovative Atmospheric Sampling System) [6]. The continuous profile (dashed line) belongs to the CAC while the discrete values (black dots) belongs to the AAC ([6]). Both profiles are showing a decrease in concentration of CH_2 and CH_4 with increasing altitude.

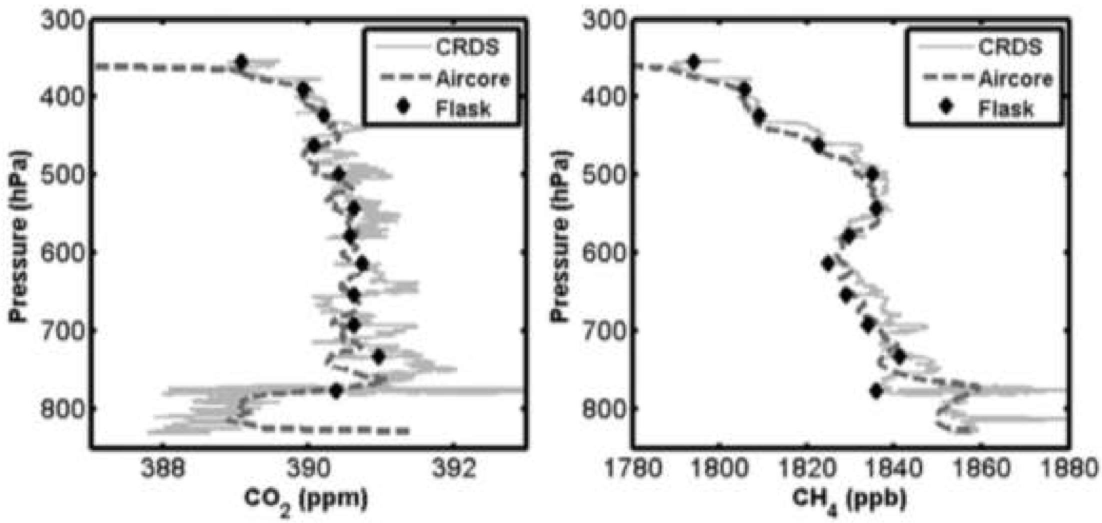


Figure 65: Pressure Profiles for (Left) CO_2 and (Right) CH_4 by Three Different Methods [6].

This experiment's goal was to achieve the highest vertical resolution possible. Since the vertical resolution was determined by the length and the diameter of the tube [17], a 300 m long tube was used, consisting of 2 smaller tubes. One of 200 m length with 3×10^{-3} m outside diameter and 1.3×10^{-4} m wall thickness, and another one of 100 m length with 6×10^{-3} m outside diameter and 1.3×10^{-4} m wall thickness. For achieving higher stratospheric resolution, the tube with the smaller diameter was used to sample the higher altitudes and the one with the bigger diameter for the lower ones. Figure 66 by Olivier Membrive [17] compares the vertical resolution that can be expected with three different AirCores.

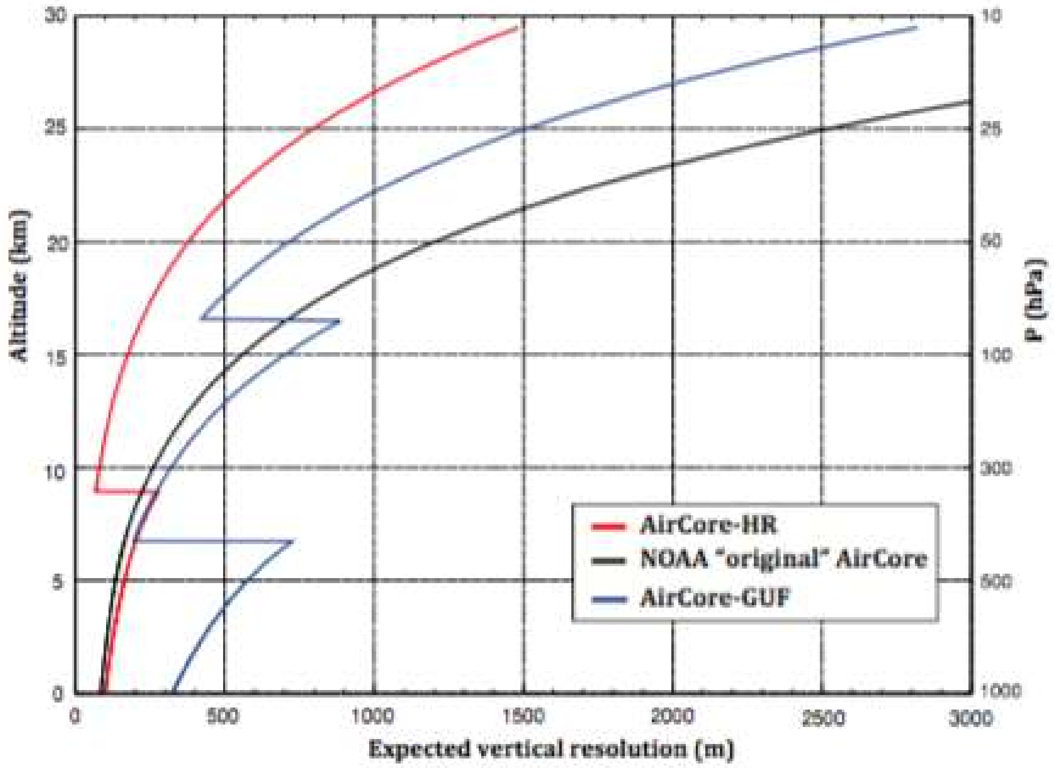


Figure 66: Comparison of the Vertical Resolutions That can be Expected with Different Air-Cores, After 3h Storage Time Before Analysis [17].

The High-Resolution AirCore-HR (red line),[17], is a combination of two tubes. One of 200 m and one of 100 m.

The NOAA 'original' CAC, [6], (black line) is a 152 m long tube and the AirCore-GUF (designed and developed at Goethe University Frankfurt), (blue line) is a combination of three tubes, 100 m long in total.

The longer AirCore, AirCore-HR, achieved a higher resolution throughout the whole sampled air.

In addition, the vertical resolution depends on the the mixing inside the tube.

This experiment took into account two types of mixing. Molecular diffusion and the shear flow diffusion, known as Taylor dispersion. The effect of molecular diffusion was described by the root-mean-square of the distance of molecular travel,

$$X_{rms} = \sqrt{2Dt} \tag{5}$$

where, D was the molecular diffusivity of the molecule in the surrounding gas, and t was the time over which travel occurs, [6]. For the tubing dimension that were used in this experiment, the flow of air through the CAC, was laminar. In such a flow, a parabolic velocity profile existed inside the tube, causing longitudinal mixing (Taylor dispersion).

Before their experiment was recovered, only molecular diffusion affected the sample, but during analysis both molecular diffusion and Taylor dispersion affected the sample. Combining both of them, an effective diffusion coefficient was calculated as,

$$Deff = D + \frac{a^2\overline{V^2}}{48D} \tag{6}$$

where D was the molecular diffusivity, a was the tube's inner radius, and $\overline{V}$ was the average velocity [17]. The first term translated into the longitudinal direction, while the second one was the Taylor dispersion.

After completing Test 4 and Test 18 as seen in Tables 25, and 35 respectively, the team managed to get the standard flow rate readings for the different altitudes. Standard flow rate is the volumetric flow rate of a gas corrected to standarized conditions of temperature and pressure. In this case the logged flow rates correspond to sea level conditions. Table 55 shows the standard flow rates at the sampling altitudes.

	Sampling Altitudes	**Ambient Pressure**	**Standard Flow rate**
Ascent Phase	18 km	75.0 hPa	∼0.38 L/min
	21 km	46.8 hPa	∼0.21 L/min
Descent Phase	17.5 km	81.2 hPa	∼0.41 L/min
	16 km	102.9 hPa	∼0.55 L/min
	14 km	141.0 hPa	∼0.79 L/min
	12 km	193.3 hPa	∼1.22 L/min

Table 55: Sampling Altitudes as well as the Corresponding Ambient Pressures According to the 1976 US Standard Atmosphere and the Standard Flow Rates at Each Altitude.

It was necessary to also calculate the actual flow rates at the different altitudes. The conversion was done using the equation [1]: $Volumetricflow = (Standardflowrate) \cdot \left(\frac{T_{alt}}{T_{std}}\right) \cdot \left(\frac{P_{std}}{P_{alt}}\right)$
where,
$P_{std} = 1013hPa$ was the standard pressure.
$T_{std} = 294.25K$ was the standard temperature.
T_{alt} was the temperature at the different altitudes.
P_{alt} was the pressure at the different altitudes.

Table 56, shows the actual flow rates at the sampling altitudes.

	Sampling Altitudes	**Ambient Pressure**	**Actual Flow rate**
Ascent Phase	18 km	75.0 hPa	∼3.78 L/min
	21 km	46.8 hPa	∼3.36 L/min
Descent Phase	17.5 km	81.2 hPa	∼3.77 L/min
	16 km	102.9 hPa	∼3.99 L/min
	14 km	141.0 hPa	∼4.18 L/min
	12 km	193.3 hPa	∼4.71 L/min

Table 56: Sampling Altitudes as well as the Corresponding Ambient Pressures According to the 1976 US Standard Atmosphere and the Normal Flow Rates at Each Altitude.

Finally, storage time, that was the time from the moment the tube was sealed until the end of the analysis, was a key factor that affected the experiment's results in terms of resolution.

Figure 67 shows the effect of time delay between landing and analysis, on the expected vertical resolution.

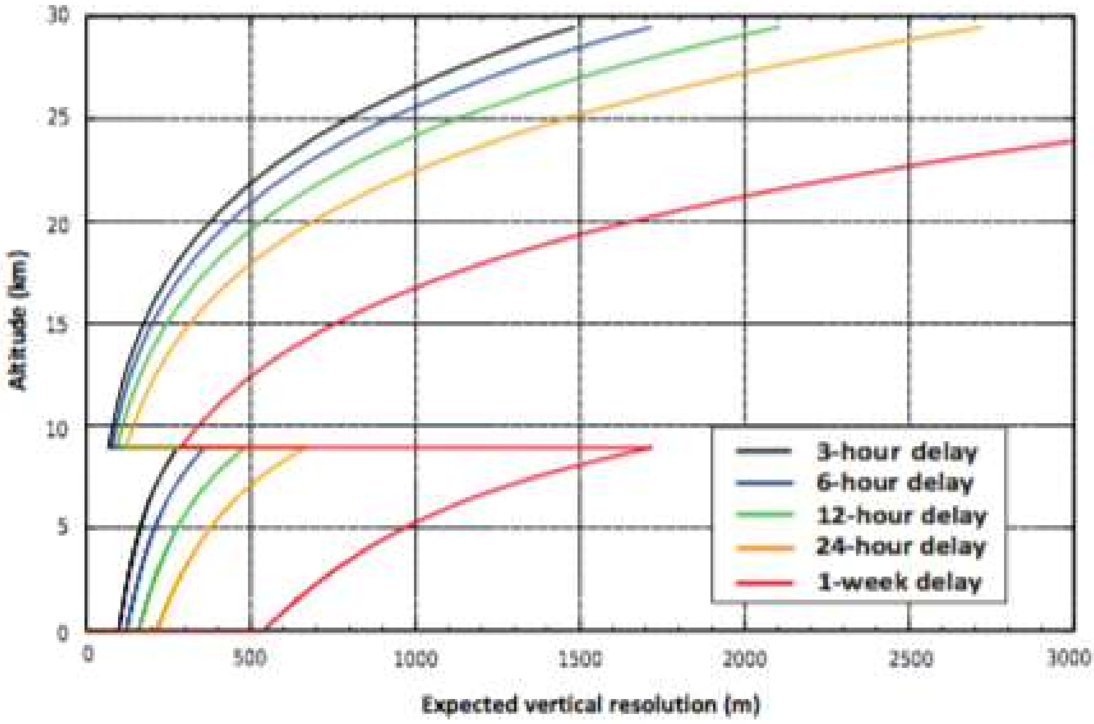


Figure 67: Expected Vertical Resolution of AirCore-HR, for a Storage Time of 3h (Black), 6h (Blue), 12h (Green), 24h (Orange) and 1 Week (Red) [17].

It is clear that the sooner the samples were analyzed, the better the results for the vertical resolution of the CAC sample. At an altitude of 20 km the resolution decreased significantly from 300 m to 500 m for 6h and 12h of delay, respectively, [17]. But even after a week of storage, a vertical profile could still be achieved with lower resolution.

Based on past BEXUS projects, the time to experiment recovery was estimated at 12 to 24 hours, if not multiple days. As such, it was expected that the desired vertical resolution of gas analysis favoured AAC configuration over that of CAC due to mixing of gases in the latter configuration, resulting in poorer vertical resolution.

The vertical resolution for the AAC was expected to be approximately 500 m. This would have been achieved assuring the airflow intake rate. For Ascent Phase, a nominal speed of 5 m/s was considered, which meant that it would take 28.57 seconds to fill a sampling bag with 1.8L of air while ascending 142.85 m, and an actual airflow intake rate of approximately 3.78 L/min at 18 km of altitude. For Descent Phase, the nominal speed was assumed to be 8 m/s. While descending 156.4 m a sampling bag would be filled in 19.55 seconds, with 1.3 L of air and an actual airflow intake rate of 3.99 L/min at 16 km of altitude. However, taking into account that the volume of the samples, at sea level, would have been lower, the sampling time would have been longer and the vertical resolution closer to 500m.

For a 500 m of vertical displacement, the horizontal resolution of the AAC was approximated based on past BEXUS flights data obtained from the BEXUS manual [8]. The average horizontal resolution obtained for Ascent Phase was 588m and for Descent Phase was 186.5 m. This meant that the square area covered by the sample would have been 500 m x 588 m and 500 m x 186.5 m for ascent and Descent Phases respectively.

7.3.6 Scientific Results

From the ambient temperature profile, seen in Figure 68, the tropopause was estimated to be at 165.2 hPa. The AirCore onboard the CAC system operated nominally resulting in high resolution profiles for CO, CO2, and CH4. These profiles are presented in Figure 69. The data from 400 hPa down to 1000 hPa were deleted. During those measurements the CAC valve was closed and the gases were leaking inside the coil with some unknown delay, and from inside the box (not from the troposphere).

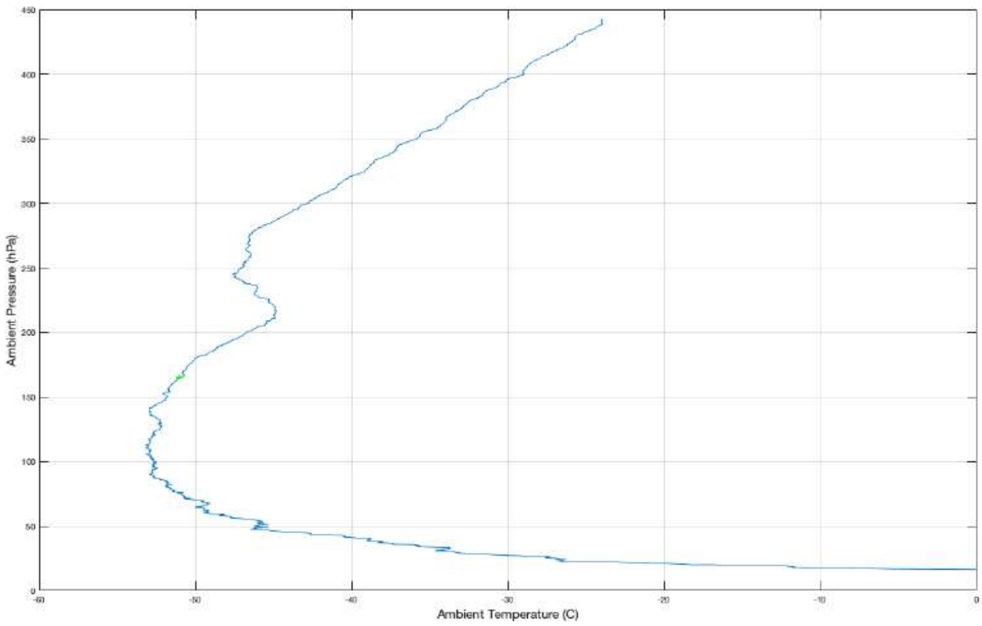


Figure 68: Ambient Temperature in °C Over Ambient Pressure in hPa.

Trace gas concentrations are measured in parts per million (ppm) and parts per billion (ppb). A decreasing concentration trend is observed for CO2, CH4, and CO as the altitude increases. The maximum values are approximately 407 ppm for CO2, 1.9 ppm for CH4, and close to 89 ppb for CO.

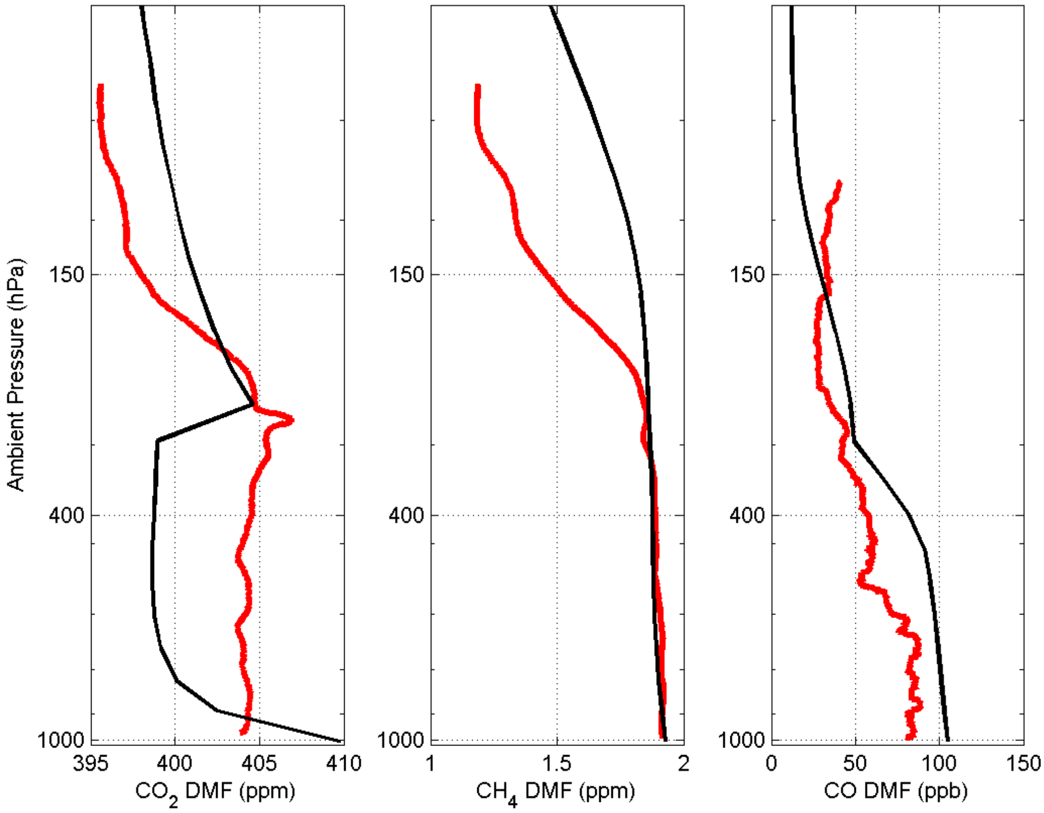


Figure 69: AirCore profiles for CO, CO2, and CH4 (in black) with their respective forecasts (in grey). The red line denotes the tropopause boundary between the troposphere and the stratosphere. The red asterisk denotes a reference point for 1,000 hPa surface level concentrations measured at 20 km from the landing site.

A sharp decrease of CO2 can be observed in the first layers above the tropopause. Tropopause altitude was at 274 hPa, about 9.8 km. In the stratosphere, values are lower since the exchange between the upper troposphere and lower stratosphere takes several years [17]. Variability is higher near the ground, which agrees with the idea that CO2 may have negative and positive anomalies at the surface that are mainly associated with vegetation uptake and anthropogenic emissions [17].

The mixing ratios of CH4 have a small variability in the troposphere. A strong decrease in the stratosphere is easy to spot with a value of 1.85 ppm near the tropopause and 1.33 ppm at 15.2 km (118 hPa). Variability is higher in the mid-to-upper troposphere and in the stratosphere, which is mostly due to positive anomalies coming from the surface and negative anomalies coming from the stratosphere [17].

It is difficult to draw any conclusions based on measurements extracted from a single sampling flight. Variations of greenhouse gas concentrations would have to be observed through time with data collected over numerous reflights.

7.3.7 Future Work

It was expected that the AAC would serve as model enabling a cost-effective large scale deployment scheme for regular high altitude greenhouse gas measurement. Unlike CAC, the design of AAC would have not imposed experimental restrictions based on the proximity of infrastructure for shipping and analysis. As such, a successful proof of concept of AAC sampling system would have served as a basis to enable reliable cost-effective measurements in remote areas.

Despite the end of the BEXUS 26 programme, future flights can still be designed that will resolve the problems discovered during the campaign. Notably, using a different or dedicated battery set for the TUBULAR experiment.

The TUBULAR Team has presented its findings in two conferences and published experiment's results in proceeding for the 24th ESA Symposium on European Rocket Balloon Programmes and Related Research [3] and the 3rd Symposium on Space Educational Activities [11]. These publications can serve as references for future work.

7.4 Failure Analysis

During the flight the experiment experienced unexpected errors. This section will go into the procedures and results of the failure analysis. In general there was two stages of analysis, firstly the post flight analysis that was made as soon as the experiment was retrieved during campaign and, secondly the lab analysis that was made in the lab some time after launch campaign.

7.4.1 Post flight analysis

Shortly after the conclusion of failure on the AAC system an investigation plan was created to make sure that the team did not destroy any potential evidence. Deducted from the behaviour during flight, a list of potential problems was made and can be seen in Table 57. Most possible causes were unlikely due to the extensive testing made before flight.

1	Shorted output pin on Arduino
2	Pump elastic diaphragm broke
3	Pump too cold
4	Short circuit in pump
5	Pump MOSFET broken
6	Pump current draw too high
7	Pump drive shaft blocked
8	Pump tubing blocked

Table 57: List of Potential Failure Causes

Shortly after the experiment was retrieved a structured post flight investigation was made to investigate the possible causes of the in flight failure. The experiment walls were removed one at a time and there was no unexpected smells when opening the walls of the experiment that might have indicated burning of components. After the main PCB board was accessible, resistance measurements were taken on the MOSFET's. Which all were the same, indicating that the MOSFET's were not damaged. There were no shorts anywhere on the PCB either. The forward resistance of the pump was measured and compared to the forward resistance of a spare pump. The resistances were similar and deemed not to be suspicious. There was no discontinuities on the PCB where they were not expected. No problems were found from electrical measurements and visual inspection.

Thus the next step in the procedure was to try to start the system from a power supply and check functionality. The power supply was set to 28.8V and a current limit of 1.8A. The system was turned on and data was feed out nominally as it did during flight as well. After inspecting basic functionality of the experiment the pump and the flushing valve were turned on and opened to see if the same issue occurred as during flight. The pump turned on and the valve opened nominally and pumped air through the system. Since the pipes going out were dismounted at this point and one of the concerns was that the pump might have been blocked, the inlet of the pump was blocked and the procedure repeated. The pump turned on again, although without blowing air, as expected.

At this point the team had suspicions that it might be a current limitation problem since the same behaviour has been seen before in the lab when the experiment could not be supplied with enough current. Thus a decision was made to change the settings of the bench power supply used during testing. It was first set to 24V and 1.8A current limitation and the experiment continued to work nominally. Next, the power supply was set to 24V and 1A and the pump could no longer start at this point and the exact same behaviour as during flight was seen. The system shut down, stopped sending data to the ground station, then rebooted and reestablished the telemetry feed. At this point, no further testing was made at the campaign due to others needing the used facilities and it was deemed safe to continue the testing in the lab later on.

7.4.2 Lab analysis

The lab analysis mainly focused on the power consumption of the pump and what happened power wise when the pump was turned on. The whole system was powered through a bench power supply with a 206m Ohm resistance in series to be able to measure the peak currents when the pump turns on by measure the voltage drop over this resistance with an oscilloscope. There were two notable peaks when starting the pump, the first was on a time scale of 100ms and produced a total current draw of 1.019A. The second was on the time scale of 110µs and had a total current draw of 7.56A. Although, it is not certain that the second peak is real, it could have been produced by other disturbances since similar behaviours have been seen before on the same scope when other devices on the power net have been turned on or off.

After these test were performed, the experiment was tested with a test battery pack consisting of eight SAFT LSH20 cells. Although, the specific cells tested with had already been used and it is known that these batteries self drain once they have been used once. When trying to start the pump, the same behaviour as during flight failure was seen. Furthermore the voltage on the batteries dropped drastically to 3.5V from 22.9V which would explain the system shutdown. This can be seen in Figure 70.

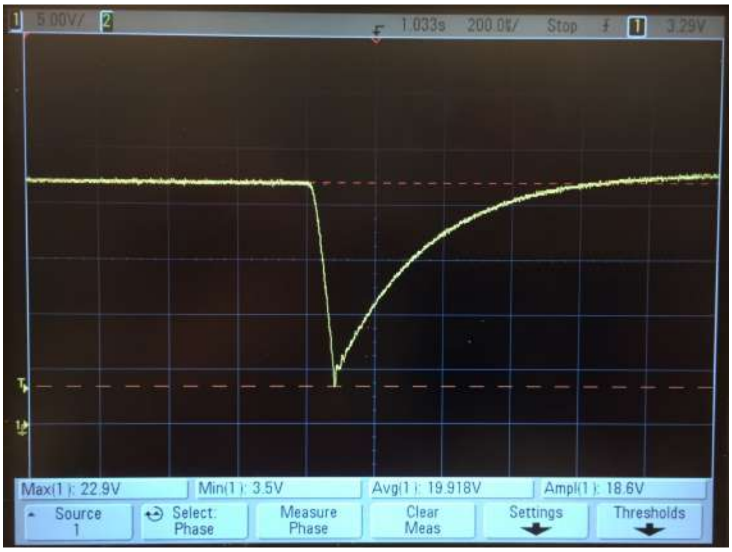


Figure 70: Supply Voltage During Pump Start While Running on Batteries

7.4.3 Conclusion

The experiment works within the current specifications of a single SAFT LSH20 cell. Although, the supplier has not specified the single cell behaviour for short peaks such as 100µs. The effects on current specifications when using these cells in series is also unknown. Although, it is known that lithium-thionyl chloride batteries have a relatively large internal resistance which might affect the performance. Thus the conclusion is that the experiment was current limited and thus reset itself, but the source of limitation is still unknown.

Since it was not possible to start the pump during the pre-flight readiness review as a result of the flushing already being made, starting the pump while running on batteries should have been tested before. Either in the Lab, or before the system was flushed at launch campaign. Then the issue might have been discovered before the flight.

7.5 Lessons Learned

At the end of the project, the TUBULAR Team has learned many important lessons regarding document creation as well as learning how to build an idea into a project, integrating it, testing it, flying it and analysisng the data afterwards.

The TUBULAR Team found that the REXUS/BEXUS programme was rewarding in terms of experience regarding balloon craft design and development, with real deadlines, published documents, and team work.

7.5.1 Management Division

- Coordination between multiple project stakeholders.
- Task definition, estimation, and management.
- Task integration.
- Conflict management and resolution.
- Communication flows.
- Funding research and outreach.
- Identifying team member strengths as well as weaknesses and assigning responsibilities accordingly without neglecting the opportunities to improve on weaknesses.
- Do not assume cross-division communication will take place without organizing/planning it.
- Reviewing progress of assigned task should be continuous rather than waiting for their due dates.
- Agree on and clearly communicate to the team definition of “Done” when referring to tasks being completed.
- Agree on and clearly communicate to the team the definition of “Final Version” when referring to schematics, diagrams, and component lists.
- The lessons learned section of previous BEXUS SEDs is an invaluable resource that answers many BEXUS related recurring questions.
- If changes in management are required it is important that there is a sufficiently long change over period to allow a transfer of knowledge.
- Tasks that are not completed on time or were simply not worked on during the assigned time will impact projected deadlines and these situations must be planned for and mitigated against. An early red flag for this is if the reported team working hours tend to be lower than expected at which point one can expect to have to make up those hours up before a deadline. These concerns must continuously be communicated to the team.
- The REXUS/BEXUS programme is a significant investment in time and resources from all programme partners and as such the unique opportunity is not limited to participating students but to component manufacturers and suppliers as well. With this in mind,

the team should not shy away from aggressively seeking funds or sponsorships from component manufacturers and suppliers as they stand to benefit from such a partnership to show case the robustness of their products.

- Testing will always take longer than expected and so time must be planned to account for this.
- When working with many remote team members extra time must be allowed for tasks to be completed as the communication is slower. Internal earlier deadlines help a lot.
- During manufacture and test having many smaller deadlines has proven useful in ensuring things stick to the time plan.
- When things don't go to plan during flight it is essential to keep a cool head and think things through calmly. It might be hard to make final decisions on things but it is important to ensure appropriate actions are taken in a timely and sensible fashion.
- You can never do too much testing!

7.5.2 Scientific Division

After an extended research in trace gases and climate change, as well as in atmospheric sampling methods, the science team has gained so far:

- General knowledge in climate change.
- General knowledge in the different sampling methods of the atmosphere; its characteristics and applications.
- Study scientific papers in detail.
- Outreach to scientific community.
- Translating scientific concepts to technical teams.
- Knowledge of how to design the scientific requirements in such a way that are in the permitted limits of the budget while the technical requirements are fulfilled.
- How to sufficiently distribute the tasks within the science team and keep good communication with the other departments.
- Experience, that writing down the tasks that need to be done, and keep tracking on them is better rather than having them as goals.
- Experience in producing a presentation only with the key points of a project and presenting it in front of other people.
- Work as a group from different locations.
- How to prepare and plan a test, under the real environment of the experiment.
- The importance of testing, and how to sufficiently deal with problems that come up unexpectedly.
- How to perform a failure analysis, documenting every step.

- Knowledge in data analysis procedure and how to extract the desired results from raw data.
- Using MATLAB to obtain the vertical profiles of the CO_2, CH_4, and CO gasses.

7.5.3 Electrical Division

The electrical team has enhanced its understanding of the electronics design as well as gained confidence in selecting appropriate components as per requirements. Some of the points team improved as their general understanding are listed below:

- Gained confidence in designing electronics circuitry.
- Familiarized with the selection of the electrical components.
- By reading through large number of data sheets, team is now able to easily extract and understand technical details.
- Learned and developed power calculation skills.
- Got experience of using the Eagle software and how to find and make the libraries, footprints, and schematics for the required components.
- How to test the components in the vacuum chamber.
- Learned about the different connectors, wires and how to place the components on the PCB so the actual design can fit into the experiment box.
- Discovered the cascading consequences of changing one component.
- Finding how having big sheets with a lot of information can be preferable to several sheets with less specification.
- While designing PCB's with Eagle it's a good idea to draw the traces manually rather than using autotracer. Since it allows you double check your schematics while pulling the traces.
- When using netnaming to design schematics for later PCB designs in Eagle it's very important to triple check the net names since they sometimes change in unexpected ways.
- Got practical experience of soldering the different types of sensors, wires and connectors.
- Learned how to solder SMD miniature pressure sensors onto the PCB.
- Familiarized with using work shop tools and machinery.
- Got experience how to work around spontaneous problems arise due to design changes by the other departments and the testings.
- Learned how to conduct failure analysis; it's basic methodology and rules required in order to avoid destruction of any evidence for the post-flight analysis.
- Learned how important electrical housekeeping data could be during a in-flight errors.

- Learned how to come up with and assess compromises during launch campaign to accommodate to eventual changes.

7.5.4 Software Division

- Learned more about version control in the form of Git.
- Learned how to implement an RTOS on Arduino.
- Learned how to translate experiment requirements to a software design.
- Learned how to split functionality into several testable functions.
- Gained experience on software unit testing.
- Learned how to design and create GUI using MATLAB GUIDE.
- Learned how to use Git, a version control system for tracking changes in computer files and coordinating work on those files among multiple people.
- Learned how to implement TCP/IP and UDP on ethernet connection.
- Learned how to make telecommand and telemetry.
- Learned how the I2C and SPI protocols work and operate.
- Learned how to efficiently debug software.
- Learned that when suppressing the output of a system, it would also be good to not ignore it.
- Learned that using a sequence based system is not optimal when said system is wished to not be operated non sequentially.
- Learned that the expected cases one designs around, may not be the actual cases which encountered in real life.

7.5.5 Mechanical Division

- Come up with real design solutions starting from conceptual problems.
- Make a proper use of both space and mass.
- Learn mechanical *tricks* when designing.
- Adapt the design to components availability and characteristics.
- Select and contact with vendors.
- Implement a real pneumatic system.
- Compute structural analysis.
- Team collaboration with other departments, i.e. Electrical, Science, and Thermal.
- Design is trickier when it comes to implementation.

- Always document specific department knowledge. If who designed a certain part of the experiment is not available for the manufacture phase, whoever works on it should be able to figure out most of the solutions by themselves.
- Manufacturing and integration of the different subsystems of the experiment takes longer than expected during design phase.
- The design is never frozen until everything is built and working properly.
- Good planning when designing and manufacturing allows to avoid last minute *tricks* during Launch Campaign.
- After flying the experiment and thinking of what could be changed to improve it, several ideas arise.

7.5.6 Thermal Division

- Learned how to do Steady-State and Transient thermal analysis in ANSYS.
- Coordinate between other division to find a solution that works for everyone.
- Do a thermal plan and structure up what needs to be done for a long period of time.
- How to improve and be more efficient when adjusting to sudden changes in design.
- How to balance details in simulations.
- How to do thermal test, analyze the result and make improvement of the results.
- How to work with Styrofoam.
- How temperatures inside component operating ranges can impact component performances.
- How the real flight actually is different from test and simulations and it is hard to do a perfect test and simulations beforehand.

8 Abbreviations and References

8.1 Abbreviations

AAC	Alternative to the Air Coil
ASC	Air Sampling Control
ANSYS	ANalysis SYStem
BEXUS	Balloon Experiment for University Students
CAC	Conventional Air Coil
CAD	Computer Aided Design
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
CH_4	Methane
CLK	Serial Clock
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COG	Center of Gravity
CRDS	Cavity Ring Down Spectrometer
DC	Direct Current
DFM	Design for Manufacturability
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EB	Electronic Box
EBASS	Esrange BAlloon Service System
ECTS	European Credit Transfer System
EPDM	Ethylene Propylene Diene Monomer
ESA	European Space Agency
FCS	Frame Check Sequence
FEA	Finite Element Analysis
FMI	Finnish Meteorological Institute
GC	Ground Control Station
GPIO	General Pins Input Output
GPS	Global Positioning System
GUI	Graphical User Interface
H_20	Water
HOOD	Hierarchic Object-Oriented Design
I2C	Inter-Integrated Circuit
IDE	Integrated Software Environment
I/O	Input/Output
IR	Infra-Red
IRF	Institutet för rymdfysik (Swedish Institute for Space Physics)
LED	Light Emitting Diode
LTU	Luleå University of Technology
MATLAB	MATrix LABoratory
MB	Mega Byte
MISO	Master Input Slave Output
MORABA	Mobile Rocket Base

MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MOSI	Master Output Slave Input
MSc	Master of Science
NOAA	National Oceanographic and Atmospheric Administration
OBC	Onboard Computer
ppb	parts per billion
ppm	parts per million
PCB	Printed Circuit Board
PDR	Preliminary Design Review
REXUS	Rocket Experiment for University Students
RJ45	Registered Jack 45
RTOS	Real-time operating system
SAFT	Société des Accumulateurs Fixes et de Traction
SCP	Serial Clock Pin
SD	Secure Digital (Storage)
SDP	Serial Data Pin
SED	Student Experiment Documentation
SNSA	Swedish National Space Agency
SPI	Serial Peripheral Interface
SSC	Swedish Space Corporation
STP	Standard Temperature Pressure
TBC	To Be Confirmed
TBD	To Be Determined
TCP	Transmission Control Protocol
TT&C	Telemetry, Tracking, and Command
UDP	User Datagram Protocol
VC	Valve Center
ZARM	Zentrum für angewandte Raumfahrttechnologie und Mikrogravitation

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Appendix A Experiment Reviews

A.1 Preliminary Design Review (PDR)

REXUS / BEXUS

Experiment Preliminary Design Review

Flight: BEXUS 26

Payload Manager: TBC

Experiment: TUBULAR

Location: SSC, Esrange Space Center, Sweden **Date:** 6th Feb. 2018

1. Review Board members

Stefan Kramer, SSC (chair)
Veronica Botti (minutes)
Giorgio Parzianello, ESA
Koen Debeule, ESA
Simon Mawn, ZARM
Dieter Bischoff, ZARM
Katharina Schuettauf, DLR MORABA
Maria Holmström, SSC
Klas Nehrman, SSC
Jörgen Blomberg, SSC
Juha Keinström, SSC
Jianning, Li SSC

2. Experiment Team members

Gustav Dyrssen
Jordi Coll Ortega
Natalie Lawton
Nuria Agües Paszkowsky
Hamad Siddiqi
Muhammad Ansyar Rafi Putra
Pau Molas Roca

3. General Comments

- Presentation
  - The presentation was clear and well done.
- SED
  - In general, the SED was well done and appreciated by the panel.
  - The team should clarify better the objectives.
  - In general, the team should include more labelled diagrams instead of long pages of text.

4. Panel Comments and Recommendations

- Requirements and constraints (SED chapter 2)
  - There are too many functional requirements. The team should reduce them.
  - The requirements F16 to F27 do not need to be listed.
  - The team shall add a performance requirement about the volume of air to analyse.
  - The requirements P16 to P22 are all design requirements.
  - For the requirement P16 the team should specify the altitude.
  - The design requirement D8 is fine, but the team should remember that that 374Wh is the capacity of the battery at nominal temperature and with a current draw of 0.1A. A more typical capacity of 7Ah (196 Wh).
  - Regarding the design requirement D13 the team might expect the experiment environment to be below -30C.
  - The constraints listed in the SED are not real constraints.

- Mechanics
  - The team should consider also the locations and accessibility of the external electronic interface.
  - The team should think about a solution to access the experiment without taking it off from the gondola.
  - The set-up of the box needs to be re-discussed.
  - The team should consider a thermal insulation for the experiment since the experiment is drawing cold air from the environment.
  - The team should check the capability of the pump is enough to suck the required amount of air.

- Electronics and data management (SED chapter 4.2.2, 4.2.3, 4.5, 4.7, 4.9)
  - A consumption of 1 mA is underestimated.
  - The team should check how to connect the device to the microcontroller and choose a possible interface.
  - To reduce the voltage to that required the team shall use a DC/DC converter.

- Thermal (SED chapter 4.2.4 & 4.6)
  - The team should perform a thermal analysis of the experiment, especially considering that the experiment will suck very cold air from the external environment.
  - The team should finish to list the temperature ranges of the components.
  - The team should clarify which temperature they need inside the box.
  - The team should find an alternative solution to access the experiment in order to prevent unwanted openings of the box.

- Software (SED chapter 4.8)
  - The software design was well done.
  - The team should consider to perform some manual actions on the experiment. The experiment does not need to be all automatized.
  - If the team wants to keep the triggered watchdog, all the events should be activated from the beginning of the countdown. Maybe it's better to remove the watchdog.

- Verification and testing (SED chapter 5)
  - The verification matrix must be reviewed.
  - In general, not everything can be verified by test. Test is often proceeded by an analysis or review.
  - The team should make sure that the test really covers the requirement. M
  - any requirements point to the same test so a detailed test plan will be needed to ensure the test specifically addresses that requirement.
  - In some cases, it might be better to split out separate tests.
  - The team should add a test to verify the functioning of the pumping system.
  - The team should verify that the pump is able to produce the required velocity with such a small delta-p.
  - It's very important for the team to test the opening and closing of the valves.

- Safety and risk analysis (SED chapter 3.5)
  - The team, in general, should review the risk register.
  - In general, the risks are underestimated.
  - The team should foresee some managerial risks, such as the risk of someone leaving the team.
  - The team should consider as a major risk the partnership with the Finnish.
  - The team should consider as a major risk also the use of the single pump. This should be ordered early and tested and maybe it would be better to order at least two pumps.

- Launch and operations (SED chapter 6)

  - The chapter was well done, however the team should add more information about the recovery, since it is a critical part of the experiment.
  - The team should clarify where did they get the data about balloon descent rate.
  - The team should specify why they cannot flush on the ground.
  - The team should clarify whether the valve operation is linked to time or altitude.

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- Organisation, project planning & outreach (SED chapters 3.1, 3.2, 3.3 & 3.4)
  - The team should clarify the work packages and specific tasks of each team member in the WBS.
  - The Gantt chart is too basic and should be refined.
  - There is no mapping of team availability over the project period to the work required.
  - The team should clarify whether the project is part of a course.
  - The budget description is too basic. The team should describe all the costs and clarify better what is already covered and what needs to be covered.
  - The outreach plan is good but not implemented yet. The team should create soon a webpage and a page in different social media.

5. Internal Panel Discussion

- Summary of main actions for the experiment team
  - The team should verify that the bags and the pump work properly before the CDR.
  - The team should review the Requirements and Constraints section.
  - The team should further develop and document their electronics design.
  - The team should provide a more defined thermal analysis.
  - The team should improve the management section.

- PDR Result: conditional pass
- Next SED version due: v1-2, 12th March 2018

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A.2 Critical Design Review (CDR)

BEXUS
Experiment Critical Design Review

Flight: **BEXUS 26**

Payload Manager: TBC

Experiment: **TUBULAR**

Location: ESA, ESTEC, Noordwijk, The Netherlands **Date: 31 May 2018**

1. Review Board members

- Michael Becker (DLR)
- Kristine Dannenberg (SNSB)
- Alexander Kinnaird (ESA)
- Veronica Botti (ESA) –Minutes
- Stefan Krämer (SSC) – Chair
- Maria Snäll (SSC)
- Koen DeBeule (ESA)
- Piotr Skrzypek (ESA)
- Grzegorz Izworski (ESA)
- Katharina Schüttauf (DLR MORABA)
- Dieter Bischoff (ZARM)
- Simon Mawn (ZARM)

2. Experiment Team members

- Natalie Lawton
- Erik Fagerström
- Pau Molas Roca
- Gustav Dryssen

3. General Comments

Presentation
- The presentation was very clear and complete and the panel appreciated the approach of the team in analysing and finding a solution to possible issues.

SED
- The team may read the SEDs of BX_COSPA or BX_A5UNIBO for more information about similar pumps and experiment principles.
- The team should be consistent with thousand markers (,) and decimal markers (.) (e.g. in the budget).
- The team should keep the appendices as indicated in the SED Guidelines (in particular A for the review reports and B for outreach) but, in general, there are some excellent additional information.
- The document is going to end up very long. This is not a problem, but the team must try to be succinct using diagrams and summary tables where possible and not including unnecessary 'discussion'.
- The team should keep images compressed without reducing the readability.
- The team should describe what the "Brain" is the first time they mention it in the document.

4. Panel Comments and Recommendations

Requirements and constraints (SED chapter 2)
- Since the team deleted a lot of requirements and the document is getting very big, maybe it would be better to rewrite the updated requirements and put the old ones in the appendix.
- The team should add a note in the introduction and in the objectives to explain the reasons for changing, the type of gas that will be detected during the flight (i.e. from N2O to CO).
- Req. F6-F7: they are software requirements. The team should be aware that it's difficult to justify them in system level functional requirements. If they really want to keep them for verification it's ok,

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but in that case it would be better to put them in the design requirements or re-word them and put them in operational requirements..
- Req. F10 to F12: instead of saying “shall collect data”, the team should say “shall measure”.
- There are still some performance requirements missing, such as: amount of air, range accuracy and frequency of the flow rate, pressure measurements, temperature measurements and humidity. These requirements should be separate in different performance requirements.
- Req. D3: The requirement “shall not disturb the launch vehicle” should not be deleted but rather reworded such that is unambiguous and verifiable.
- Req. D4: the team should be more specific and define the type of connector, protocol, etc.
- Req. D5: the team should be more specific and define the type of connector, voltage, ripple, grounding, etc.
- Req. D7: the requirement only makes sense with the reference voltage. The team should add it.
- Deleting the duplicated temperature requirements does make sense, but the team shouldn’t delete those ranges. The team is advised to put them in the verification plan now.
- When stating “profiles of flight” the team should either state the specifics and/or reference the section manual.

Mechanics (SED chapter 4.2.1 & 4.4)
- The rack built out of strut profiles is a good choice because of flexibility in fixating the components inside and stiffness properties. The team should consider the attachment to the gondola which does not allow tolerances of the rails and which functions as lot of heat bridges.
- The team should consider how to absorb vibrations/shocks of the pumps? (“Bismat” clamps could be a solution).
- The team should specify how they plan to activate the valves. The team should be aware that they will heat up after a while and that there are valves with a high activation power but a lower holding power.
- The team should specify what kind of tubes and connectors are used and consider how to perform a leakage test, how to access any connection and how to seal any connection (it could be easy just raising the torque a little more, but could be difficult as well in case that an O-ring or sealing has to be changed).
- The team should avoid sharp corners, especially at racks with lower space and fulfilled with equipment (such as the “brain”.).
- Inline pressure sensor from ”FESTO” could be good.
- Mechanical pressure sensors based on pitot tubes may also be an option.
- The team should clarify what is the expected maximum pressure inside the bags and tubes. The team is advised to check the datasheet of the valves regarding leakage rate or perform tests with different pressure on both sides to ensure proper function.
- The team should make sure to define and use the right procedure to clean pumps and valves.

Electronics and data management (SED chapter 4.2.2, 4.2.3, 4.5, 4.7, 4.9)
- The team should consider the connector location carefully. It is very good to have easy access but it’s not good to have the cables/connector pointing out of the gondola, because the turn may protrude outside and increase the risk of damage during launch/landing. This issue can be discussed with payload manager during accommodation session.
- In general, the accessibility of the connector panel is pretty good but without any protection. The team should move this panel upwards to the top cover (access from above).

Thermal (SED chapter 4.2.4 & 4.6)
- Regarding the EPS extruded Styrofoam, the team should ensure that this material is suitable for low pressure environment. Many foams expand when the pressure decreases but do not restore completely when back in normal pressure which would cause open gaps of the insulation cover.
- From a thermal point of view the team is suggested to install big heat bridges with this attachment. It would be better to use a flat material or another strut profile fixated with thermal spacers and attached to the gondola with the help of rubber bumpers.
- The team should investigate any hot spots of the setup and try to spread the heat with heat sinks to serve better conditions for the surrounding components.
- In general, there are too many heat bridges in the experiment setup.
- To raise the conditions at the beginning the team could insert chemical heater(s) like hand warmers during late access.
- The team could colour the strut profiles with black paint to count on the effect by heating up by the sun while the setup faces into it.

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- The team should be aware that the expected lowest temperature on a BEXUS launch in October (day flight) is around -55°C.
- The team should specify how will the implementation of the insulation material looks.
- An internal temperature around +5°C is low. The team should consider that the performance decreases at lower temperatures.

Software (SED chapter 4.8)
- The team is suggested to implement hysteresis for automatic mode change and to filter the sensors.
- Regarding the process diagram in figure 44, there is no way out from the manual mode. The team should specify what are they planning to do if the connection to the ground station is lost.
- The team should clarify if/how they are planning to keep track of the time.
- A list of telecommands and supported telemetries is missing. The team should not forget to insert a command to query the storage status, general system status, update automatic timeline, update time and perhaps reinitialise/clean up the storage.
- The team should specify which is the file system used on the SD card. FAT is not recommended.
- The team should clarify the concept of mode switching based on the pressure sensors.
- It's a good choice to use three tasks for Arduino but in the Software design section the identification of these three tasks is missing. The team should add it.

Verification and testing (SED chapter 5)
- Only positive software testing is currently foreseen. The team should explore failure scenarios: resets of the microcontroller (during auto mode), loss of communication at inconvenient times, multiple loss of communication, loss of SD card (unplug, broken filesystem, etc.).
- Req. P12 to P14: the requirement should be verified by Review of Design and not by Inspection (you review a data sheet you inspect a model/build).
- The team should be careful that where items are already verified by analysis, the analysis remains valid if/when the design changes/evolves.
- The team should state within the test plan whether the testing item is flight, prototype or another kind of model; they should also state within the test plan which requirements will be verified and then write the plan to make sure it will clearly verify those requirements.
- The team should insert all these tests in the Gantt Chart and have a global test plan which would lays them out logically.
- The team should consider what happens if a test fails and a change is needed and understand how far to come back in the test plan.
- Doing a vibration test on a shaker is good learning experience for the team, but the team should pay attention to which spectrum(s) are applied to the experiment, as there are none specified for BEXUS.
- There is no need to remove the walls during the test. The team should engage a good test engineer to understand the process.
- The team should include a summary of one or two paragraphs (maybe with figure where relevant) for each test, and then make a separate complete report in the appendix.
- The team should specify for which reasons there are no concerns about bag burst.

Safety and risk analysis (SED chapter 3.5)
- Risk TC40: the severity is too low.
- The team, in general, should avoid the word "proper" when defining an action to mitigate any risks.
- EN10: the team should better clarify which is the risk and which is the foreseen action. "Vibration" does not mean anything.
- The team should consider some management risks, in particular regarding time availability.
- The team should also consider some operational risks.
- The team should check again the severity of some risks. In general, it is too high.
- In general there are many risk with the same code (same probability and severity) that are considered sometimes acceptable and sometimes unacceptable and an action is always foreseen. This is confusing. The team should clarify what is an acceptable risk for them and what is unacceptable and, based on that, they should think of an action or accept the risk.

Launch and operations (SED chapter 6)
- The team should add any safety risks associated with pressurised vessels during recovery.
- It is very good that there is already a checklist. The team should check it with SSC to confirm it is all possible before flight after the final ECTs.
- The team should use this checklist during the systems tests and update them, including photos, and making sure that the person doing the final version is the person who did it before.

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- The team should add any launch site requirements, such as a room, a laboratory for preparations or testing on ground.
- The team should add risk connected to the use of chemicals.
- The team should think of what could happen in case of hard landing and exposed gas or liquid.
- The team should insert in the launch and operation chapter (or link to the appendix) the cleaning procedure of the pump and valves.
- The team should use the checklist during the tests.
- The team should be aware that from T -3h to T- 1h the experiment will work on external power.

Organisation, project planning & outreach (SED chapters 3.1, 3.2, 3.3 & 3.4)

- In the Resources section, under Table 6, it is written that all the team members are currently enrolled in LTU master programmes. However, according to the team details, most of the students are bachelor students. The team should clarify.
- The team should be aware that, during the last months they will need to allocate more resources to the experiment.
- In the outreach section is written "a website WILL be launched…". If it has already been done the verb should be at the past, not at the future.
- The team should clarify who is responsible once the subsystems are assembled (i.e. system level AIT and launch/operations).
- The team should try to trace the critical path to know where to focus their efforts.
- The team should better clarify if the exam period is really blocked out.
- It is very good to have some internal deadlines.
- It seems that there is a very little margin at the moment (testing completed at the start of October); the team should not forget to plan some buffer time and, in case of late testing, the team should think about the associated risks and how to mitigate them (e.g. good analysis).
- The team should relate their resource availability to the Gantt chart and clarify how the impact of any delays on the project planning.
- Regarding the budget, the team should specify if they have considered any contingency for unexpected events.
- It would be great to have a dedicated outreach timeline/media plan to see when these events are happening; they could be used to punctuate the project (a nice break or celebration for you) and/or to build excitement around certain events.
- The team should add a picture of the experiment on the website.
- In the "Project" Section, in the website, the first word is "Problem". The team should change it with something like "objective", or something similar.
- The team should add a headline in the website to capture the attention of the reader. Something like "we launch an experiment to the edge of space…." could be a good starting point.
- The team should look again at the relative logo sizing (SNSA is too small) in the website.
- The website loads very slowly, especially large header photos. The team should consider optimising this and check its compatibility for mobile devices.
- In the Facebook page the team should expand the "about" section to include mention of the REXUS/BEXUS programme.

5. Internal Panel Discussion

- **Summary of main actions for the experiment team**
  - Update the mechanical design as per the recommendations.
  - Make the design decision regarding inlet pressure and humidity measurement (contact their mentor for further advice).
- CDR Result: **Pass**
- Next SED version due: **SED_v3-0**, due **3 weeks before IPR. Date TBD**

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A.3 Integration Progress Review (IPR)

BEXUS

Experiment Integration Progress Review

Page 1

1. REVIEW

Flight: BEXUS 26

Experiment: TUBULAR

Review location: IRF Kiruna / Sweden

Date: 23 / 24 July 2018

Review Board Members

1. Stefan Krämer (SSC)
2. Grzegorz Izworski (ESA)

Experiment Team Members

Natalie Lawton	Emily Chen
Hamad Siddiqi	Emil Nordqvist
Gustav Dyrssen	Erik Fagerström

2. GENERAL COMMENTS

2.1. Presentation

- Good Presentation. Good status update.

2.2. SED

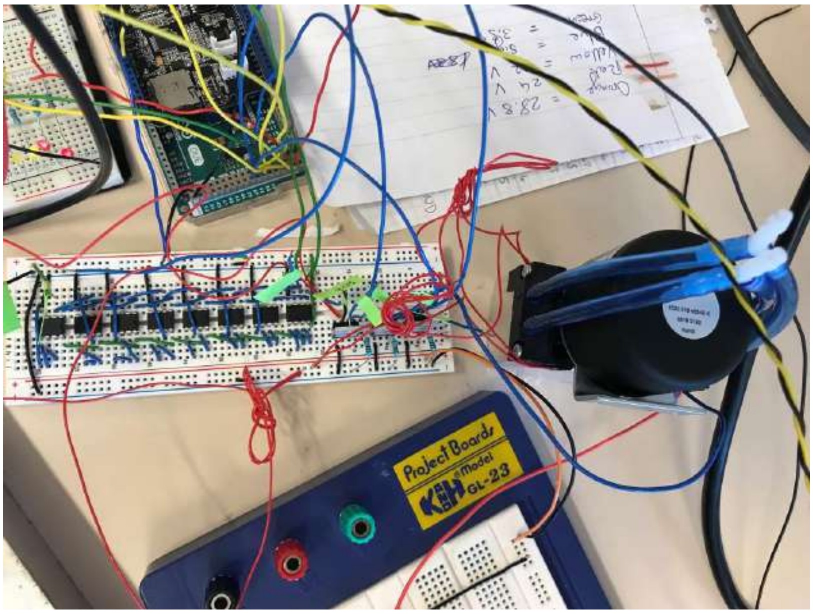
- No comments

2.3. Hardware

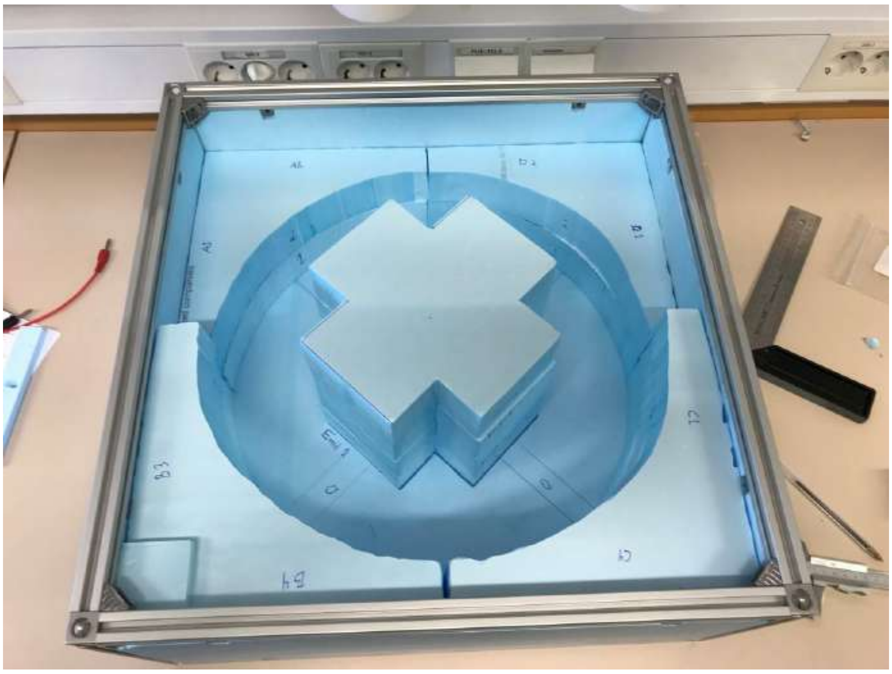
- Mechanics
  - Almost components are in house.
  - The Outer Structure made of BOSCH Profiles is mounted
  - Some parts of the insulation are cut and assembled
  - Pneumatic system not yet assembled since parts just arrived at the day of IPR.
- Electronics
  - PCB order has been send out to Manufacturer.
  - Breadboard finalised and working
    - Running Pump via Ground Station
    - Switching valves ((LED as place holders for Valves)
    - Heaters

- Power supply

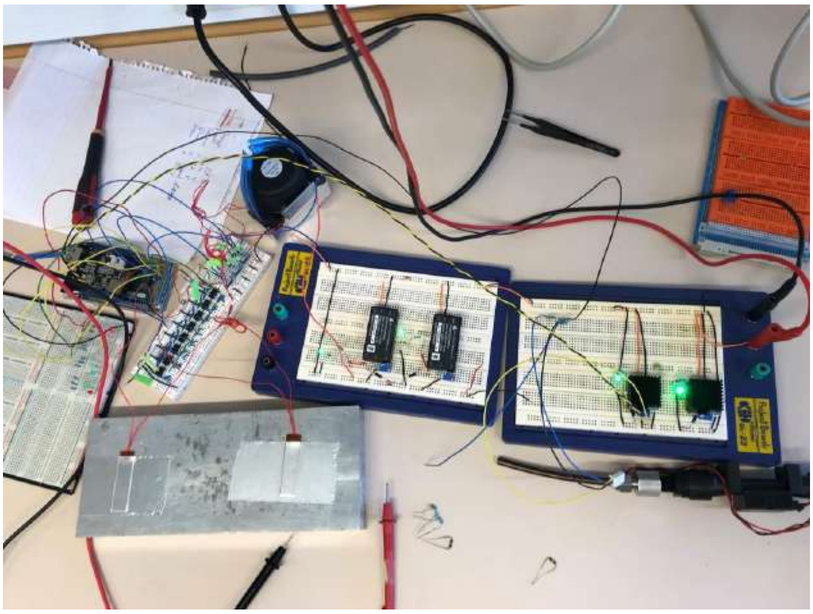
3. PHOTOGRAPHS



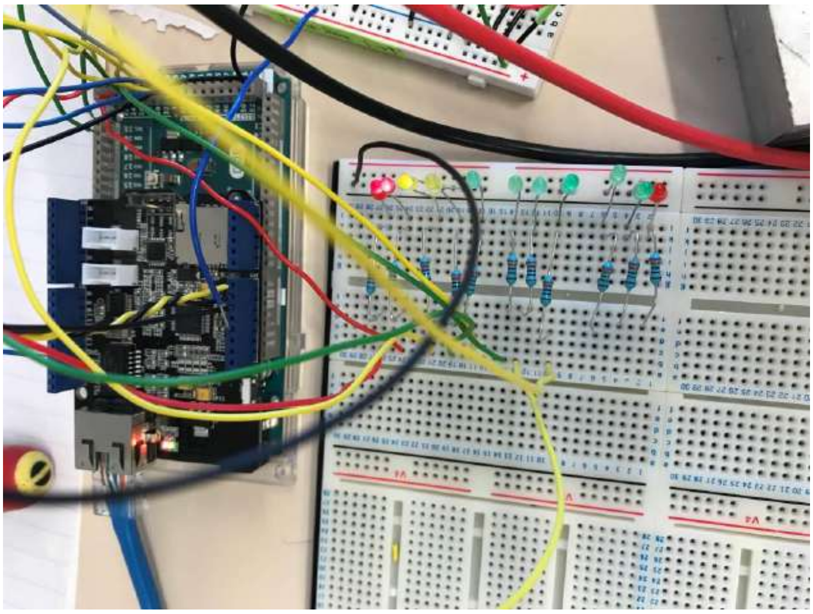
Picture 1: Pump and Temperature sensors on breadboard



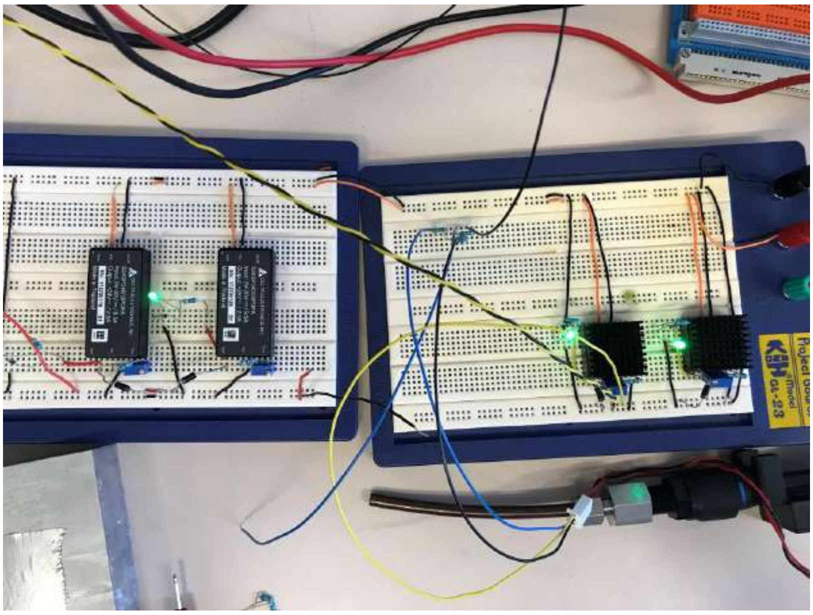
Picture 2: Frame for Air Coil including insulation material



Picture 3: Power Supply for two voltage levels on breadboard and heaters mounted to alumium block heat sink.



Picture 4: LED as placeholders for valves



Picture 5: DCDC converters on breadboard

4. REVIEW BOARD COMMENTS AND RECOMMENDATIONS

4.1. Science

- Check for suitable cleaning procedures. Cleanliness is highest priority when you manufacture and
    - Clean your tools with IPA before use
    - Clean your workspace (IPA, Aceton) thoroughly!
    - Use Gloves (powderfree !)
    - Check, if you can use the pressured air in your lab or if the system is oiled.
        - Un case of doubts, use Dried Air or Nitrogen from the bottles
        - Implement a filter on the low pressure side to avoid contamination of particles from the bottle.
    - Use standard cleanroom wipes
    - Keep the working area free from other people
    - Keep the tubes close with Kapton tape and away (boxed) from access of other people. As long the system is still open, use gloves and wipe off the ends and parts before assembly.
    - Consider flushing the system with IPA / Aceton after assembly. Leave the fluid inside the system for some hours to resolve the residual grease or oil.

4.2. Requirements and constraints (SED chapter 2)

- No comments

4.3. Mechanics (SED chapter 4.2.1 & 4.4)

- All components are in house except of:
    - Some fittings (Swagelok) for sample bags
    - Double sided tape
    - Sheet metal
    - Rail nuts
    - Pressure Sensor (ordered)
- All Tubing and fittings, valves have arrived
- Start assembling pneumatic system as soon as possible
    - Take your time for bending and fit checking. Avoid stress on tubing and fittings, it might introduce leaks!
    - Use contraction loops in straight tubes.

4.4. Electronics and data management (SED chapter 4.2.2, 4.2.3, 4.5 & 4.7)

- PCB order has been send out to Manufacturer.

- Have at least one or two spare boards ready
- Interface cable between AAC and CAC: Use self-made cable with PTFE insulation and D-Sub connector.
- Check if you have the opportunity to crimp the D-Sub connectors
- Solder according to the course you got at ESTEC.
- Test the full setup on your breadboard including all valves while you wait for the PCBs
    - Check each component on its own in the circuit and document it
    - Measure the current for the different modes

4.5. Thermal (SED chapter 4.2.4 & 4.6)

- Thermal setup with passive insulation looks ok. Will be verified by test and eventually improved

4.6. Software (SED chapter 4.8)

- Ground Station is running and the breadboard is fully operated via Ethernet
- The I2C and SPI I/F have to be verified
- All functions of Ground Station Operational mode and Manual mode work and have been verified
- The reconnection after communication loss is verified
- Status of valves and components are reflected on GS GUI
- Revise your S/W before uploading and mark your OBC with S/W version
- Team decided to continue with FAT 32 File system. Test this in a dedicated test and try to generate errors by e.g. power loss. Repeat the test many times!
- Calibrate your sensors, Temp and pressure. Calibrate all hardware spares and have the baseline measurements saved.
- Label your components

4.7. Verification and testing (SED chapter 5)

- Calibrate your sensors, Temp and pressure. Calibrate all hardware spares and have the baseline measurements saved.
- Testing Schedule and progress is reasonable. Document the results well.

4.8. Safety and risk analysis (SED chapter 3.4)

- Consider the risk of contamination during the different stages of the project
    - Manufacturing
    - Testing
    - Transport

- campaign

4.9. Launch and operations (SED chapter 6)

- Have Swagelok caps as RBF on your tubes for CD and later provided to Recovery crew.

4.10. Organisation, project planning & outreach (SED chapters 3.1, 3.2 & 3.3)

- Plan for implementation and testing is reasonable and achievable. Nevertheless, stay ahead of your planning.
- Deadline for finished and tested experiment is the first week in September for the testing campaign at FMI in Finland.
- Distribute small work packages to get stuff done

4.11. End-to-end Test

- Breadboard test with all functions and Ground Station was successfully performed
    - Placeholder LEDs instead of valves verifying the function of electronics and software
    - Pump function verified
    - Communication to ground station verified
    - Read out of I2C and SPI communication based temperature sensors not yet possible
    - Pressure sensor is to be delivered and verification of function pending
    - Heater function verified

5. FINAL REMARKS

5.1. Summary of main actions for the experiment team

- Look into the I2C and SPI libraries for sensor communication and make them work

5.2. Summary of main actions for the organisers

- Have frequent tele conference between Mentor and team.

5.3. IPR Result: pass / conditional pass / fail

- **Pass**

5.4. Next SED version due

SED_v4-0: 4th October 2018

BEXUS

Experiment Integration Progress Review

6. INTEGRATION PROGRESS REVIEW – IPR

Experiment documentation must be submitted at least five working days (the exact date will be announced) before the review (SED version 3). The input for the Campaign / Flight Requirement Plans should be updated if applicable. The IPR will generally take place at the location of the students' university, normally with the visit of one expert.

The experiment should have reached a certain status before performing the IPR:

- The experiment design should be completely frozen
- The majority of the hardware should have been fabricated
- Flight models of any PCB should have been produced or should be in production
- The majority of the software should be functional
- The majority of the verification and testing phase should have been completed

The experiment should be ready for service system simulator testing (requiring experiment hardware, electronics, software and ground segment to be at development level as minimum)

Content of IPR:

- General assessment of experiment status
- Photographic documentation of experiment integration status, with comments were necessary
- Discussion of any open design decisions if applicable
- Discussion of review items still to be closed
- Discussion of potential or newly identified review item discrepancies
- Discussion of components or material still to be ordered or received by the team
- Clarification of any technical queries directed towards the visiting expert
- Communication and functional testing (Service system simulator testing and E-link testing for REXUS and BEXUS respectively)

A.4 Experiment Acceptance Review (EAR)

BEXUS

Experiment Acceptance Review

Page 1

1. REVIEW

Flight: BEXUS 26

Experiment: TUBULAR

Review location: LTU Kiruna / Sweden

Date: 10th October 2018

Review Board Members

Stefan Krämer (SSC, Science Services, Payloads)

Experiment Team Members

Natalie Lawton	Núria Agües Paszkowsky
Kyriaki	Blazaki
Emily Chen	Jordi Coll Ortega

2. GENERAL COMMENTS

2.1. Review Summary

The Team presented a fully integrated Experiment and the functions were proven within a End to End test. The quality of manufacturing is very good and all functions were verified. The testing phase is finished and was performed successfully.

The Aircoil will be integrated at the campaign. The Experiment has been testes togher with the aircoil and fit checked.

2.2. Mechanics

Net Mass (measured)	n/a	kg
Gross Mass (measured)	24.17kg CAC: 11.95kg AAC: 12.22kg	kg

- The Mechanical integration is finished. The experiment looks is well mounted, safe and sturdy
- The separation level to the detachable CAC Box is clearly marked for recovery purpose
- Only a few sharp edges need rework

2.3. Electronics

Low Battery Voltage	24	1.17A

Average Battery Voltage	28.87V	0.750A / 1.25A
High Battery Voltage	31.64	1.5A

- The Electronics is finalised and fully tested
- The manufacturing quality is good
- The cables are harnessed

2.4. Software

Uplink	n/a
Downlink	162bytes/s

- Ground Station
  - Ground Station SW is finished and is looks good. All functions are visible.
  - Experiment status is clearly verifiable
  - The SW has a high level of complexity and information
- Experiment
  - SW design frozen since 13 Sept.
  - All functions are tested on durability
  - Communication verified

2.5. Verification and testing

- Pre campaign Testing phase is finished. All necessary tests were successfully accomplished.

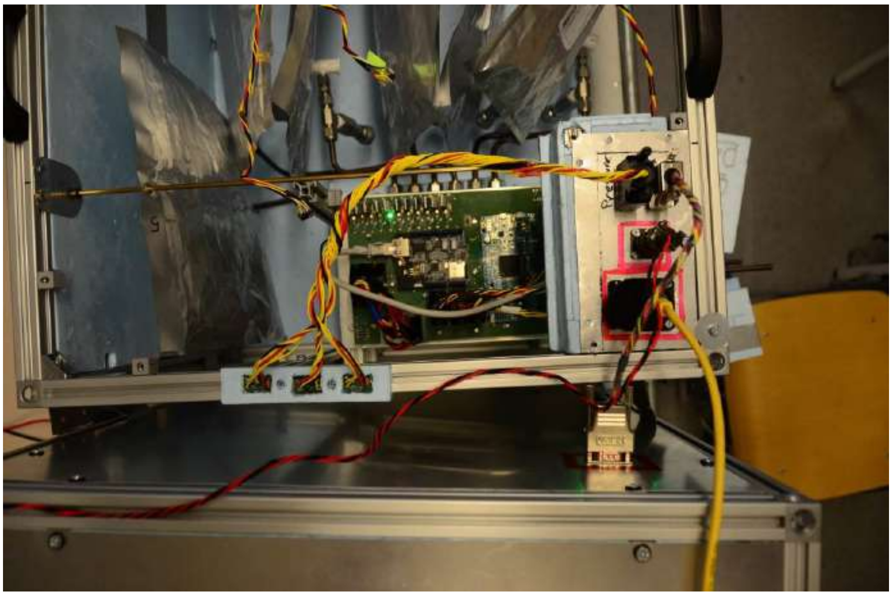
2.6. End-to-end Test

- The End to End test in a accelerated test mode was successful.
- All functions are verified.
- Valves open and close in sequence and depending on sensor input
- Bags are filled in sequence with air samples by the use of the pump

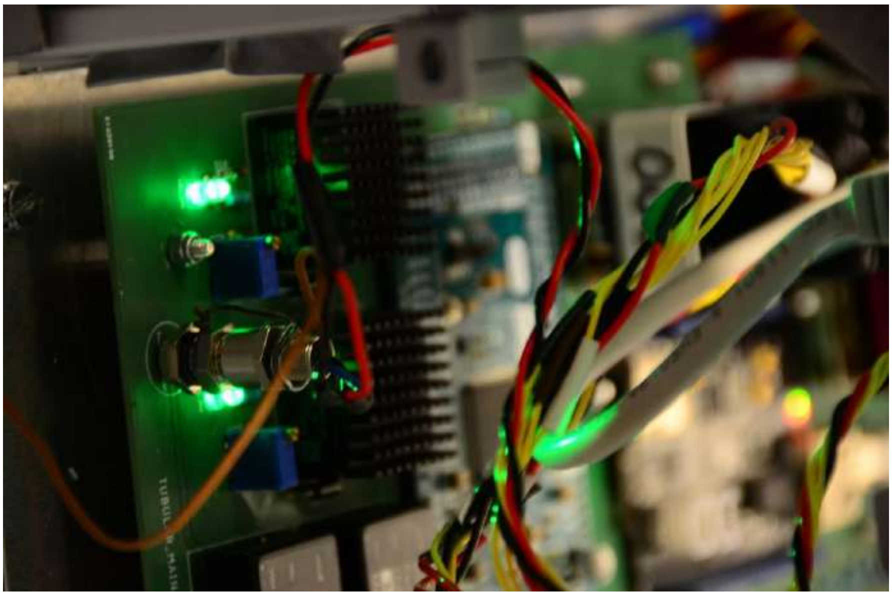
2.7. Launch Site requirements

- The team requires access to the gondola after FCT for flushing the system until Pick up of the gondola
- The procedure has been discussed and seems feasible. It will be discussed during the campaign with OPS and REC.

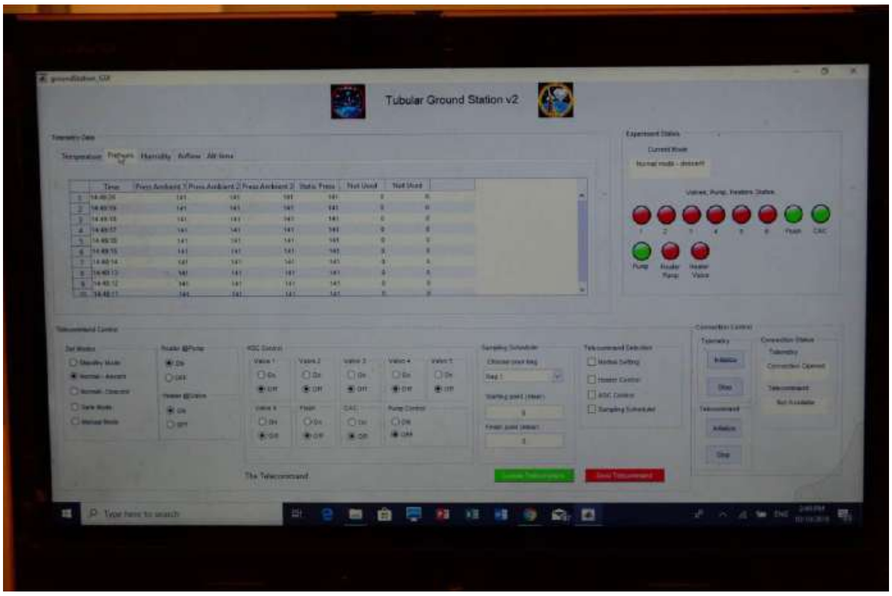
3. PHOTOGRAPHS



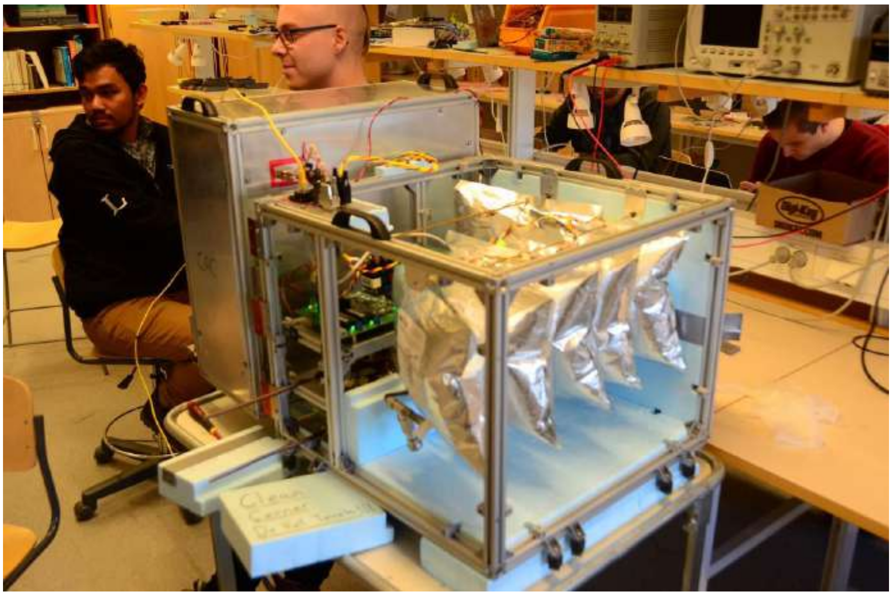
Picture 1: Top View Brain Box



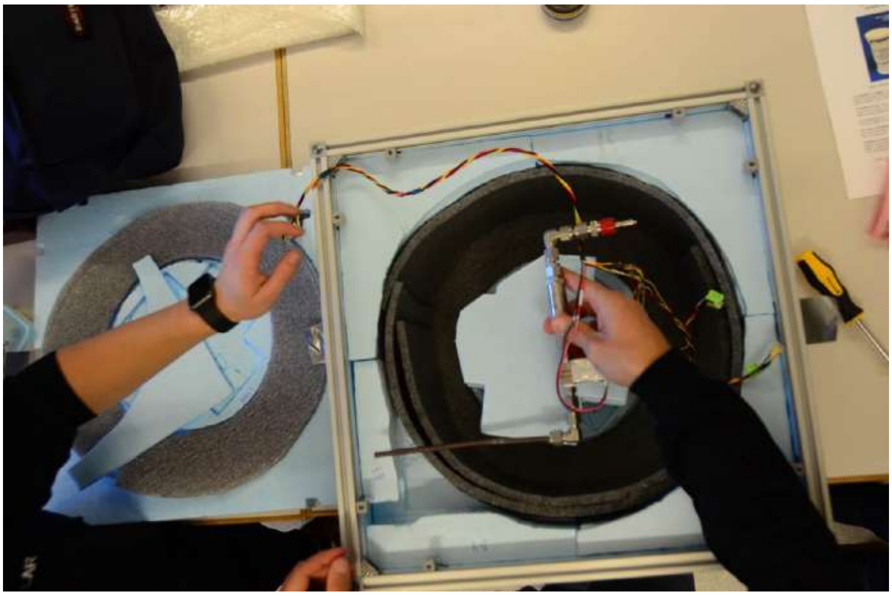
Picture 2: Detail of power connector Brain Box



Picture 3: Screenshot Ground Station GUI



Picture 4:Experiment Setup during End-to End Test with inflated bags



Picture 5: CAC box with valve for Aircoil

4. REVIEW BOARD COMMENTS AND RECOMMENDATIONS

4.1. Science

- No comments

4.2. Requirements and constraints (SED chapter 2)

- No comments

4.3. Mechanics (SED chapter 4.2.1 & 4.4)

- **Round the edges of sheet metal components**
- **Consider using some cable pads for attaching cables or tubes**
- **Replace the corner mounting brackets**

4.4. Electronics and data management (SED chapter 4.2.2, 4.2.3, 4.5 & 4.7)

- Tie cables up to structural parts where necessary
- Twisted pair only on power lines.

4.5. Thermal (SED chapter 4.2.4 & 4.6)

- No comments

4.6. Software (SED chapter 4.8)

- Ground Station

- No comments
- Experiment
  - No comments

4.7. Verification and testing (SED chapter 5)

- No comments

4.8. Safety and risk analysis (SED chapter 3.4)

- **No comments**

4.9. Organisation, project planning & outreach (SED chapters 3.1, 3.2 & 3.3)

- No comments

4.10. End-to-end Test

- No comments

5. FINAL REMARKS

5.1. Summary of main actions for the experiment team

- Bring the Experiment to Esrange and fly it.

5.2. Summary of main actions for the organisers

- **No actions**

5.3. EAR Result: pass / conditional pass / fail

- **Pass**

5.4. Next SED version due

6. EXPERIMENT ACCEPTANCE REVIEW – EAR

Experiment documentation must be submitted at least five working days (the exact date will be announced) before the review (SED version 4) This will take place upon delivery of the completed experiment to EuroLaunch. The review may take place at either the location of the students' university, or a DLR, SSC or ESA institute.

Content of EAR:

- Team presentation of project status
- Follow-up of IPR action items
- Review of schedule status with respect to REXUS program timeline and upcoming activities
- Demonstration of the fully integrated experiment
- Experiment mass properties determination/discussion
- Mechanical and electrical interface checkout
- Electrical Interface Test (REXUS service system simulator test or BEXUS E-link functionality test)
- Flight Simulation Test (FST) – including a full end to end system demonstration
- Experiment acceptance decision: Passed/conditional pass/failed. If a conditional pass is elected, the immediate action items should be discussed, along with an appropriate deadline(s)

Appendix B Outreach

B.1 Outreach on Project Website

To increase the projects out reach the TUBULAR Team created a project website. On the website there are descriptions of the project, a link to download the latest SED, information on the TUBULAR Team members and sponsors and a contact link. In addition the microblogging carried out by the TUBULAR Team is also displayed on the website.

Figure 71: The Home Page of TUBULAR's Website.

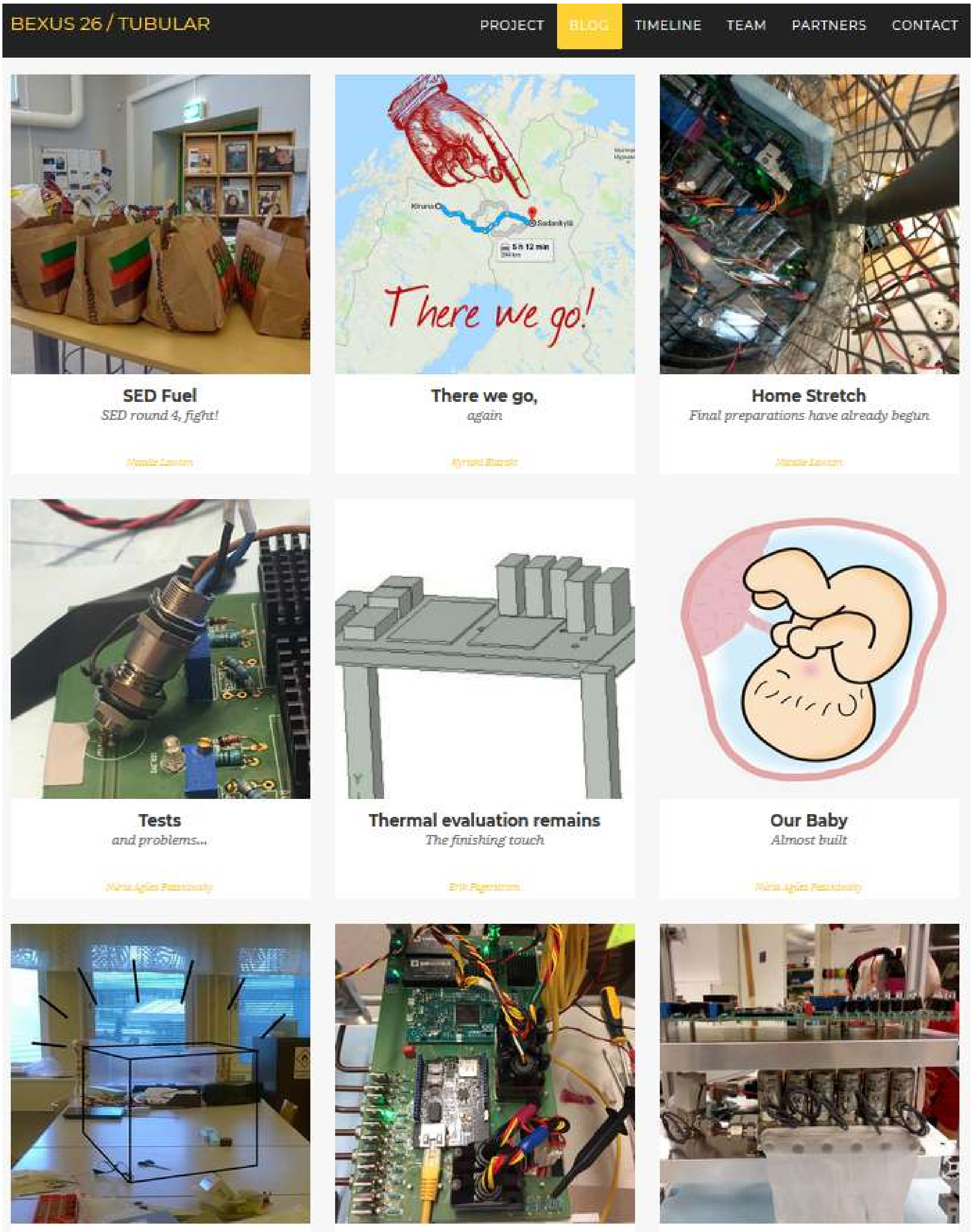


Figure 72: The Daily Microblogging Displayed on the Website.

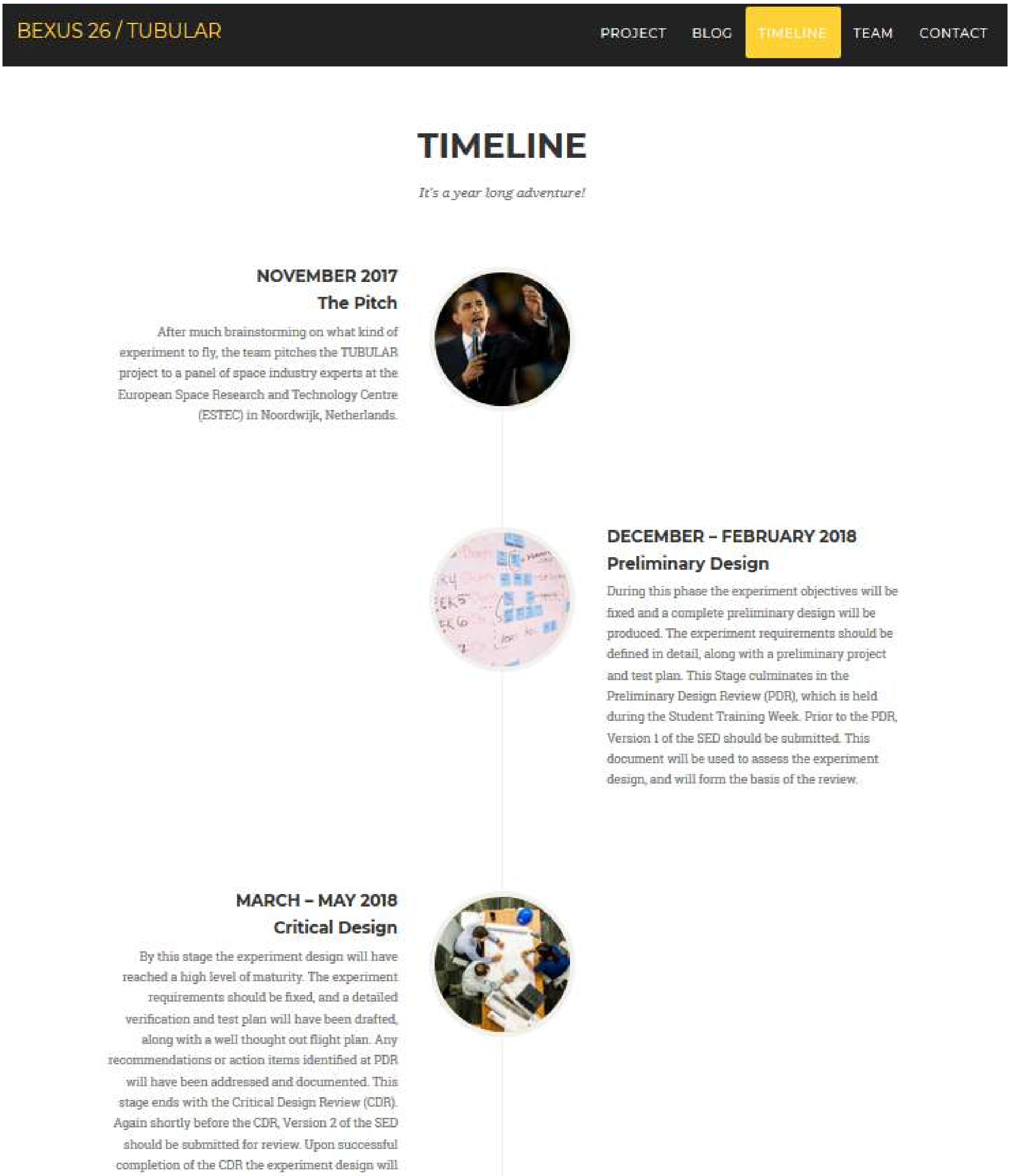


Figure 73: The Timeline for This Project Available on the Website.

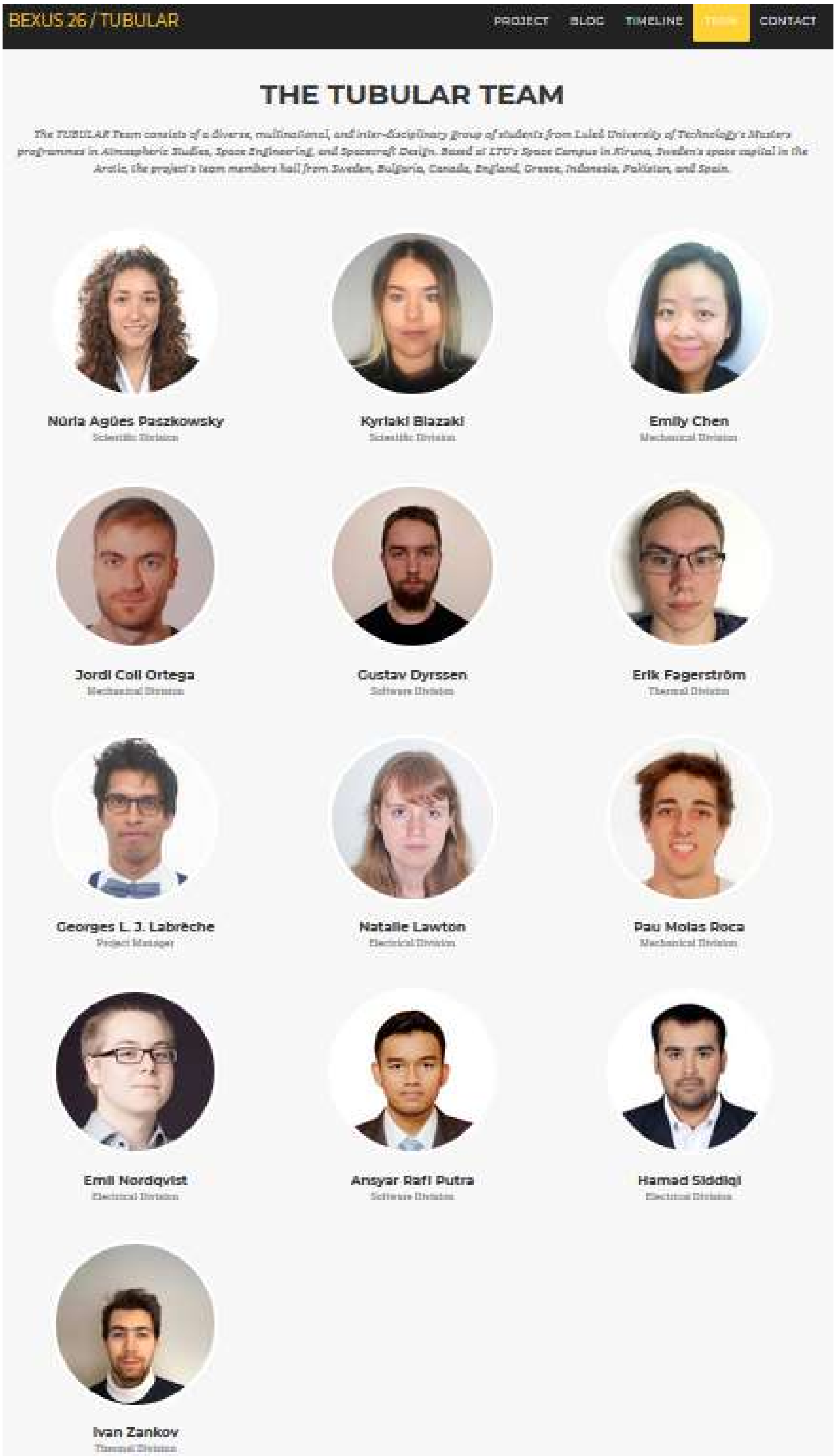
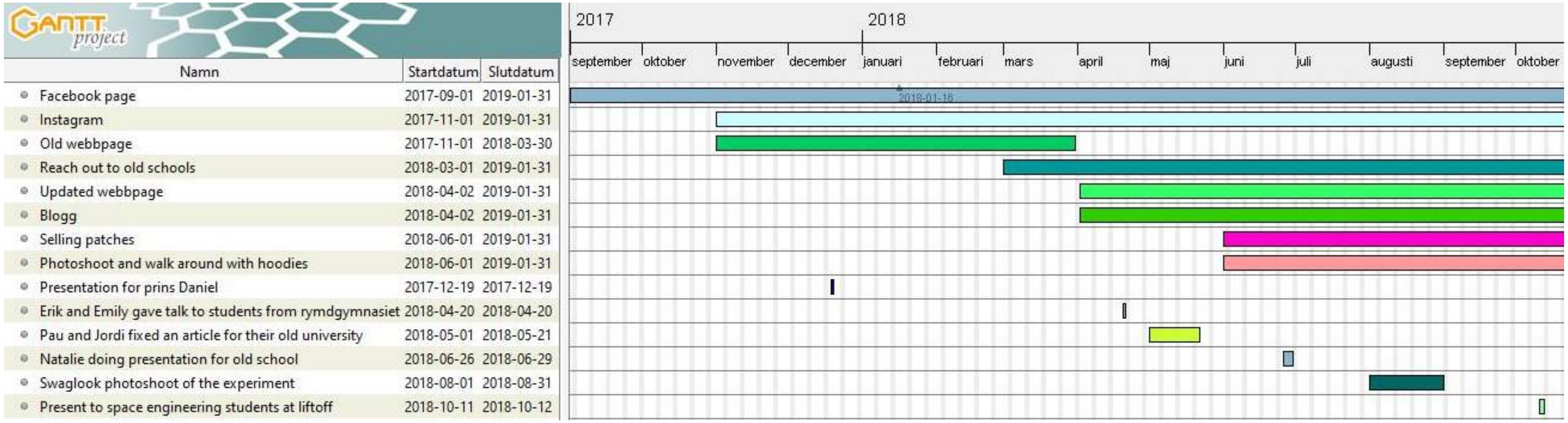


Figure 74: The Information of the Tubular's Team Members Available on the Website.

Figure 75: The Sponsors In This Project Available on the Website.

B.2 Outreach Timeline



Namn	Startdatum	Slutdatum
Facebook page	2017-09-01	2019-01-31
Instagram	2017-11-01	2019-01-31
Old webbpage	2017-11-01	2018-03-30
Reach out to old schools	2018-03-01	2019-01-31
Updated webbpage	2018-04-02	2019-01-31
Blogg	2018-04-02	2019-01-31
Selling patches	2018-06-01	2019-01-31
Photoshoot and walk around with hoodies	2018-06-01	2019-01-31
Presentation for prins Daniel	2017-12-19	2017-12-19
Erik and Emily gave talk to students from rymdgymnasiet	2018-04-20	2018-04-20
Pau and Jordi fixed an article for their old university	2018-05-01	2018-05-21
Natalie doing presentation for old school	2018-06-26	2018-06-29
Swaglook photoshoot of the experiment	2018-08-01	2018-08-31
Present to space engineering students at liftoff	2018-10-11	2018-10-12

Figure 76: Outreach Timeline for the Whole BEXUS Project.

B.3 Social Media Outreach on Facebook

Another outreach avenue is Facebook. On Facebook the TUBULAR Team posts photos, short text updates and links to our blog posts.

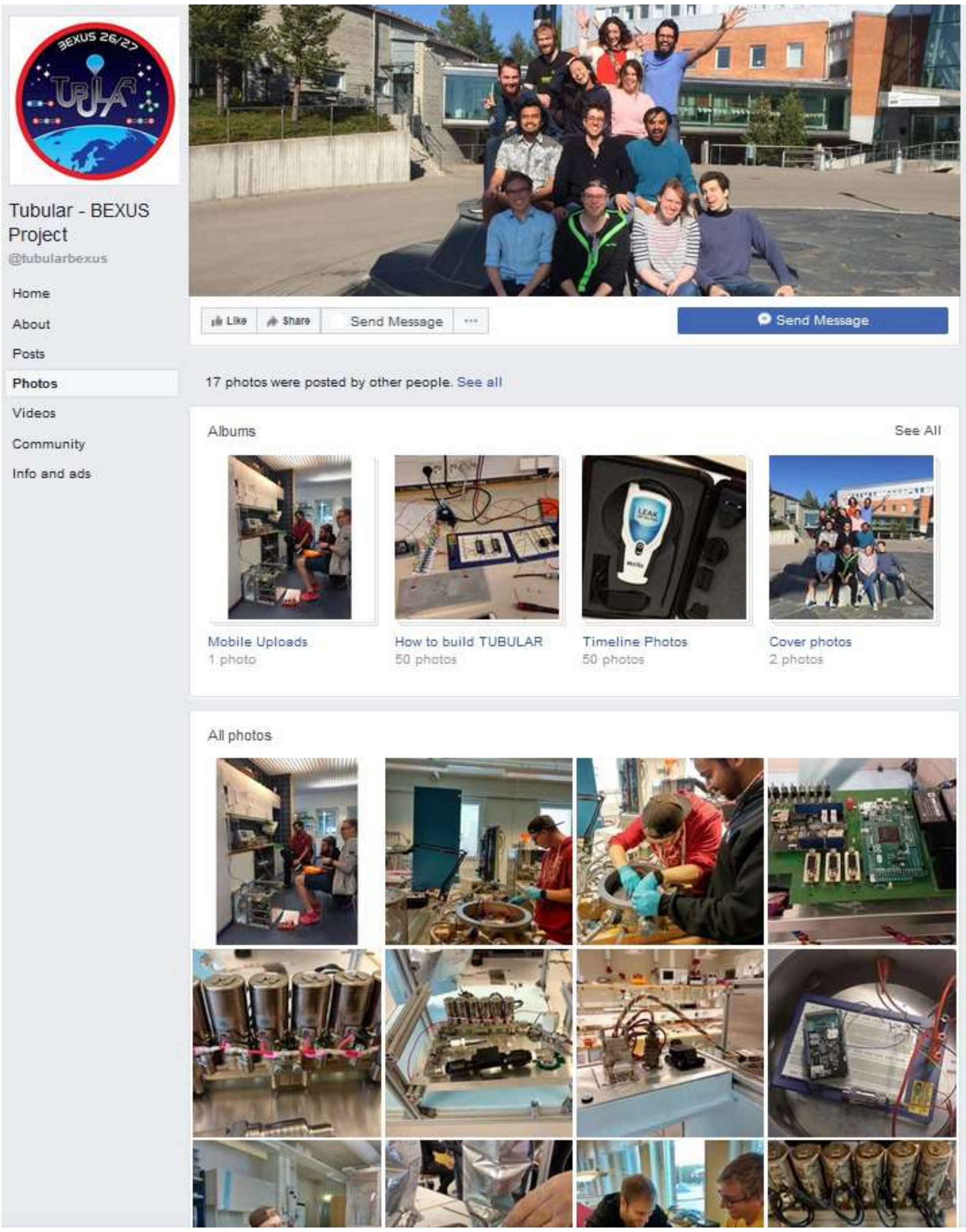


Figure 77: Photos from Social Media Outreach on Facebook.

B.4 Social Media Outreach on Instagram

On Instagram the TUBULAR Team posts regularly with updates on the project progress and what the TUBULAR Team has been up to.

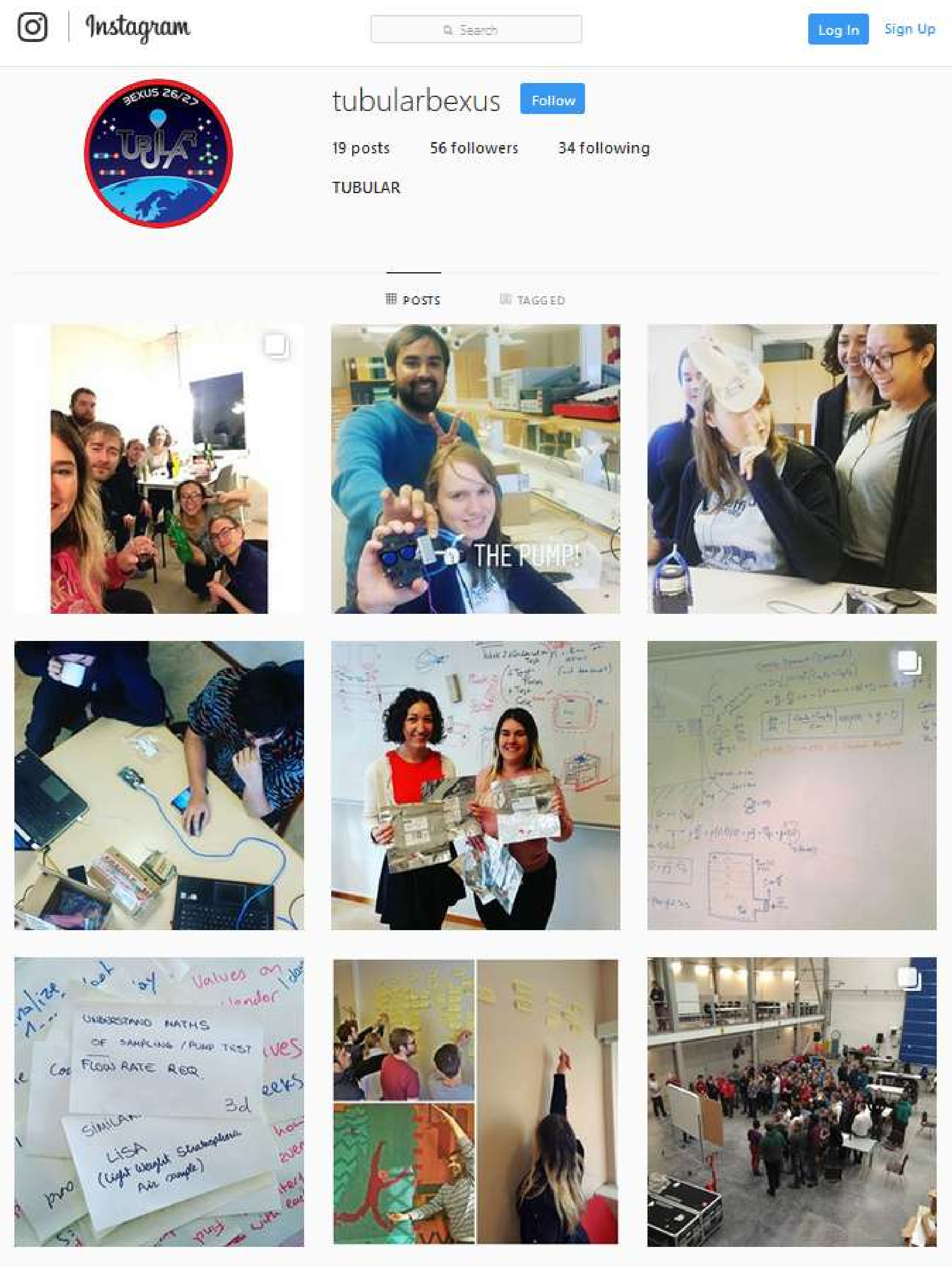


Figure 78: Some of the Social Media Outreach on Instagram.

B.5 Outreach with Open Source Code Hosted on a REXUS/BEXUS GitHub Repository

The TUBULAR Team has opened a GitHub Repository to share all the code used in the TUBULAR project. It was created with an open invite to all other REXUS/BEXUS teams to view, use and contribute to.

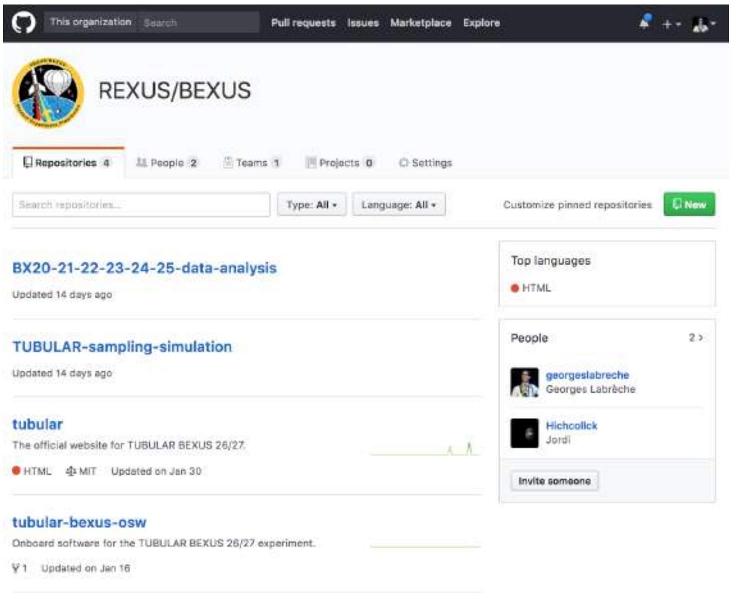


Figure 79: The Open Source Code Hosted on a REXUS/BEXUS GitHub Repository.

B.6 Outreach with Team Patch

The team also had patches made of the TUBULAR logo and 150 patches have been ordered. Around 70 of these have already been bought by the team for themselves and to give to friends and family. It is intended that the remaining 80 will be sold for a small profit at university.

Figure 80: A Photo of the Patch in Production Sent by the Company Making it.

B.7 Visit by the Canadian Ambassador

During Canadian Ambassador Heather Grant's visit at the Swedish Institute of Space Physics, the team got the honor to do a brief presentation of the TUBULAR project. It also included a short explanation regarding one of the electrical tests in the vacuum chamber. This is now displayed on the universities website with a link to the TUBULAR website.

Figure 81: Picture taken by Ella Carlsson which is shown on the LTU Website.

Ambassadörbesök på Rymdcampus

Publicerad: 21 september 2018

Rymdcampus i Kiruna har haft besök av Kanadas ambassadör Heather Grant. Värdar för besöket var Luleå tekniska universitet, Avdelningen för rymdteknik, IRF och EISCAT.

Under besöket fick organisationerna möjlighet att berätta om sina respektive verksamheter och visa upp sina lokaler.

Vid Avdelningen för rymdteknik fick Heather Grant ta del av avdelningens rymd- och atmosfärsverksamhet samt de relaterade Arktiska frågorna. Ambassadören fick också lära sig mer om vad forskningsgruppen i rymdtekniska system jobbar med i sitt nya NanoSatLab, och träffa masterstudenter som deltar i de internationella ballong- och raketprojektet Rexus/Bexus.

Läs mer om TUBULAR

Figure 82: The Text Accomopanying the Image on the LTU Webpage.

B.8 Attendance at Lift Off 2018

The team will attend Lift Off 2018 event and present the TUBULAR project for students, companies and organizations. The guests will have a chance to have a peek at the whole experiment and find out more about the REXUS/BEXUS programme.

Appendix C Additional Technical Information

C.1 Materials Properties

Material	**Density**	**Tensile strength**	0.2% **Proof stress**	**Ductile yield** A_5	**Modulus of elasticity**	**Brinell hardness**
EN AW - AlMgSi 6060	$2.7\ g/cm^3$	$245\ MPa$	$195\ MPa$	10%	$70GPa$	$75\ HB$

Table 59: Mechanical Properties of the Bosch Rexroth Strut Profiles.

Material	**Density**	**Tensile strength**	**Yield Strength**	**Modulus of elasticity**	**Brinell hardness**
Aluminum 5754	$2.67\ g/cm^3$	$190\ MPa$	$80\ MPa$	$70\ GPa$	$77\ HB$

Table 60: Mechanical Properties of the Aluminum Panels.

Material	**Density**	**Tensile strength**	**Maximum Temperature**
Styrofoam 250 SL-AN	$28\ kg/m^3$	$90\ kPa$	$75\ °C$

Table 61: Mechanical Properties of the Styrofoam Insulation/Protection.

C.2 Coiled Tube and Sampling Bag Example

C.2.1 CAC Coiled Tube

Figure 83: CAC Coiled Tube.

C.2.2 Air Sampling Bag

Figure 84: Air Sampling Bag.

C.3 Dimensions of the sampling bag

Table 62 shows how the dimensions of the bags change according to the sampled volume. This data has been obtained by testing and has been taken into account in order to determine the maximum number of bags that can be filled inside the box.

Volume	Length (horizontal)	Height (vertical)	Width
Empty	26.4 cm	28 cm	0.5 cm
0.5 L	26.4 cm	27.5 cm	1.5 cm
1 L	26 cm	27.5 cm	2 cm
1.5 L	25.5 cm	26.5 cm	4.5 cm
2 L	25 cm	25 cm	5.5 cm
2.5 L	24.5 cm	23 cm	7.5 cm
3 L	24 cm	22 cm	10.5 cm

Table 62: Dimensions of the Bags When Filled with Different Air Sample Volumes.

C.4 List of components in The Brain

Level 1 - Pump

List of components of Level 1:

A. 1 Magnesium filter

B. 1 Pump

C. 1 Temperature sensor

D. 2 Heaters

E. 3 Tubes

F. 8 interfaces

Level 2 - Valve Center

List of components of Level 2:

A. 1 Airflow sensor

B. 1 Static pressure sensor

C. 1 Temperature sensor

D. 2 Heater

E. 1 Manifold

F. 6 Sampling valves

G. 1 Flushing valve

H. 11 Tubes

I. 14 interfaces

Level 3 - Electronics

List of components of Level 3:

A. 1 PCB

B. 5 D-Sub female connectors

C. 1 E-link socket

D. 1 Power socket

All the electrical components connected to the PCB in Level 3 are summarized in Tables 63 and 64.

CAC		
Area	Electrical component	#
CAC	Solenoid valve	1
	Temperature sensor	3

Table 63: Connections to CAC Box.

AAC		
Area	Electrical component	#
Level 1	Pump	1
	Heater	2
	Temperature sensor	1
Level 2	Static Pressure sensor	1
	Airflow sensor	1
	Solenoid valves	7
	Heater	2
	Temperature sensor	1
Sampling bags center	Temperature sensor	3
Outside	Pressure sensor	3

Table 64: Connections to AAC System.

C.5 Pneumatic System Interfaces

All the fittings in the AAC and CAC subsystem were sponsored and manufactured by Swagelok.

C.5.1 Straight Fittings

(a) SS-200-6 (b) SS-400-1-2

Figure 85: Straight Tube and Male Fittings.

C.5.2 90 Degree Fittings

(a) SS-400-9 (b) SS-400-2-2 (c) SS-400-8-4

Figure 86: Various Kinds of 90 Degree Fittings

C.5.3 Tee Fittings

(a) SS-400-3 (b) SS-400-3-4TTM (c) SS-400-3-8TMT

Figure 87: Various Kinds of Tee Fittings

C.5.4 Quick Connectors

(a) SS-QC4-B-4PF (b) SS-QC4-B-200 (c) SS-QC4-D-400

Figure 88: Quick Connect Body and Quick Connect Stem With Valve

C.5.5 Reducer and Adapters Fittings

(a) SS-400-6-2 (b) SS-4-TA-7-4RG (c) SS-300-R-4

Figure 89: Various Kinds of Reducer and Adapters Fittings

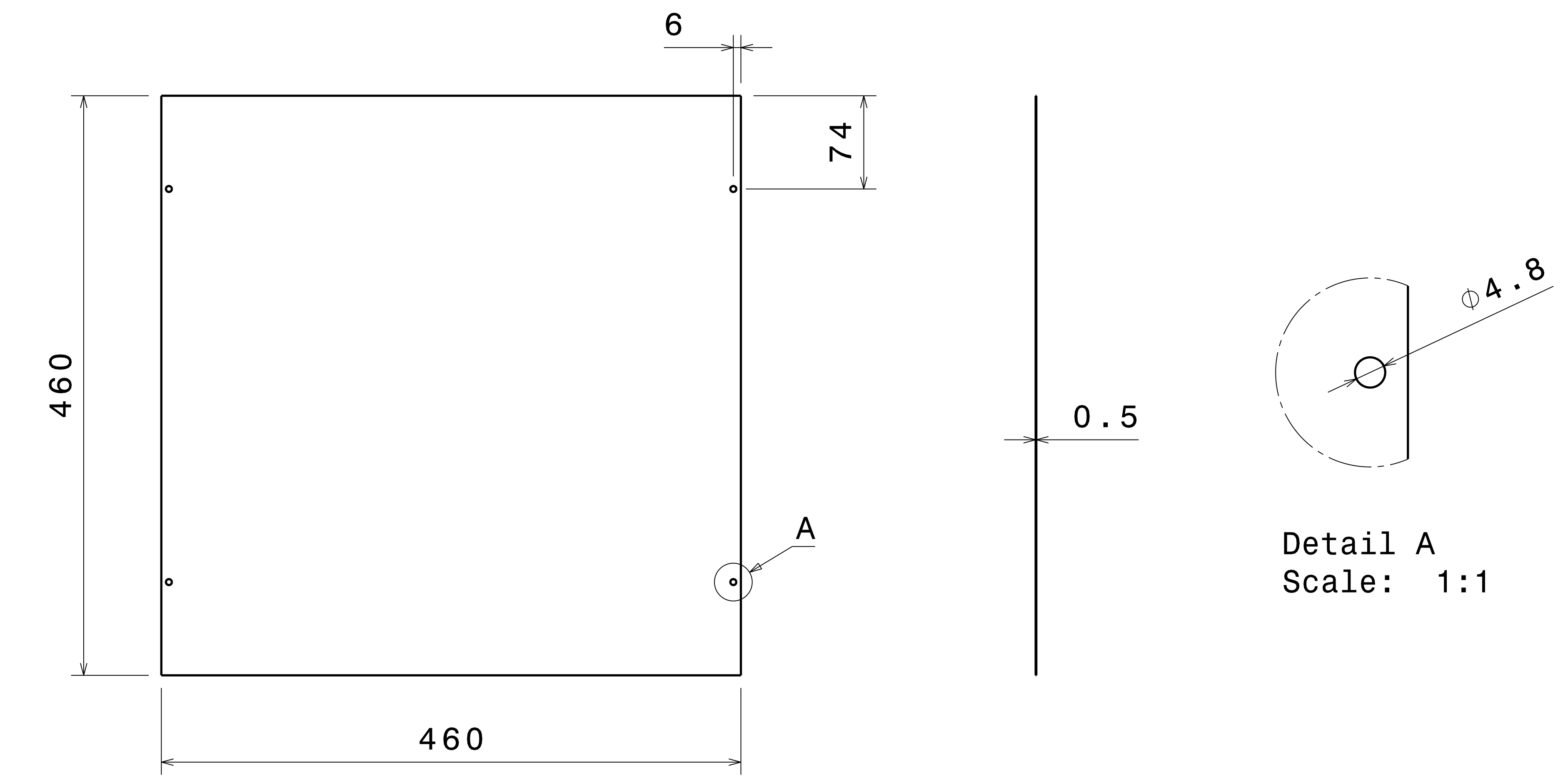
C.5.6 Port Connections and Ferrule Set

(a) SS-401-PC (b) SS-400-C (c) SS-400-SET (d) SS-6M5-4M

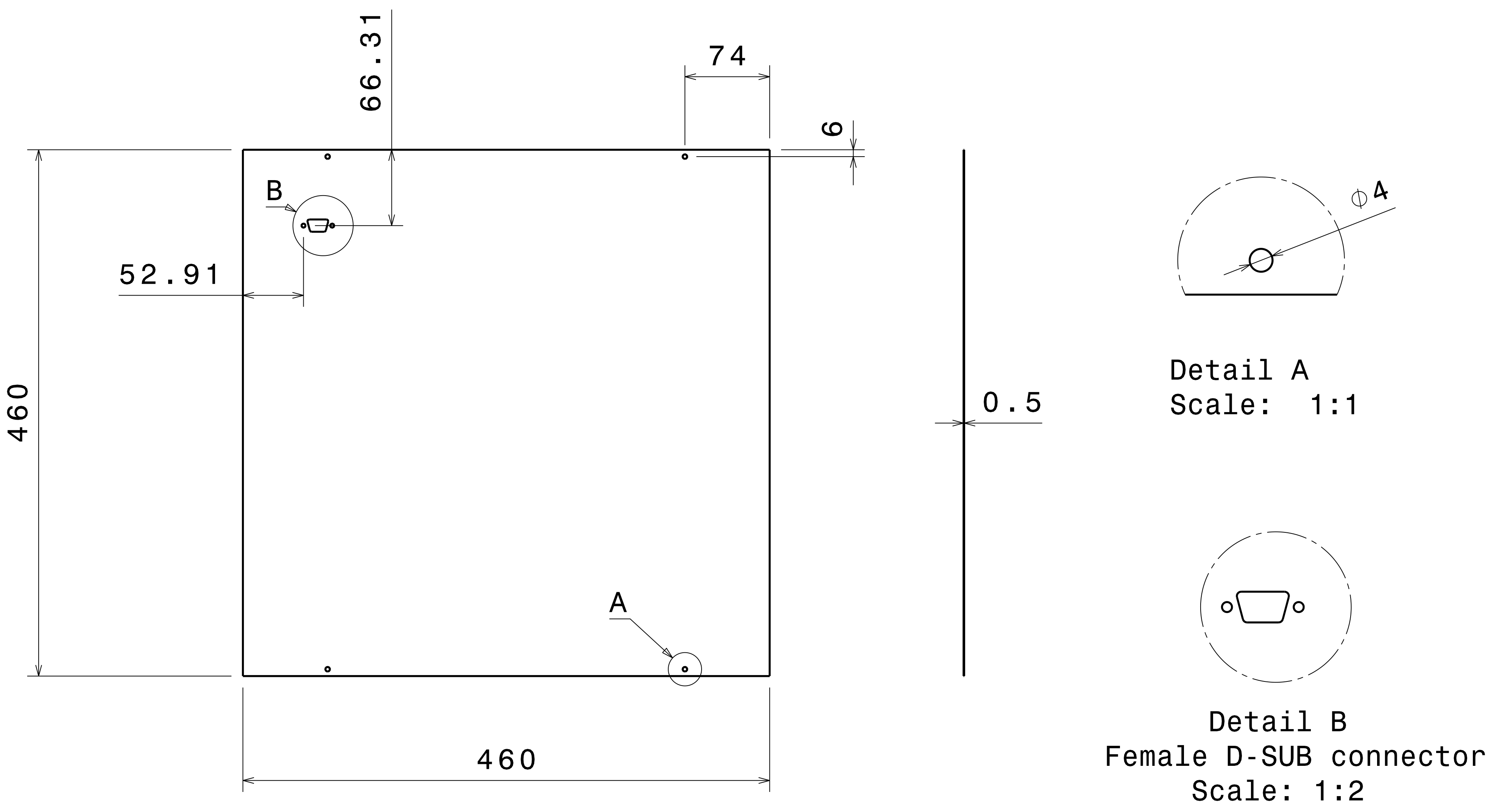
Figure 90: Various Kinds of Port Connections and Ferrule Set

C.6 Manufacturing Drawings

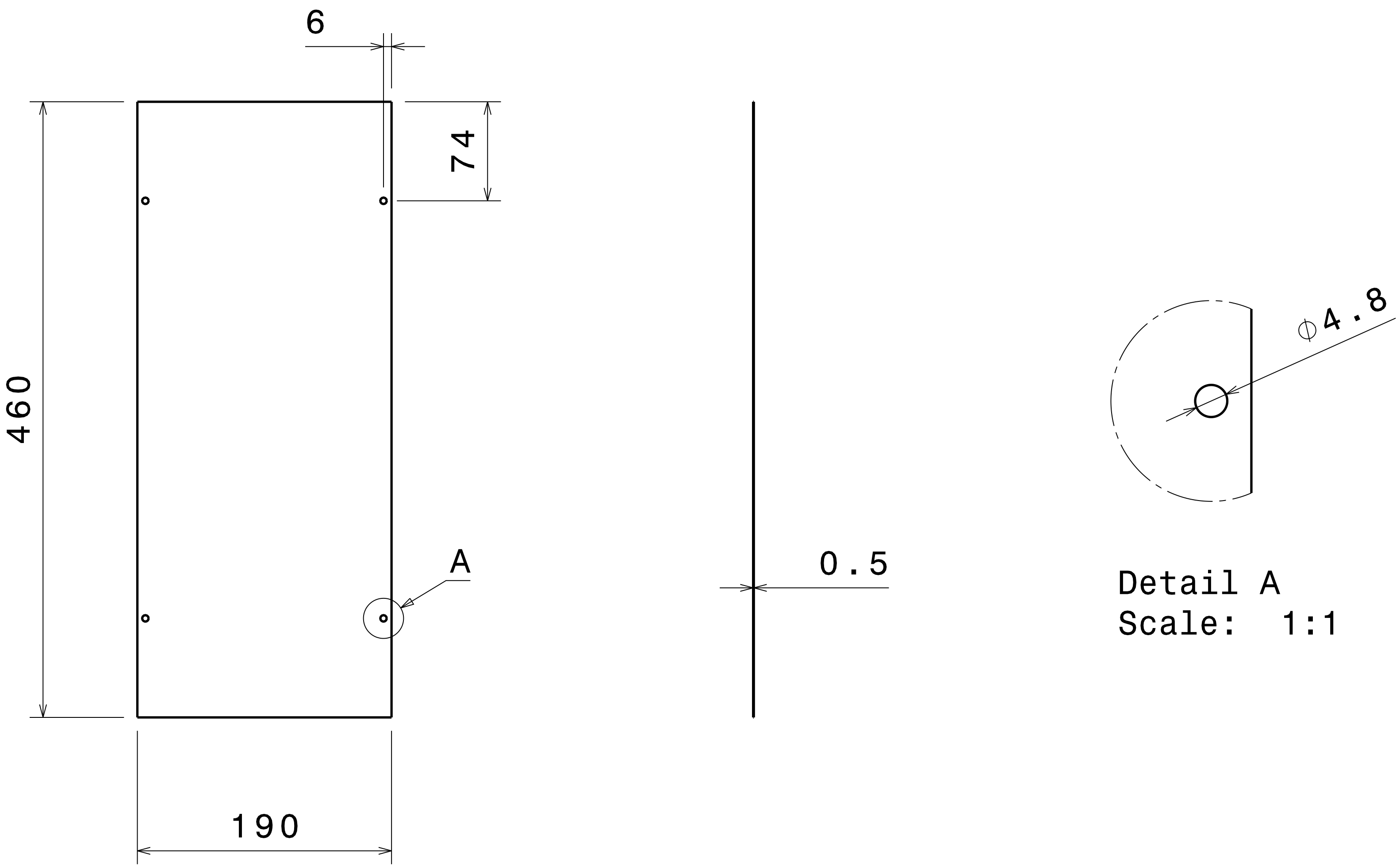
The following drafts are to be used to manufacture the mechanical components of the experiment.



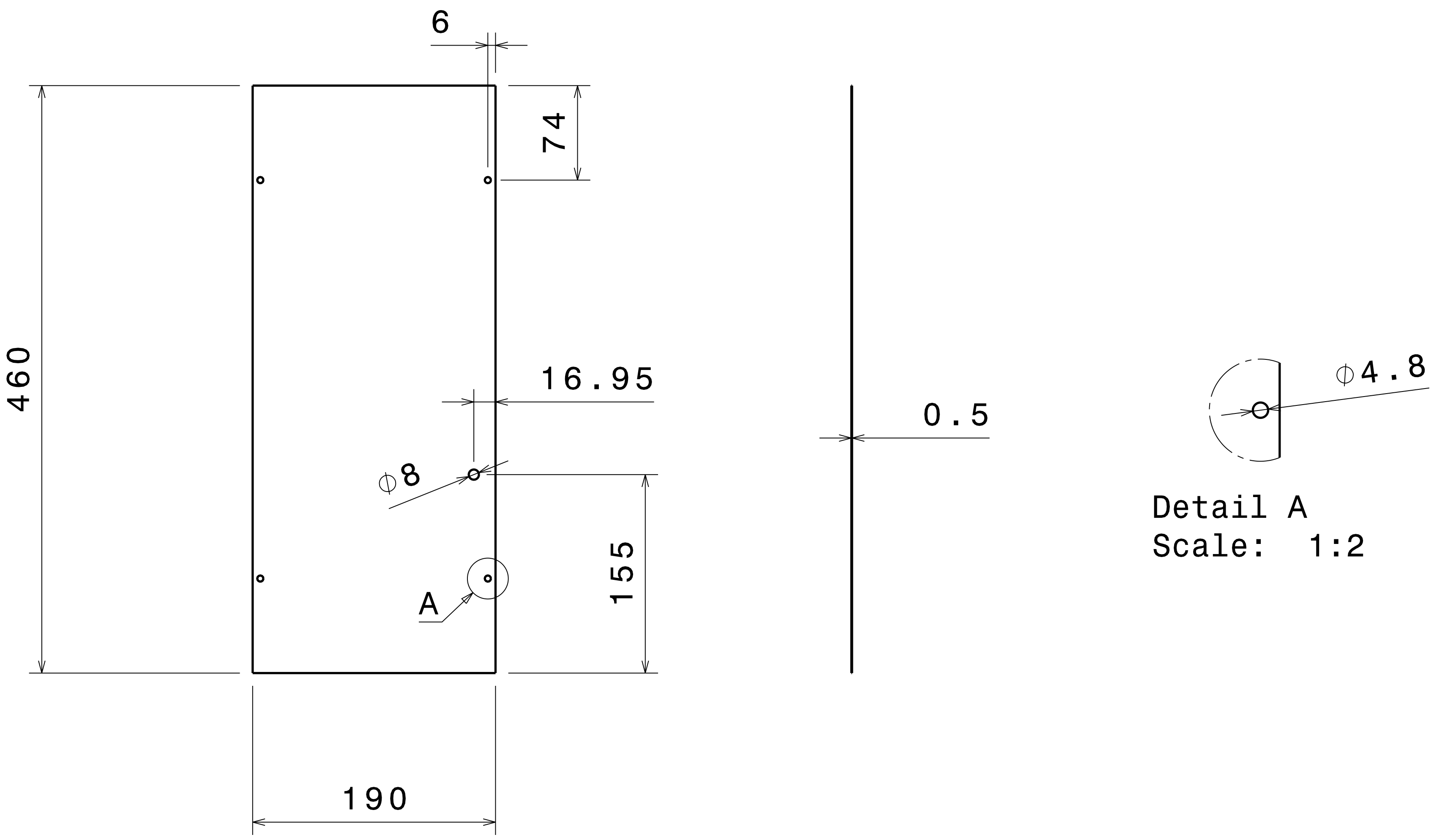
DESIGNED BY: Jordi Coll Ortega	TEAM: TUBULAR - BEXUS 26		
DATE: 26/09/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Pau Molas Roca	PART ID: M15.1	PART NAME: Bottom wall - CAC	
DATE: 27/09/2018	MATERIAL: ALUMINUM 5754		AMOUNT: 1
SIZE A4 / SCALE 1:5	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



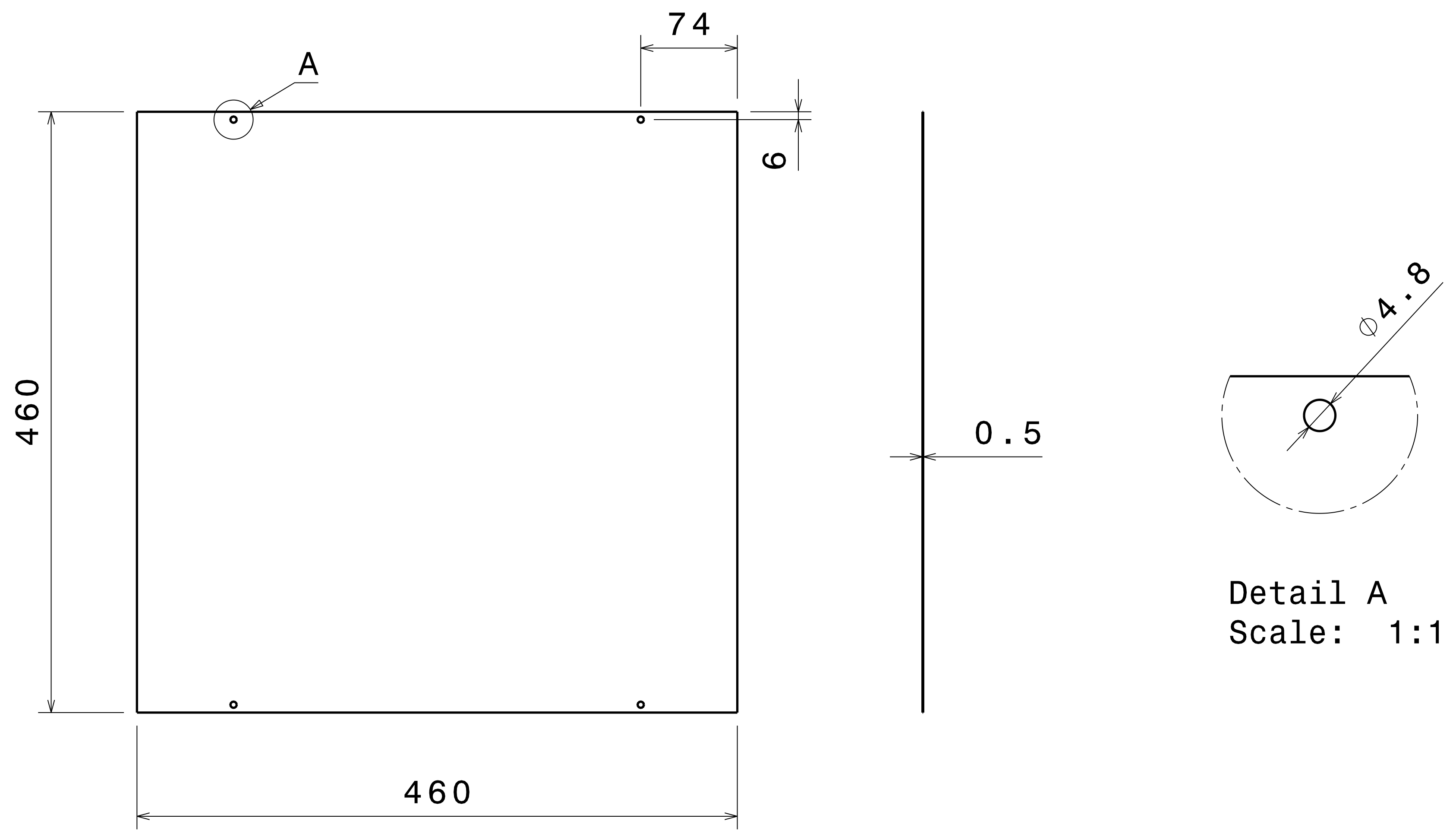
DESIGNED BY: Jordi Coll Ortega	TEAM: TUBULAR - BEXUS 26		
DATE: 26/09/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Pau Molas Roca	PART ID: M15.2	PART NAME: Top wall - CAC	
DATE: 27/09/2018	MATERIAL: ALUMINUM 5754		AMOUNT: 1
SIZE: A4 / SCALE: 1:5	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



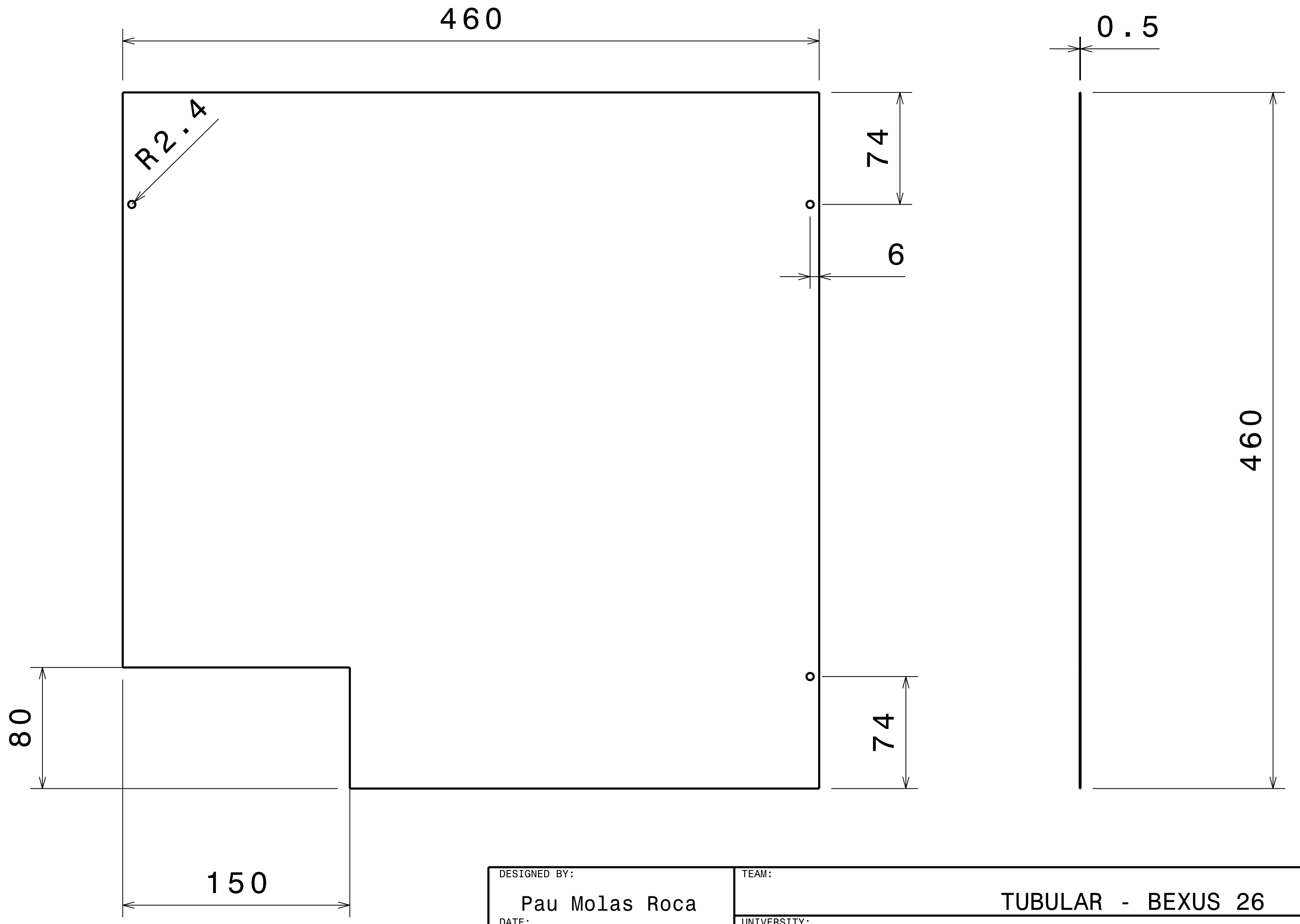
DESIGNED BY: Jordi Coll Ortega	TEAM: TUBULAR - BEXUS 26		
DATE: 26/09/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Pau Molas Roca	PART ID: M15.3	PART NAME: Lateral wall - CAC	
DATE: 27/09/2018	MATERIAL: ALUMINUM 5754		AMOUNT: 3
SIZE A4 / SCALE 1:5	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



DESIGNED BY: Jordi Coll Ortega	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Pau Molas Roca	PART ID: M15.4	PART NAME: CAC lateral wall - Inlet/Outlet	
DATE: 02/10/2018	MATERIAL: ALUMINIUM 5754		AMOUNT: 1
SIZE: A4 / SCALE: 1:5	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



DESIGNED BY: Jordi Coll Ortega	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Pau Molas Roca	PART ID: M15.5	PART NAME: Bottom wall - AAC	
DATE: 01/10/2018	MATERIAL: ALUMINUM 5754		AMOUNT: 1
SIZE A4 / SCALE 1:5	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



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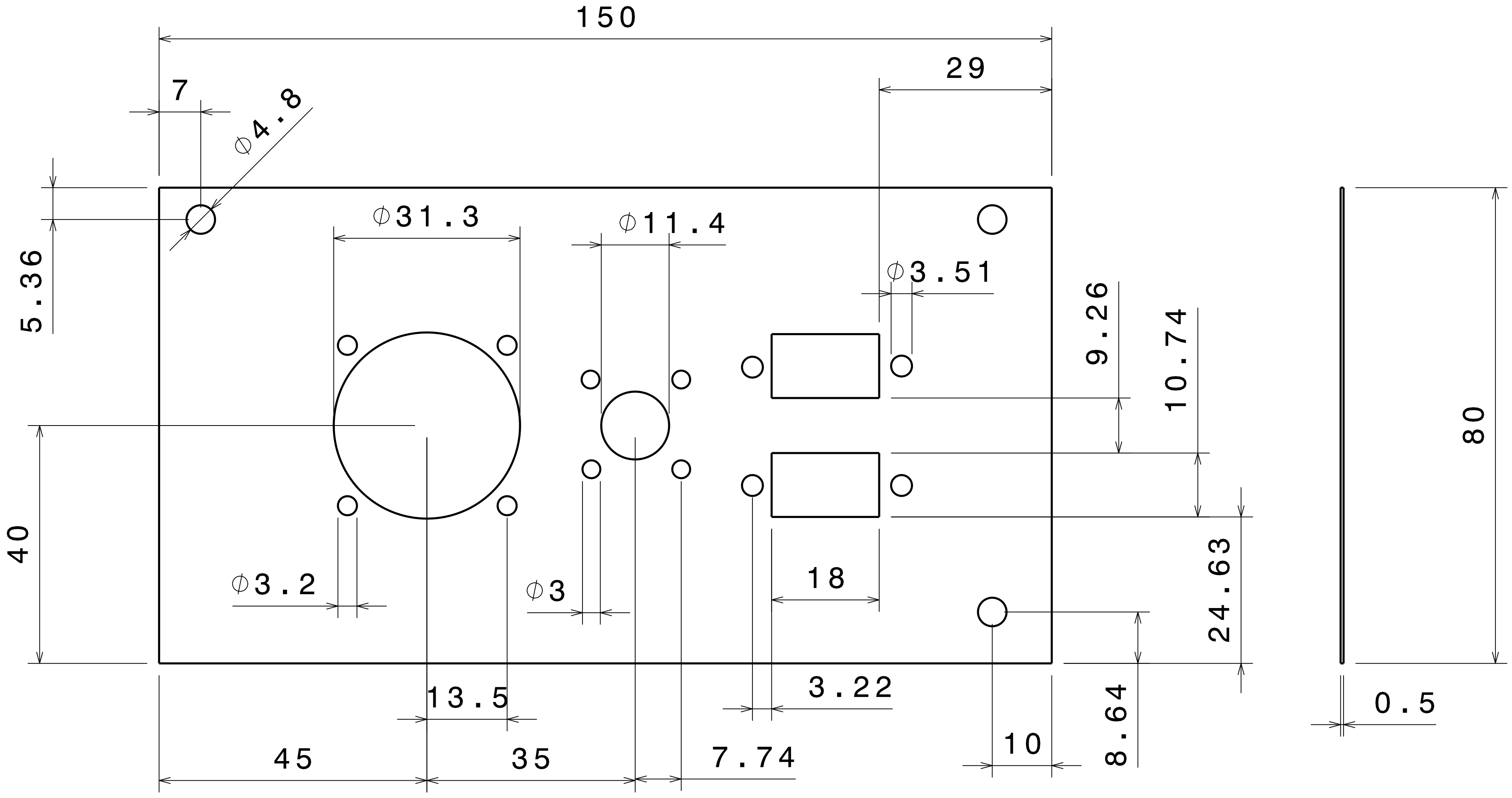
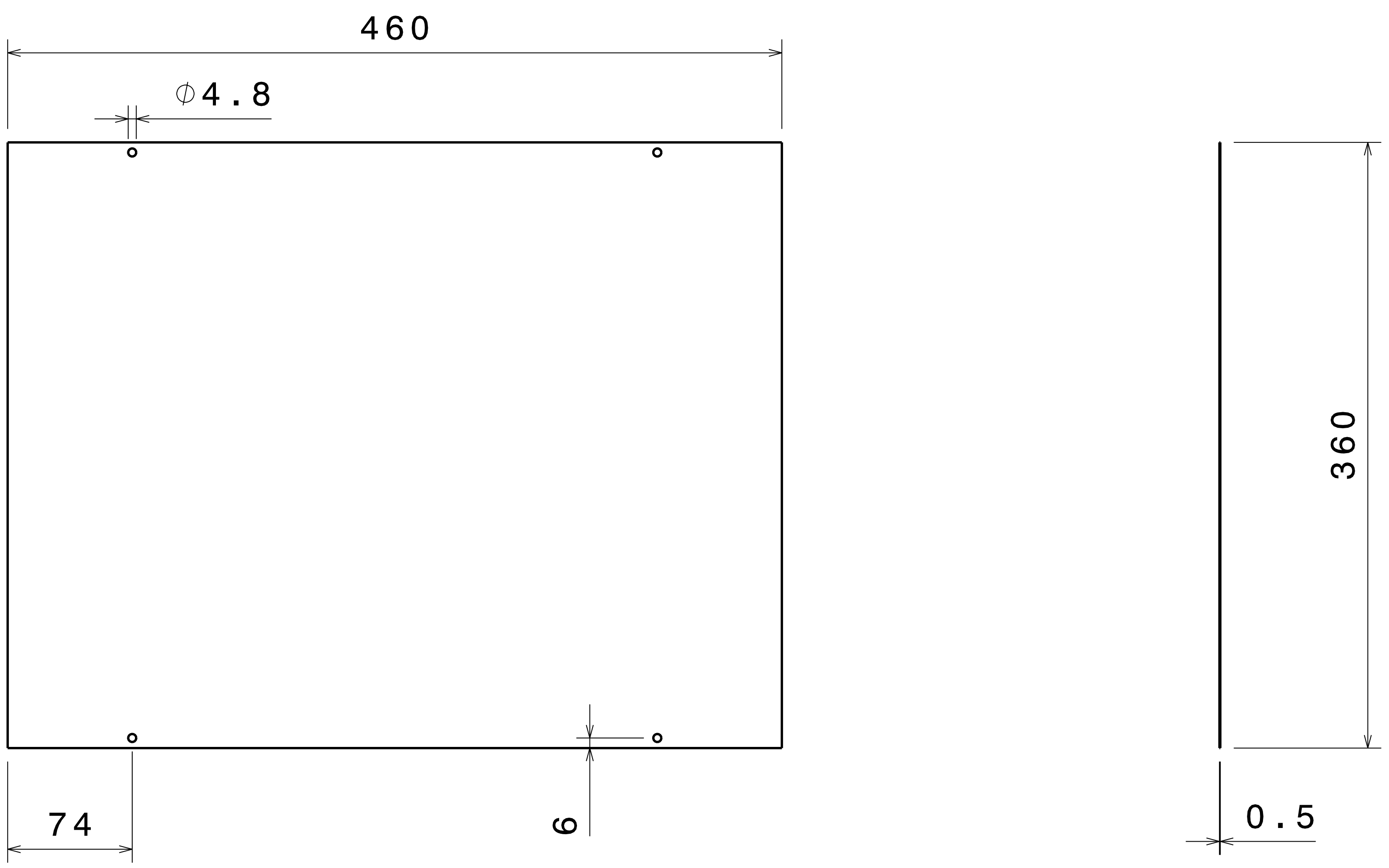
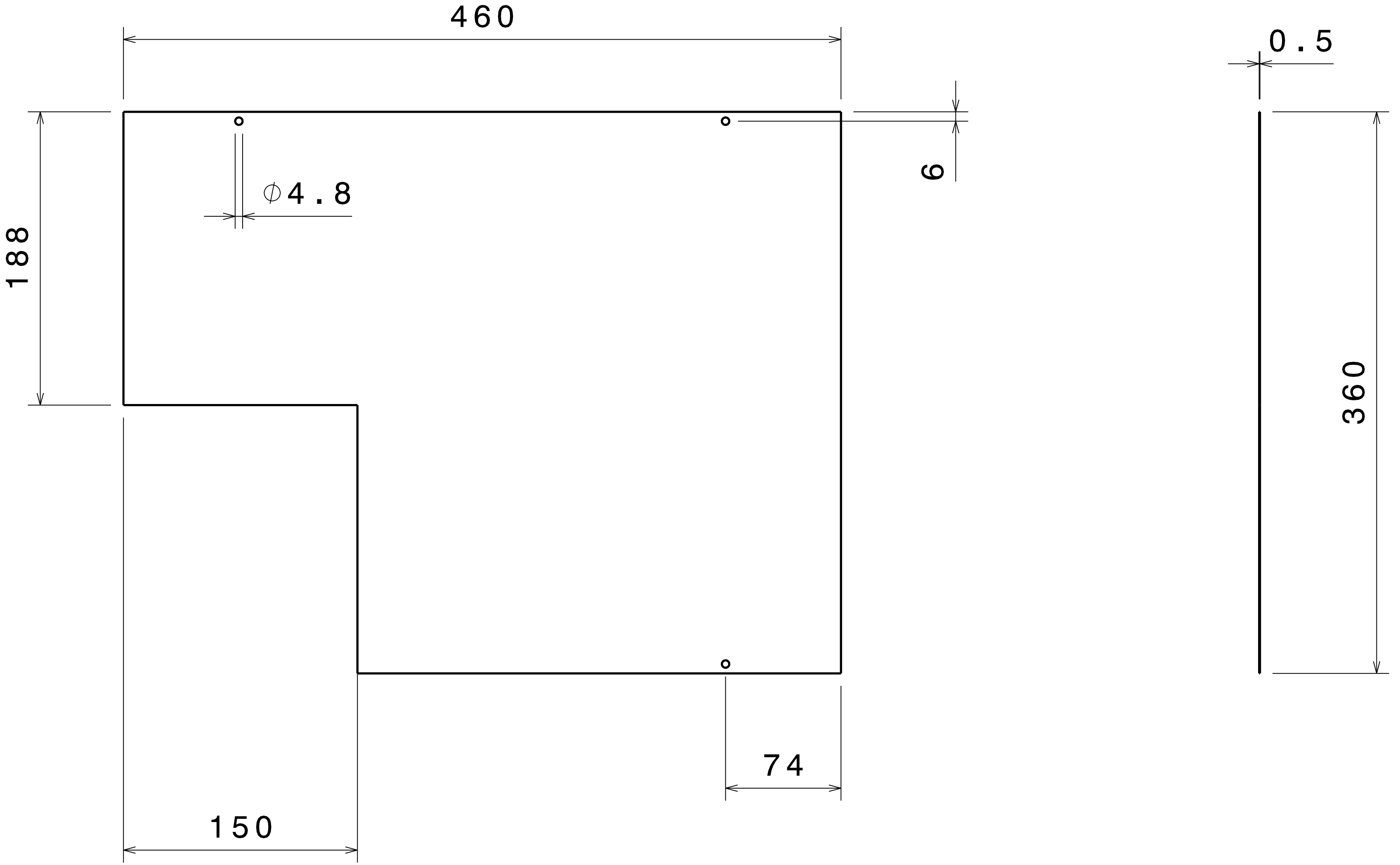
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M15.6	PART NAME: AAC - Top Wall	
DATE: 02/10/2018	MATERIAL: Aluminum Sheets		AMOUNT: 1
SIZE A4 / SCALE 1:4	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



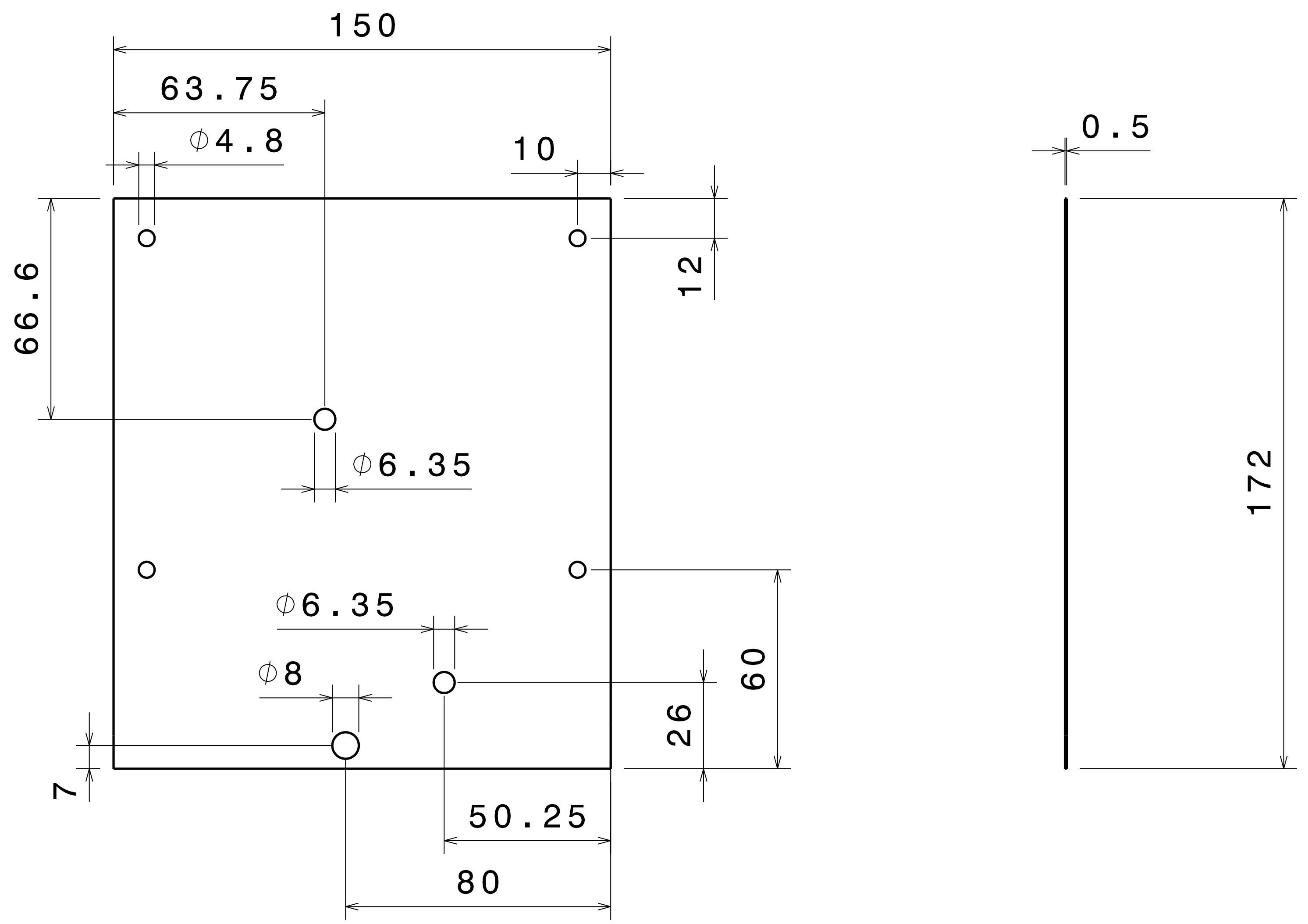
DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M15.7	PART NAME: AAC - Top Interfaces Wall	
DATE: 02/10/2018	MATERIAL: Aluminum Sheets		AMOUNT: 1
SIZE A4 / SCALE 1:1	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M15.8	PART NAME: AAC - Lateral Wall	
DATE: 02/10/2018	MATERIAL: Aluminum Sheets		AMOUNT: 3
SIZE A4 / SCALE 1:4	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M15.9	PART NAME: AAC - Front Wall	
DATE: 02/10/2018	MATERIAL: Aluminum Sheets		AMOUNT: 1
SIZE: A4 / SCALE: 1:4	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M15.10	PART NAME: AAC - Tubes Front Wall	
DATE: 02/10/2018	MATERIAL: Aluminum Sheets		AMOUNT: 1
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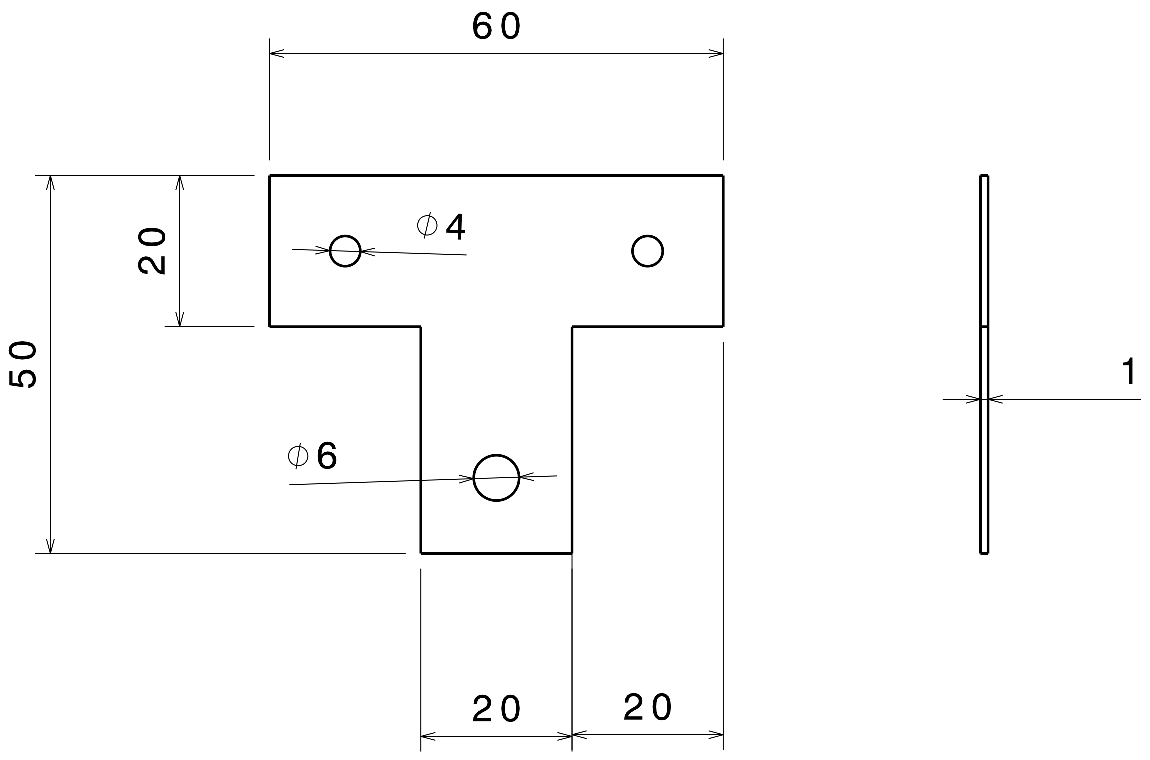
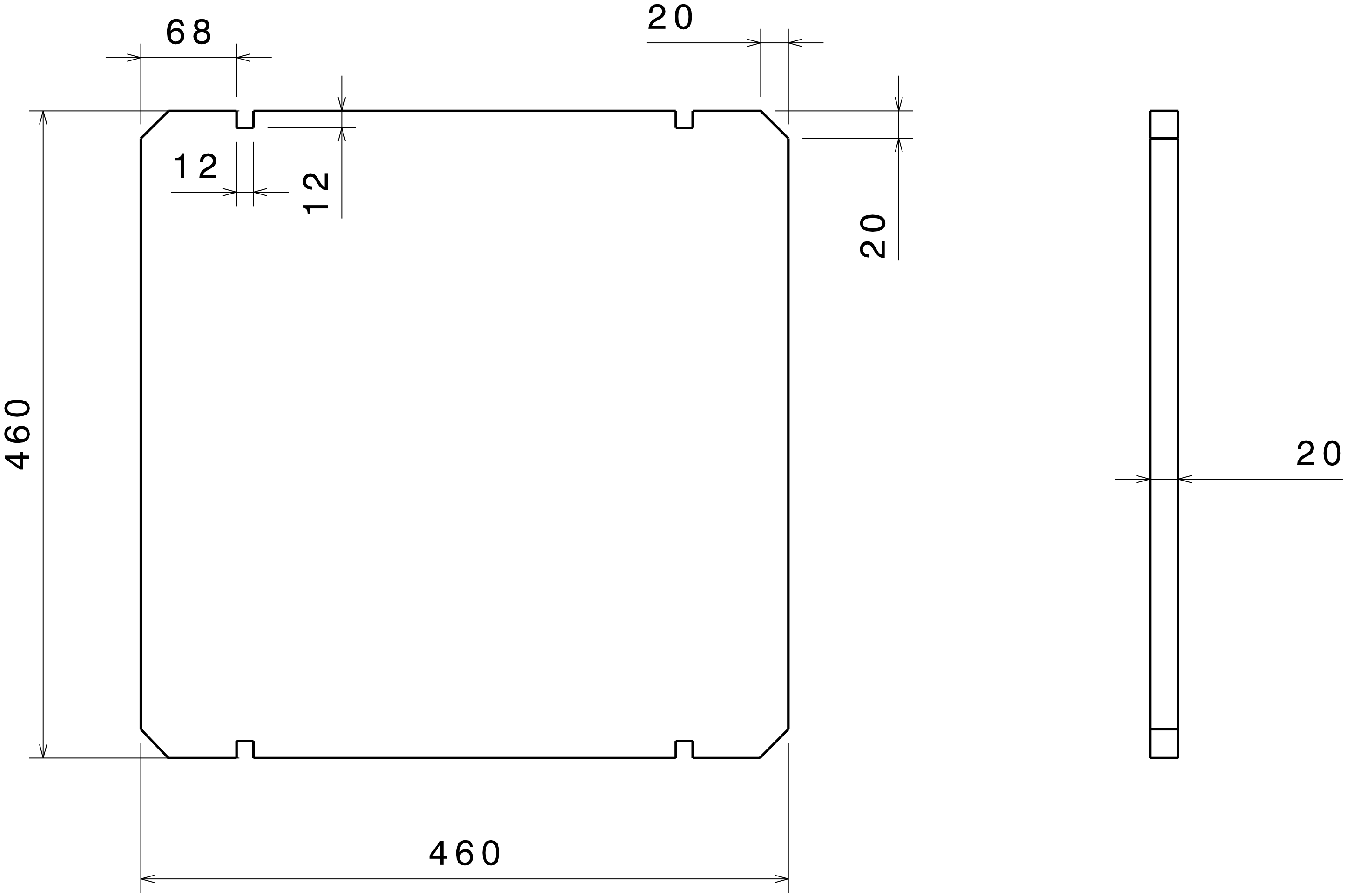
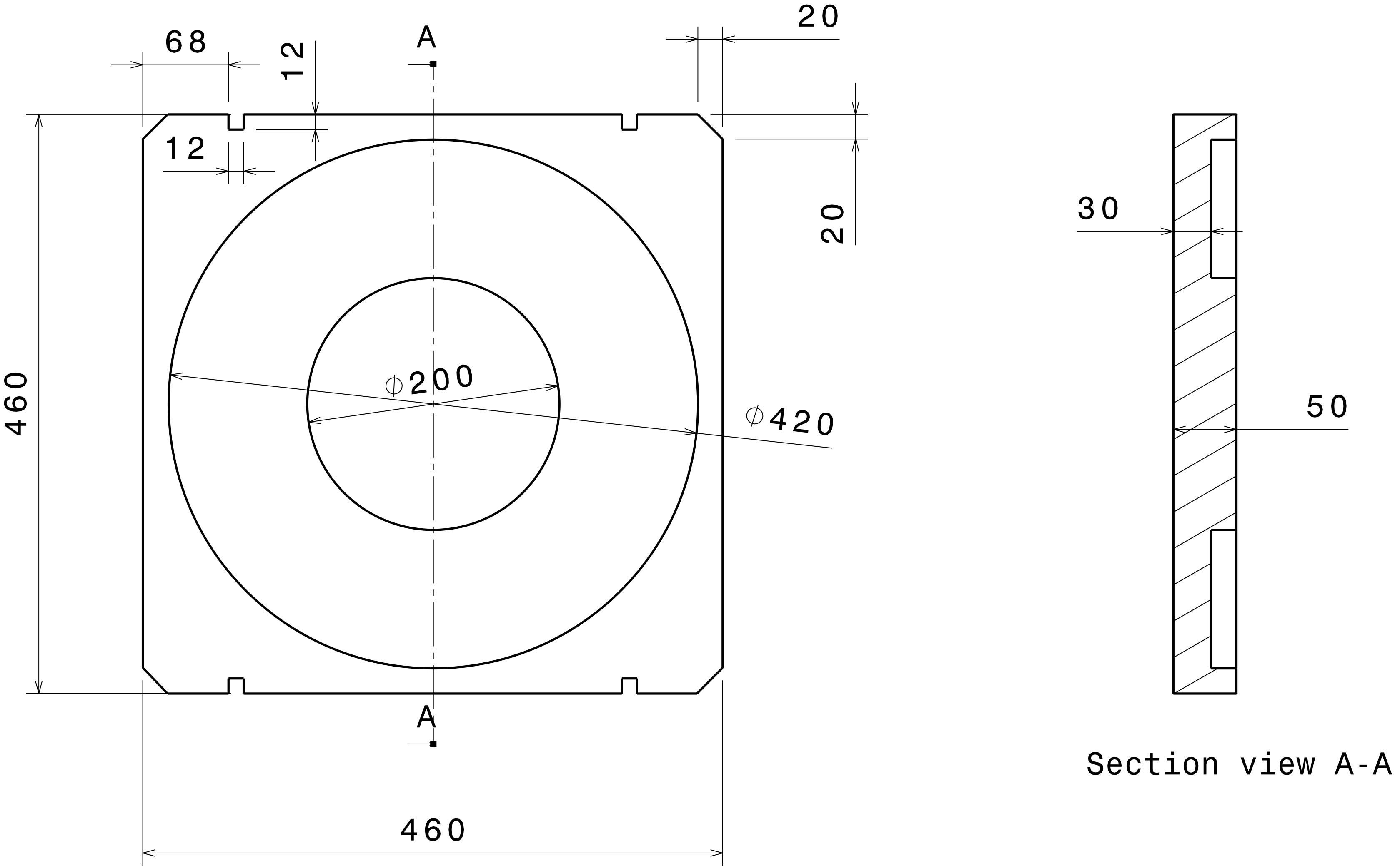


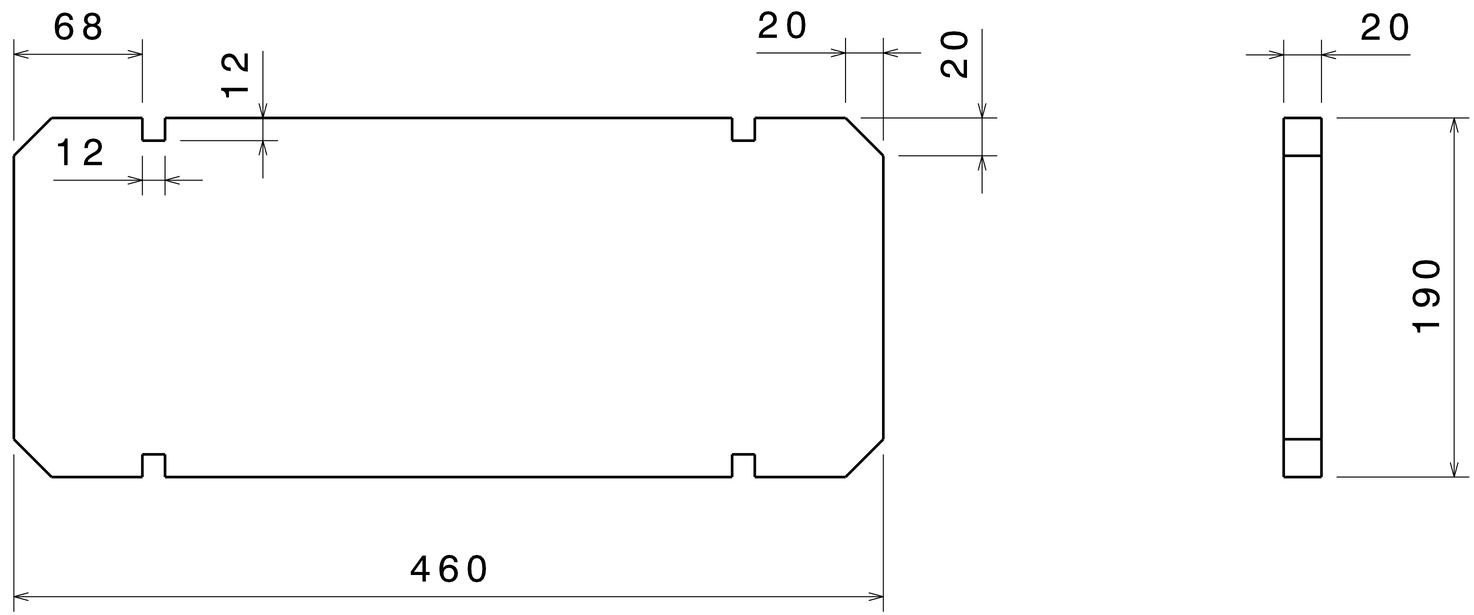
DESIGNED BY: Jordi Coll Ortega	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Pau Molas Roca	PART ID: M15.12	PART NAME: Bags bar handler T-sheet	
DATE: 02/10/2018	MATERIAL: ALUMINIUM 5754		AMOUNT: 4
SIZE: A4 / SCALE: 1:1	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



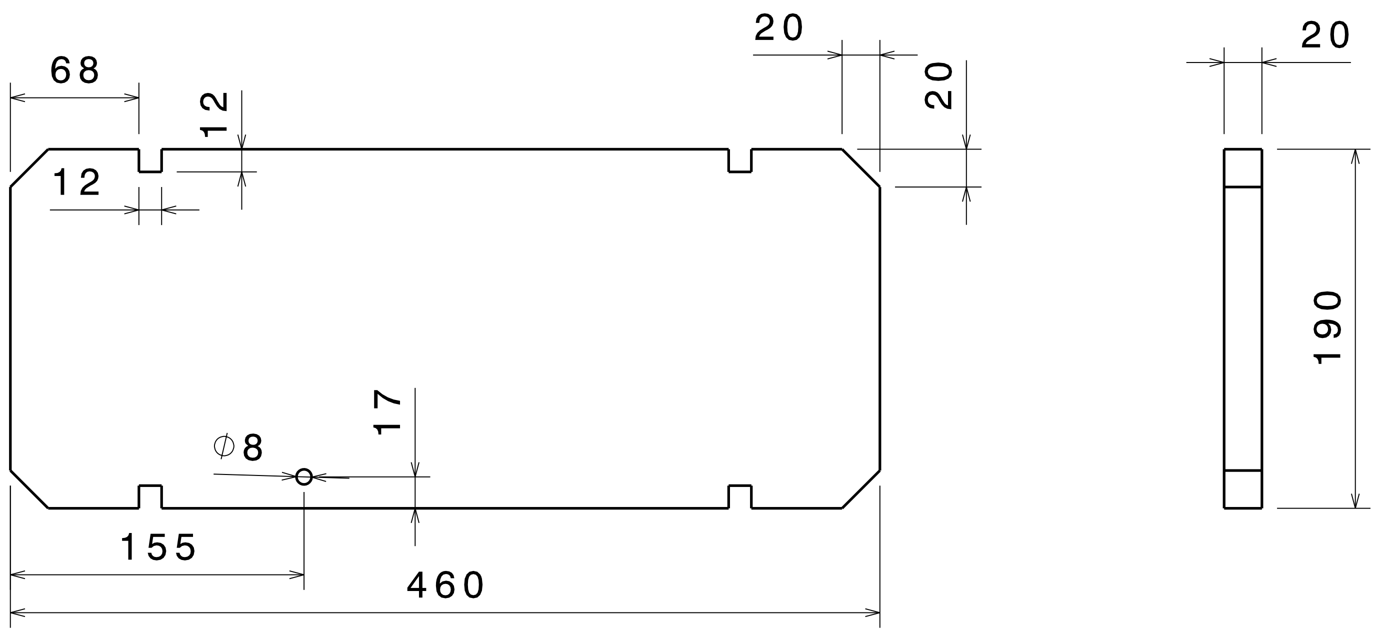
DESIGNED BY: Jordi Coll Ortega	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Pau Molas Roca	PART ID: M16.1	PART NAME: CAC Top wall Styrofoam	
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 4
SIZE: A4 / SCALE: 1:5	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



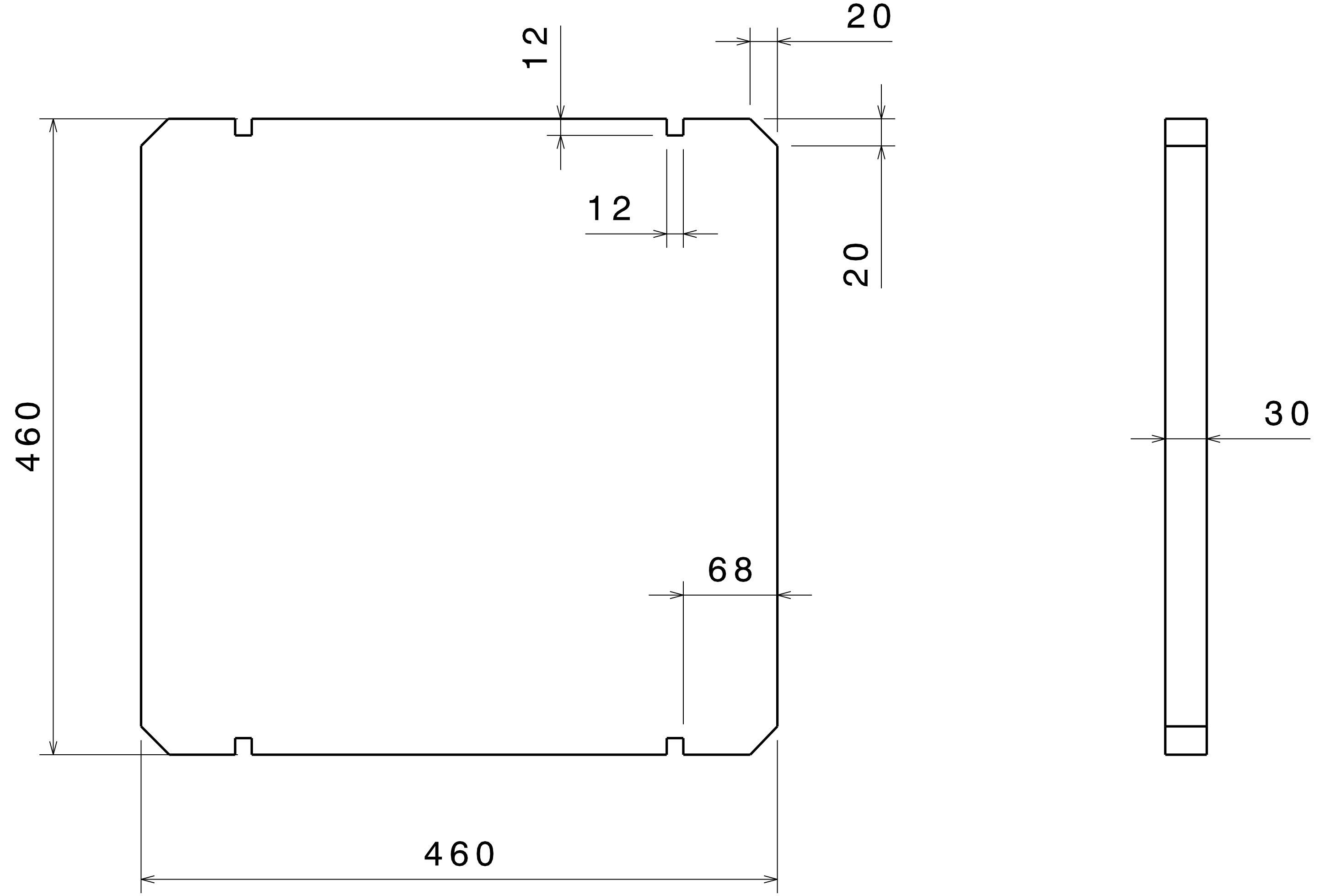
DESIGNED BY: Jordi Coll Ortega	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Pau Molas Roca	PART ID: M16.2	PART NAME: CAC wall bottom styrofoam	
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 1
SIZE: A4 / SCALE: 1:5	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



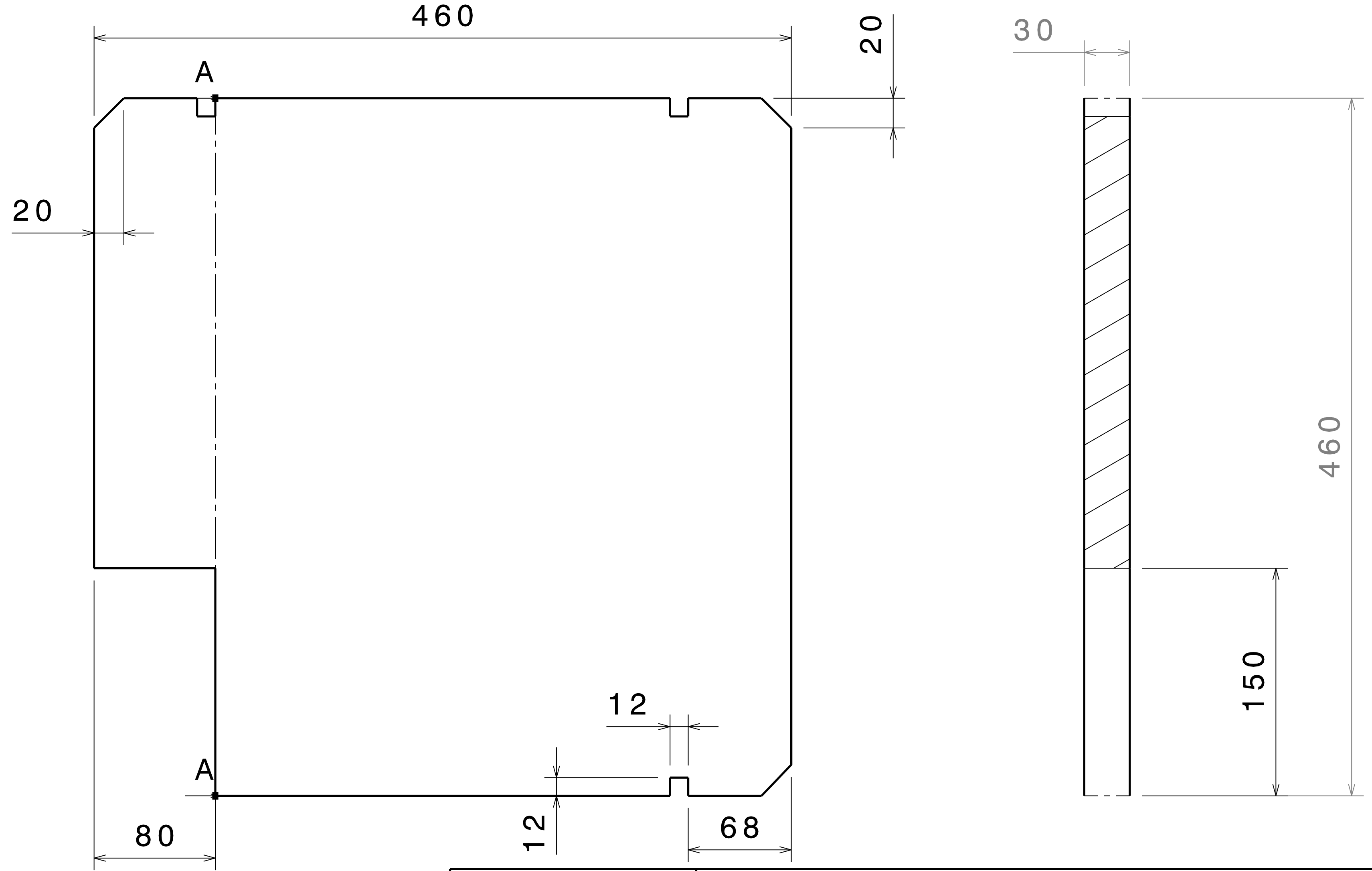
DESIGNED BY: Emily Chen	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M16.3	PART NAME: CAC Lateral	
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 3
SIZE A4 / SCALE 1:4	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



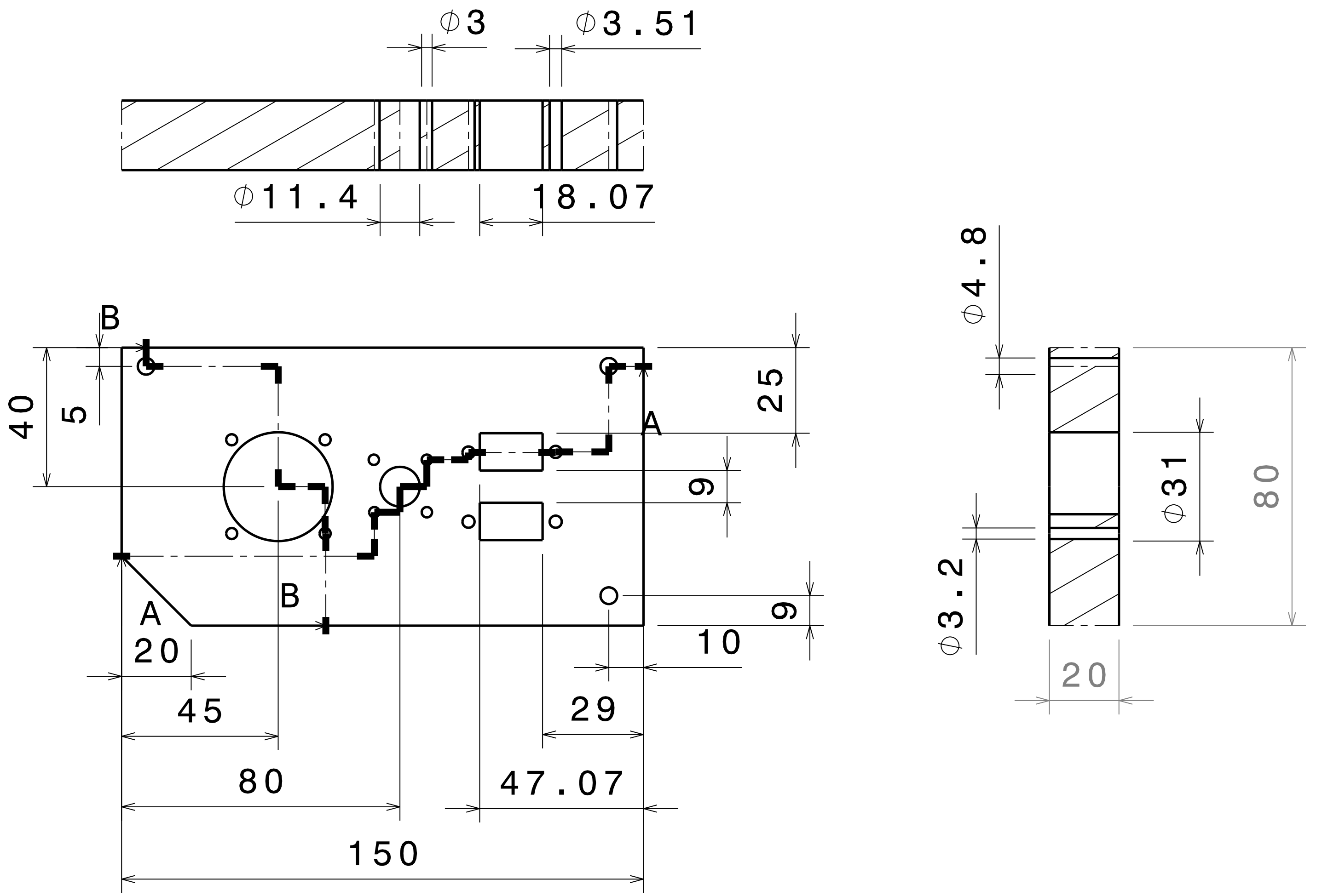
DESIGNED BY: Emily Chen	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M16.4	PART NAME: CAC Lateral (Inlet/Outlet Tube)	
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 1
SIZE: A4 / SCALE: 1:4	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



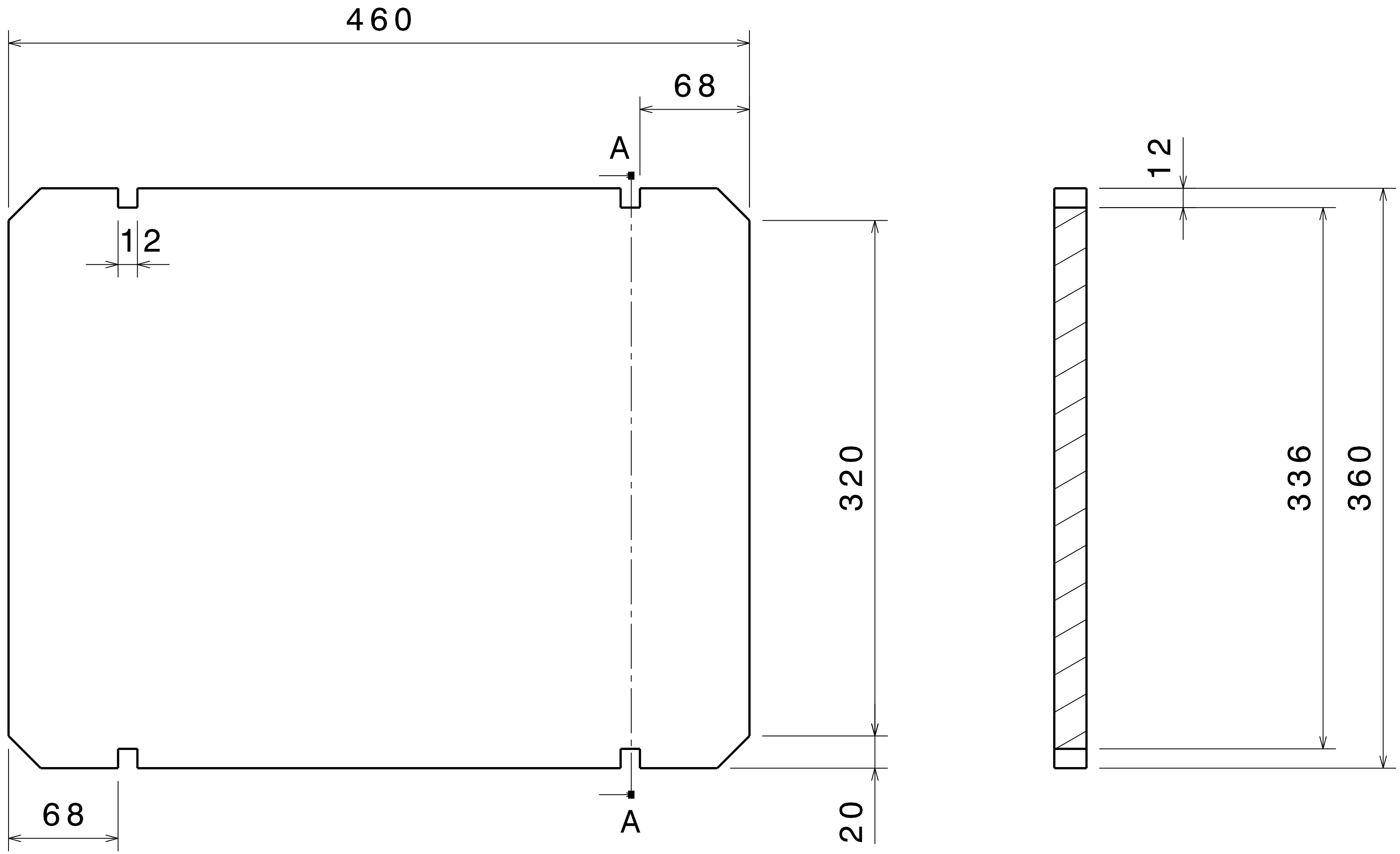
DESIGNED BY: Jordi Coll Ortega	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Pau Molas Roca	PART ID: M16.5	PART NAME: Bottom styrofoam - AAC	
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 1
SIZE: A4 / SCALE: 1:5	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



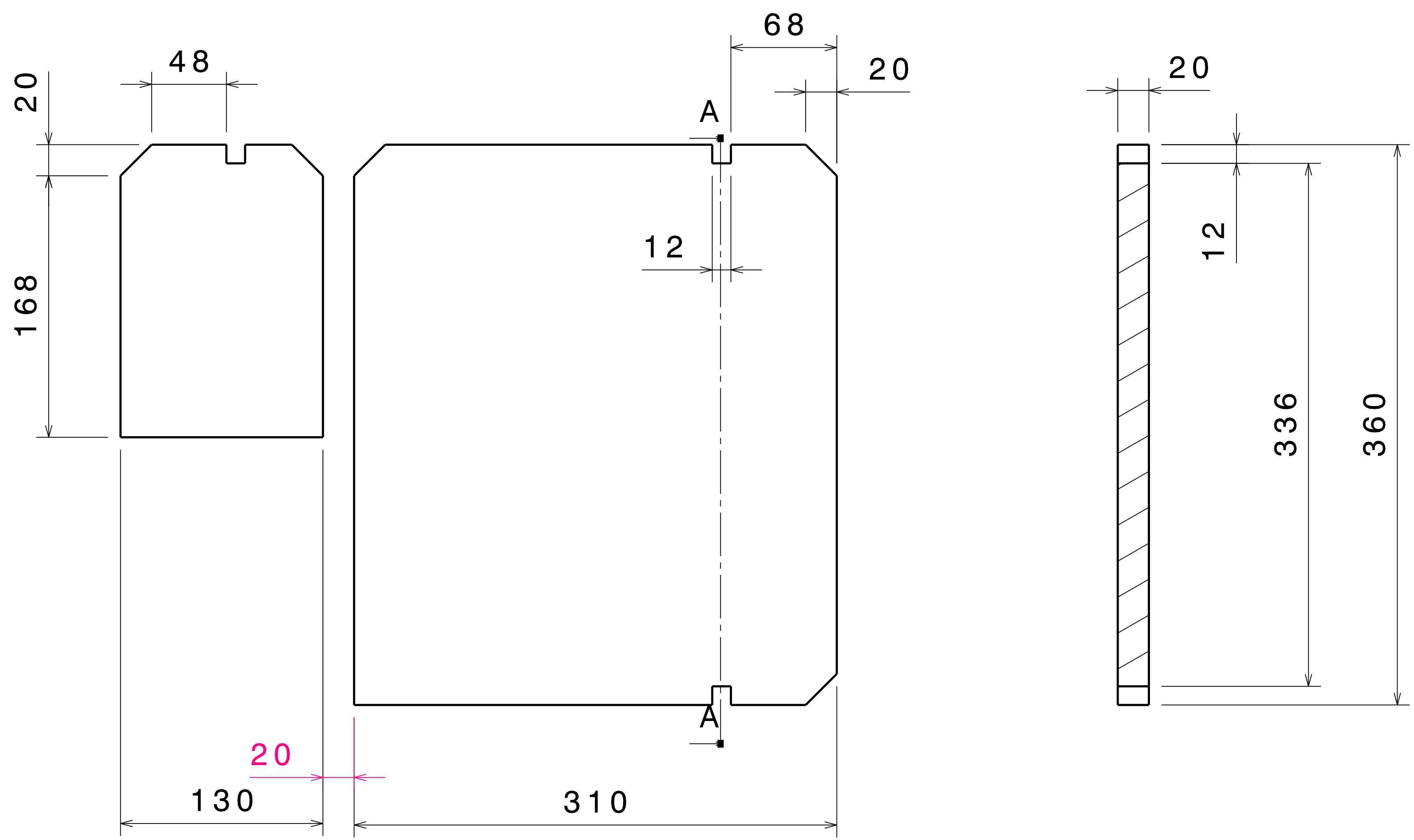
DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26	
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY	
CHECKED BY: Jordi Coll Ortega	PART ID: M16.6	PART NAME: AAC - Top Wall
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N	AMOUNT: 1
SIZE: A4 / SCALE: 1:4	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0	



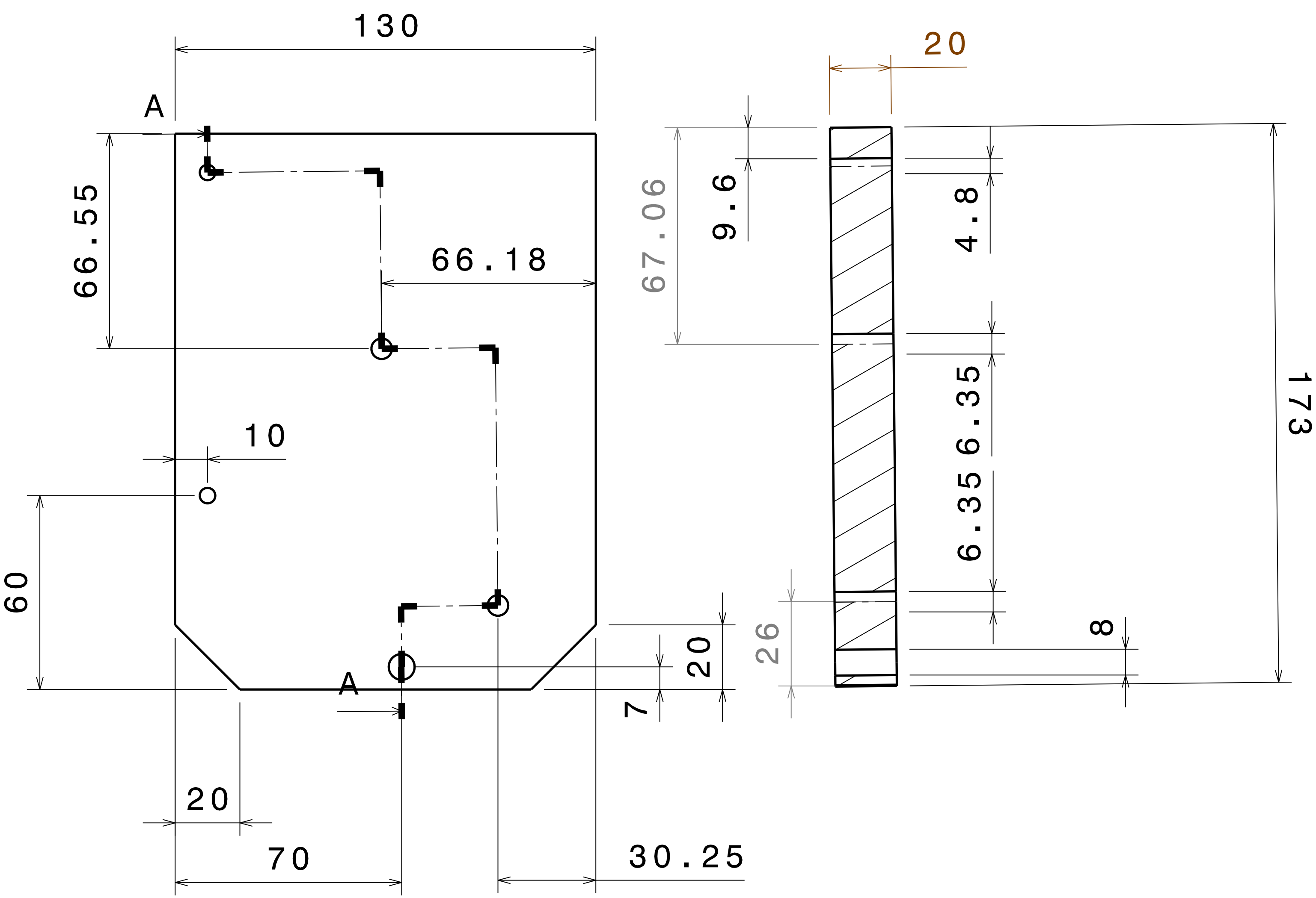
DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26	
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY	
CHECKED BY: Jordi Coll Ortega	PART ID: M16.7	PART NAME: AAC - Interfaces Top Wall
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N	AMOUNT: 1
SIZE: A4 / SCALE: 1:2	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0	



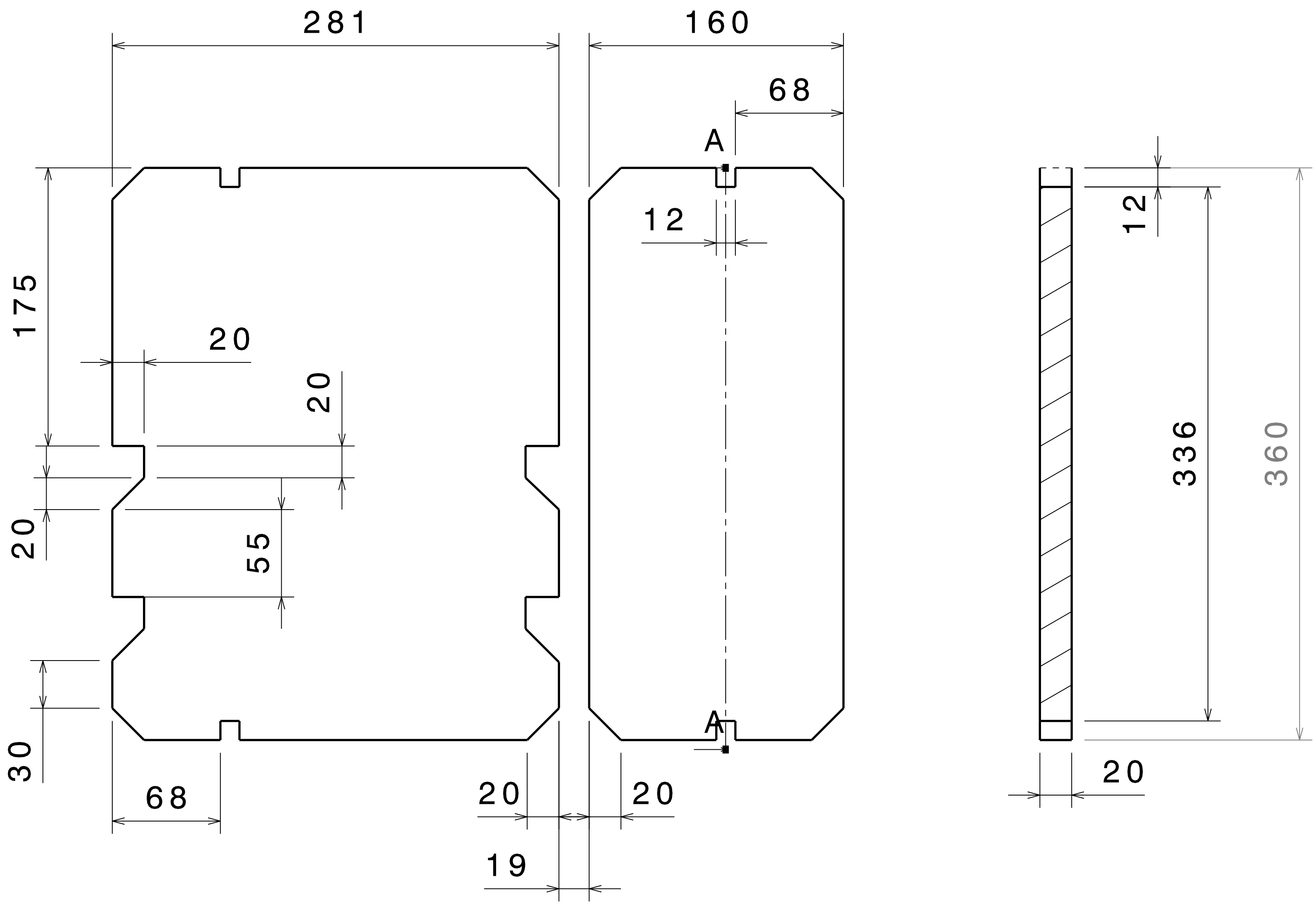
DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M16.8	PART NAME: AAC - Lateral Wall	
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 2
SIZE A4 / SCALE 1:4	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



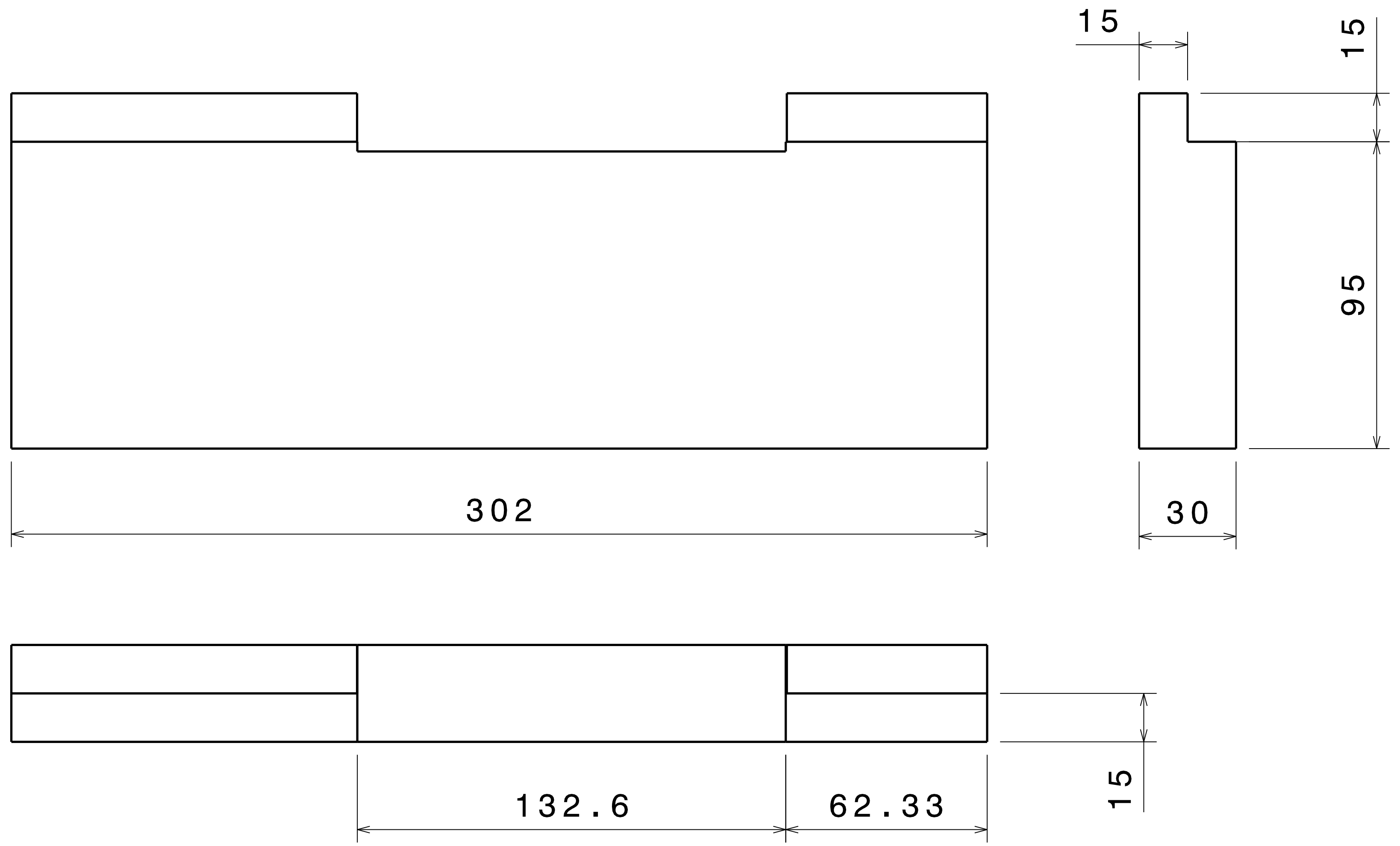
DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M16.9	PART NAME: AAC - Front Wall	
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 1
SIZE A4 / SCALE 1:4	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



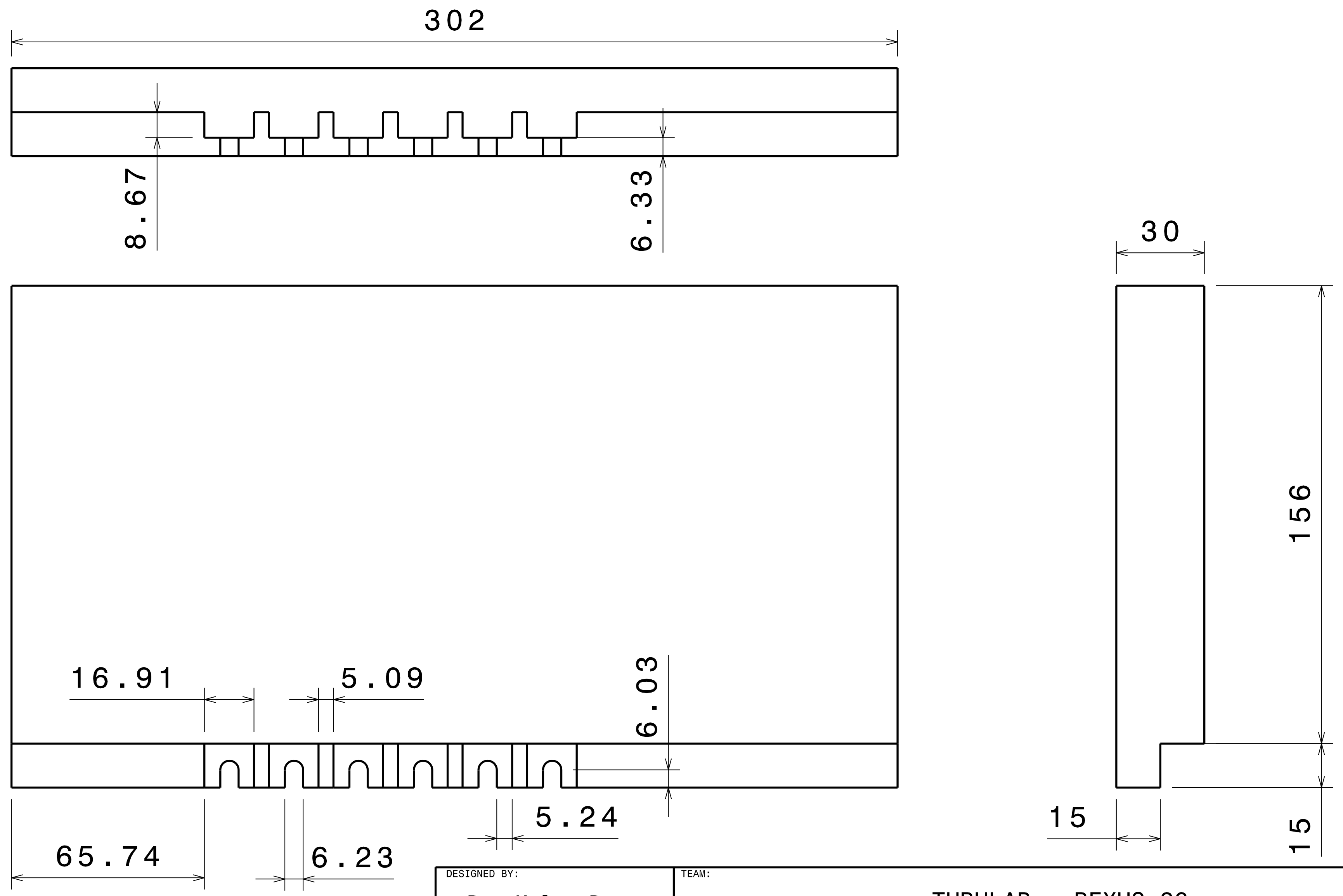
DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M16.10	PART NAME: AAC - Tubes Front Wall	
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 1
SIZE: A4 / SCALE: 1:2	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



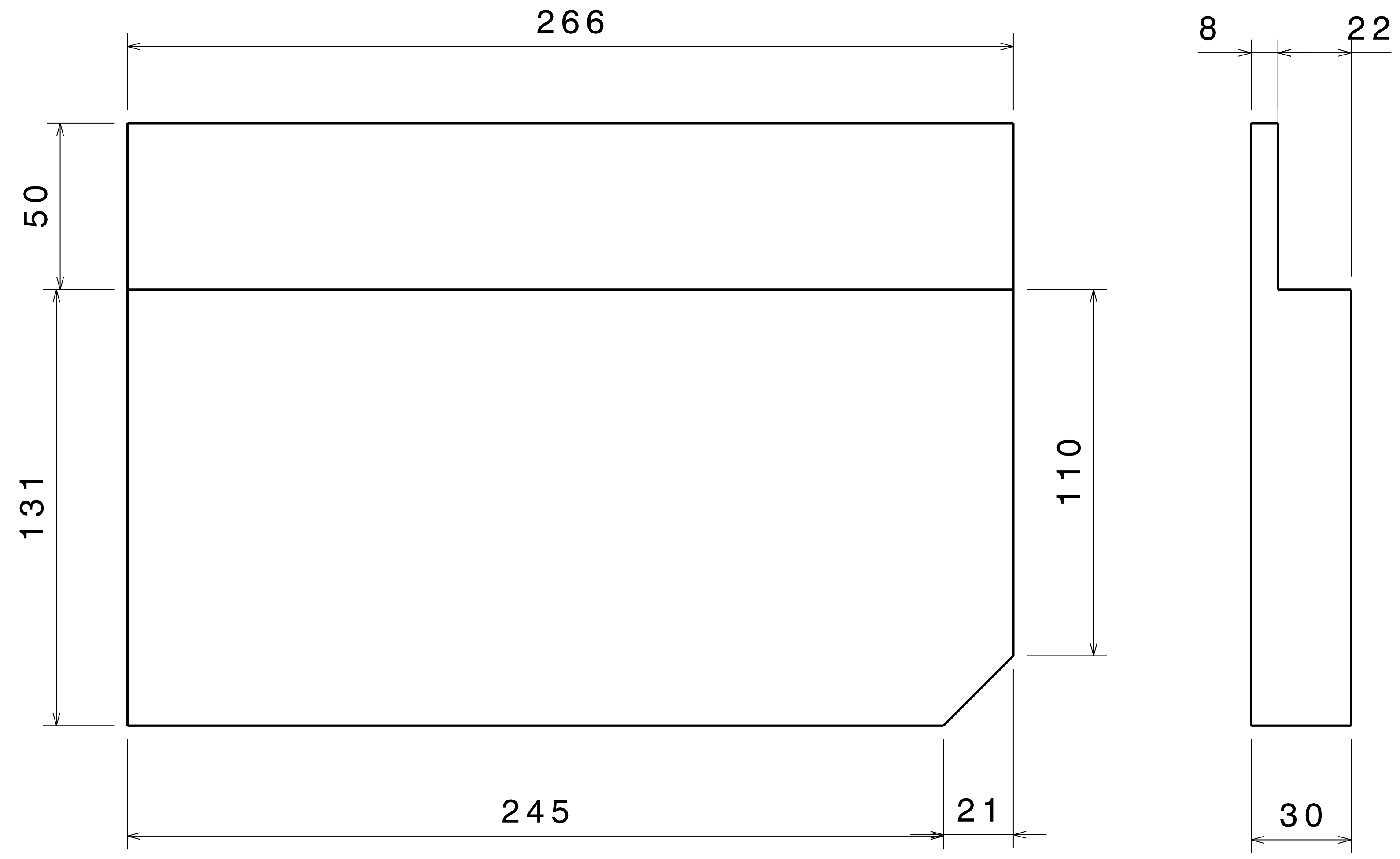
DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M16.11	PART NAME: AAC - Brain Lateral Wall	
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 1
SIZE: A4 / SCALE: 1:4	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



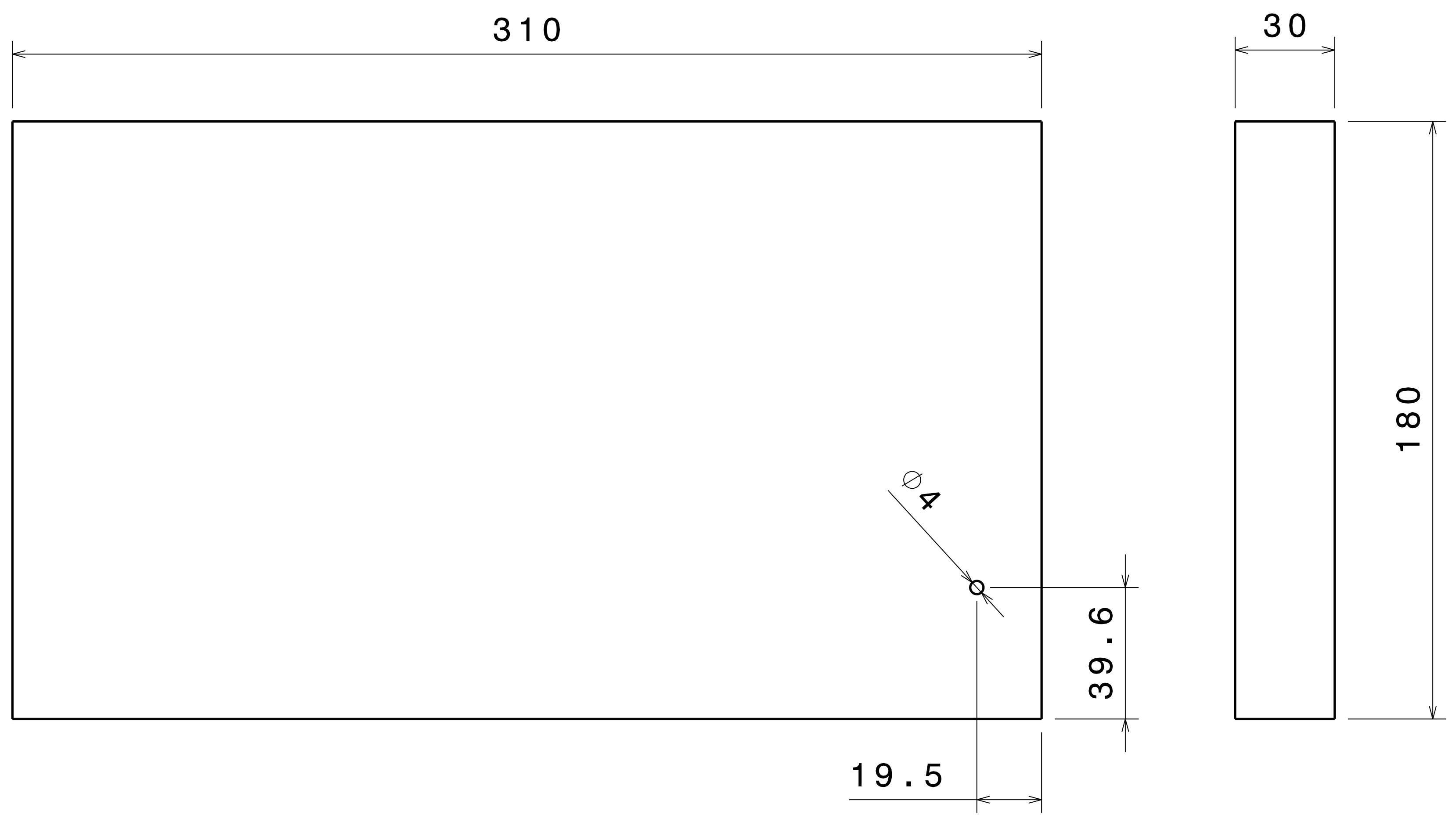
DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 30/09/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M16.12	PART NAME: Lateral Long Wall Bottom - The Brain	
DATE: 01/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 1
SIZE: A4 / SCALE: 1:2	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



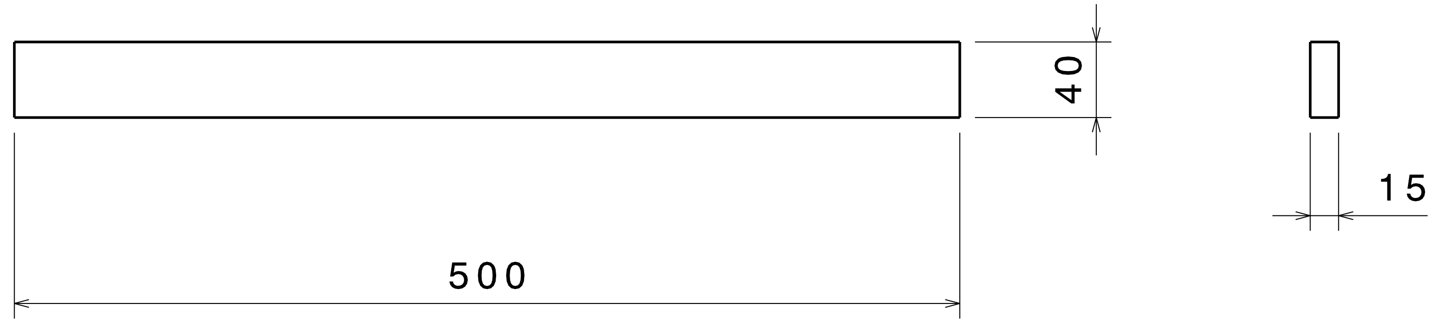
DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 30/09/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M16.13	PART NAME: Lateral Long Wall Top - The Brain	
DATE: 01/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 1
SIZE: A4 / SCALE: 1:2	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



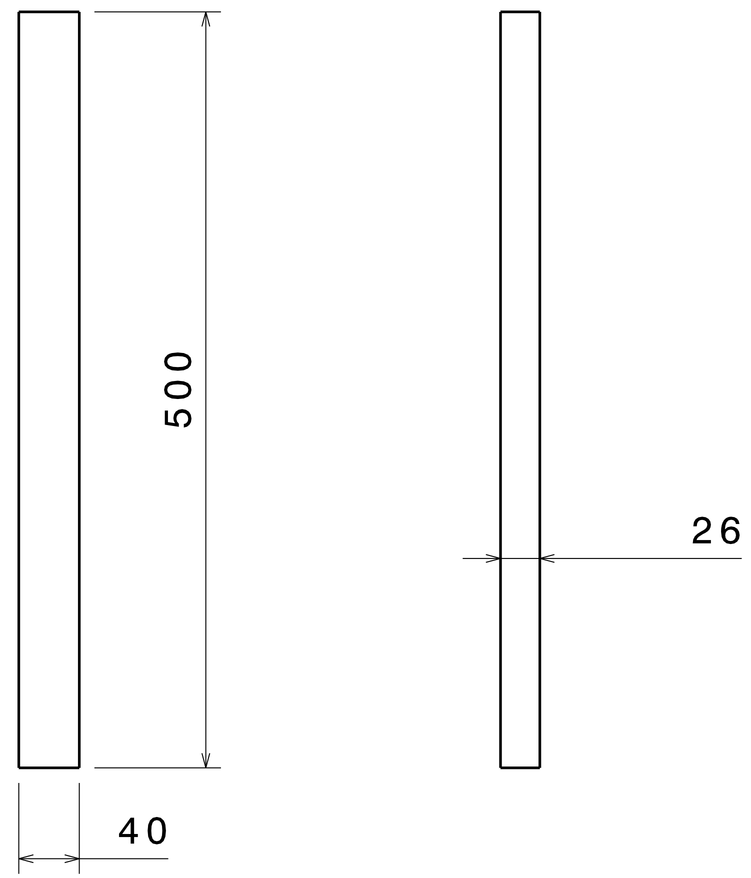
DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 30/09/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M16.14	PART NAME: Lateral Short Wall - The Brain	
DATE: 01/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 1
SIZE A4 / SCALE 1:2	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



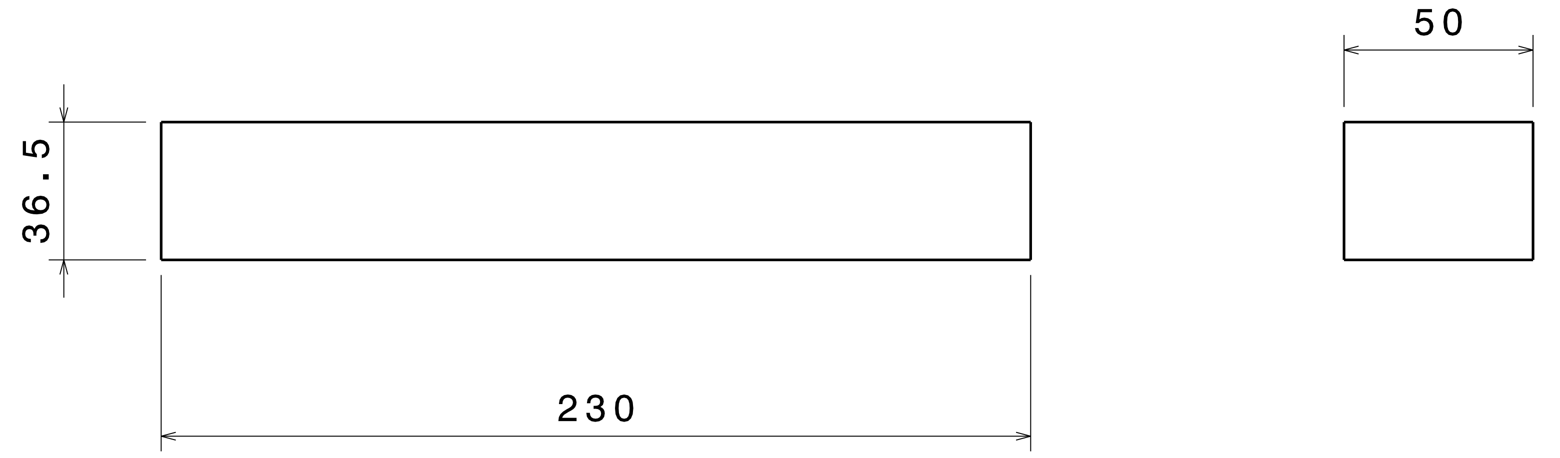
DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 30/09/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M16.15	PART NAME: Top Wall - The Brain	
DATE: 01/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 1
SIZE A4 / SCALE 1:2	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



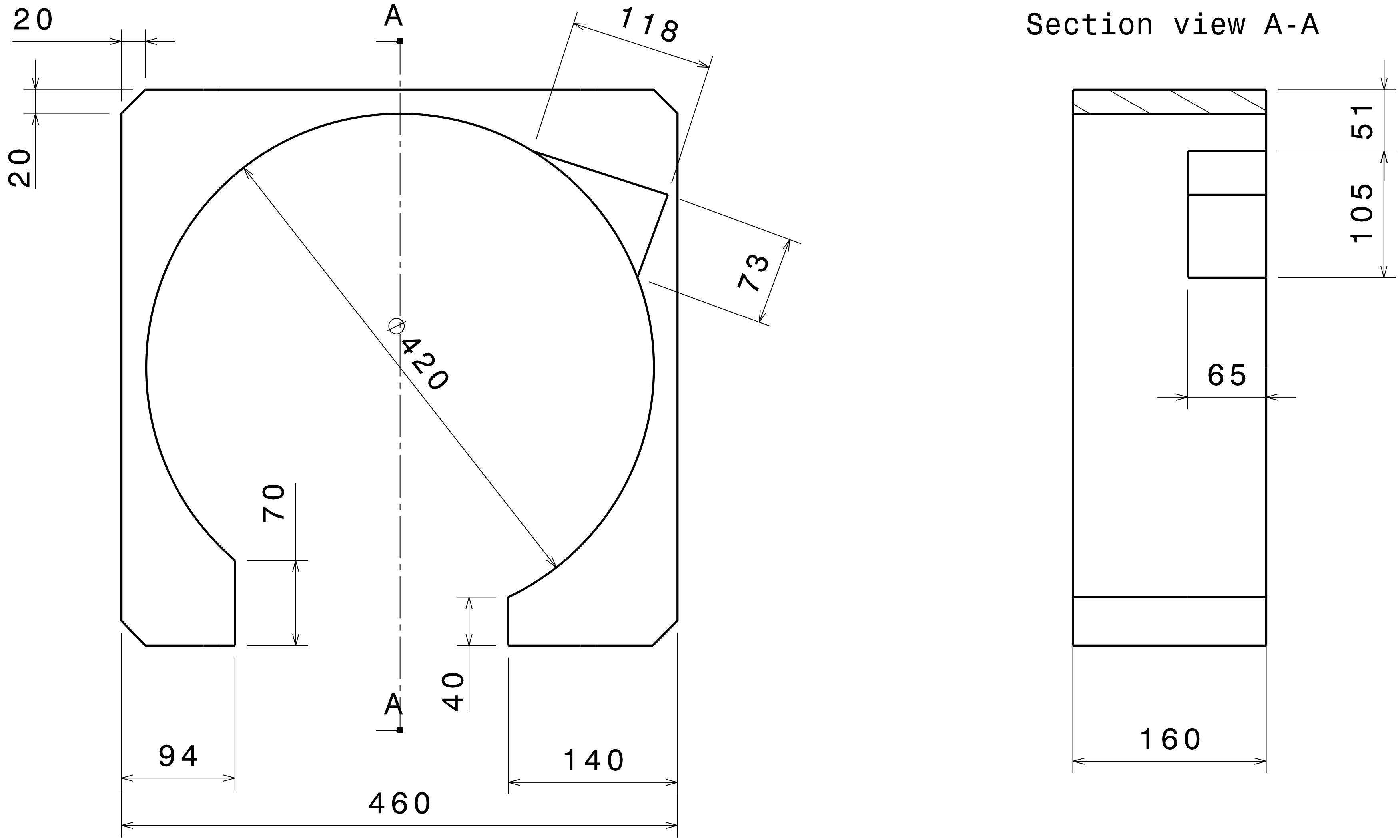
DESIGNED BY: Emily Chen	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M16.16	PART NAME: Gondola AAC Styrofoam Interface 1	
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 1
SIZE: A4 / SCALE: 1:4	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



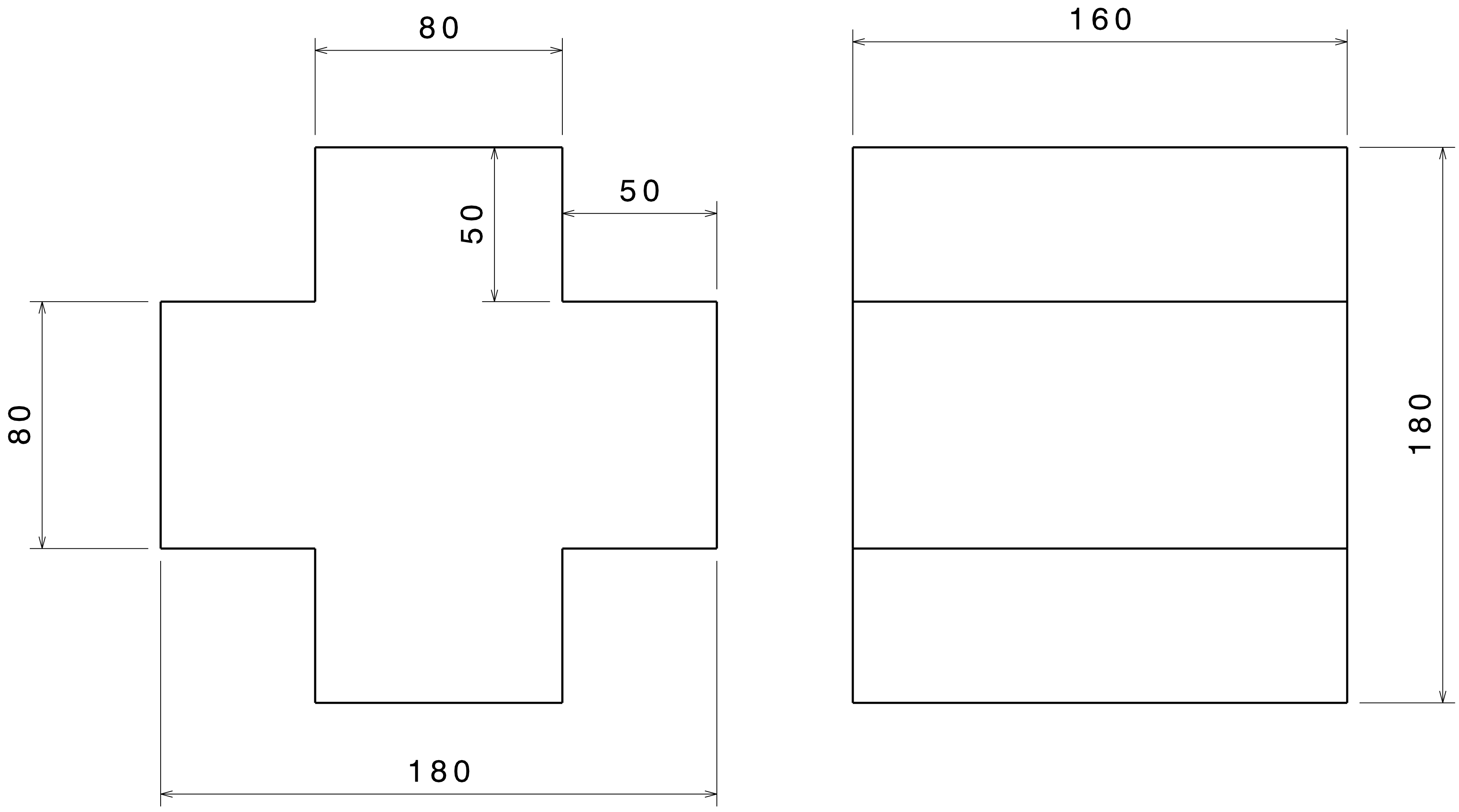
DESIGNED BY: Emily Chen		TEAM: TUBULAR - BEXUS 26	
DATE: 01/10/2018		UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY	
CHECKED BY: Jordi Coll Ortega		PART ID: M16.17	PART NAME: Gondola AAC Styrofoam Interface 2
DATE: 02/10/2018		MATERIAL: Styrofoam 250 SL-A-N	AMOUNT: 1
SIZE: A4	SCALE: 1:5	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0	



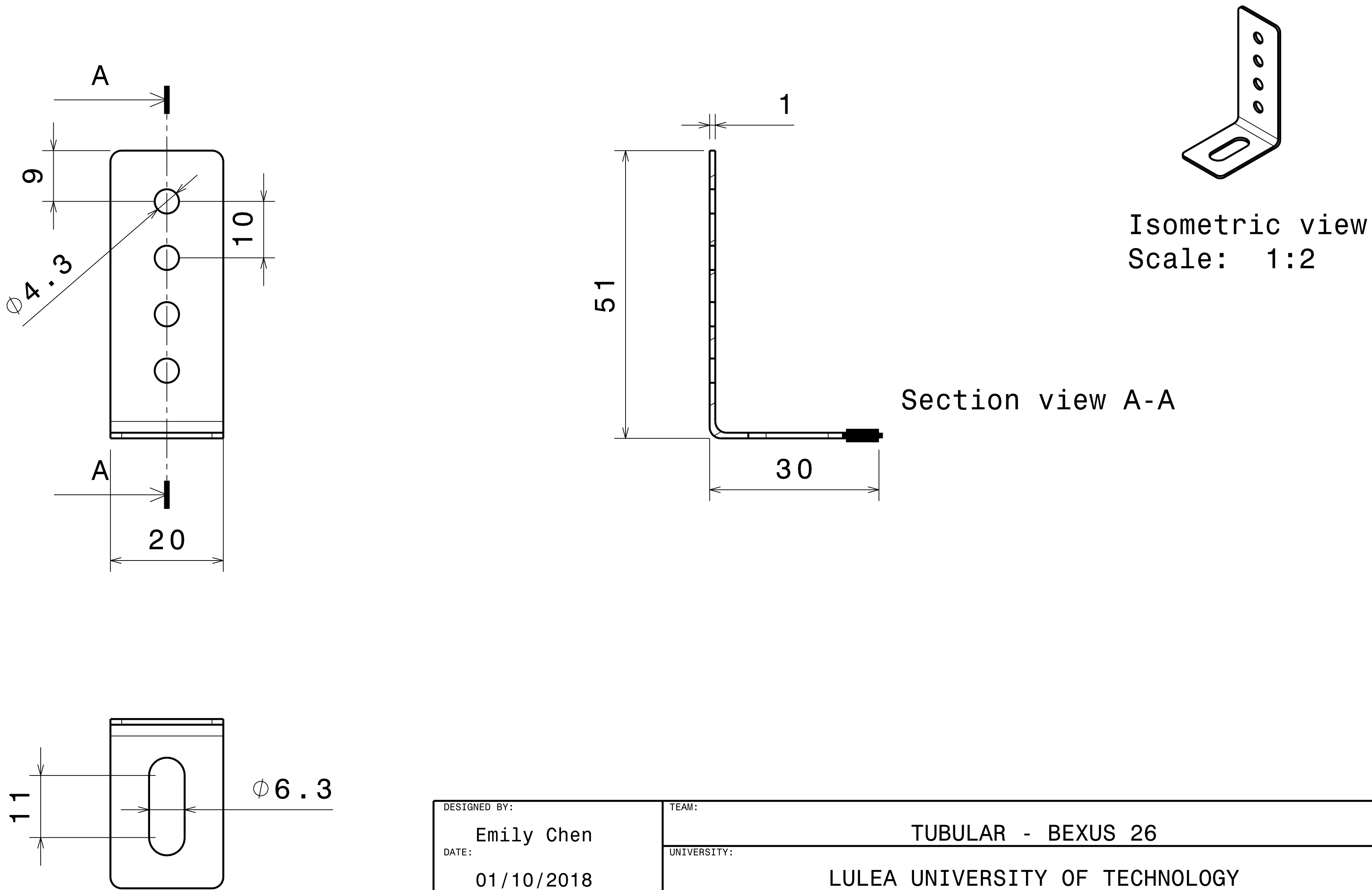
DESIGNED BY: Emily Chen	TEAM: TUBULAR - BEXUS 26	
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY	
CHECKED BY: Jordi Coll Ortega	PART ID: M16.18	PART NAME: Gondala CAC Styrofoam Interface
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N	AMOUNT: 2
SIZE: A4 / SCALE: 1:2	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0	



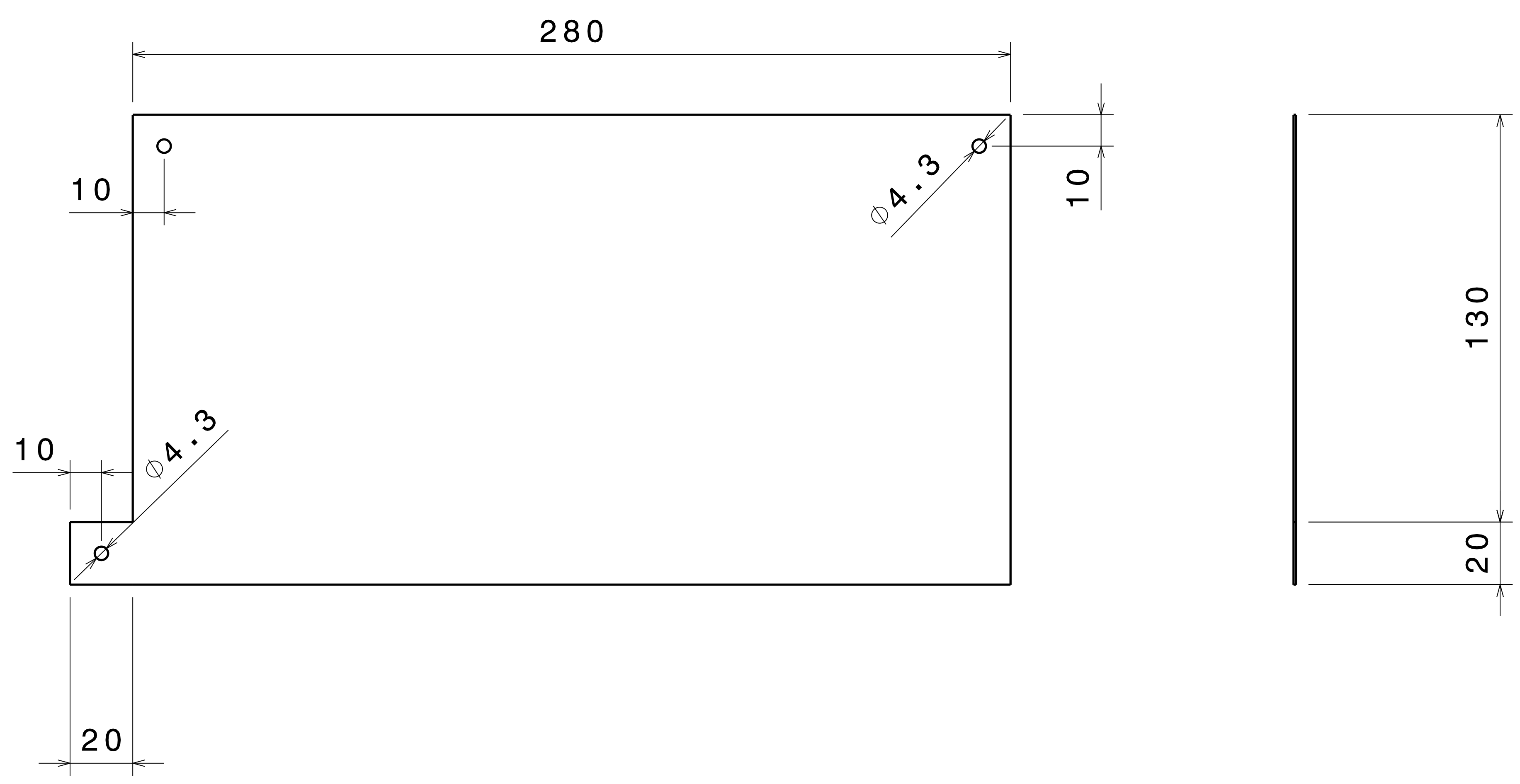
DESIGNED BY: Jordi Coll Ortega	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Pau Molas Roca	PART ID: M16.19	PART NAME: CAC Aircore protection	
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 1
SIZE A4 / SCALE 1:5	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



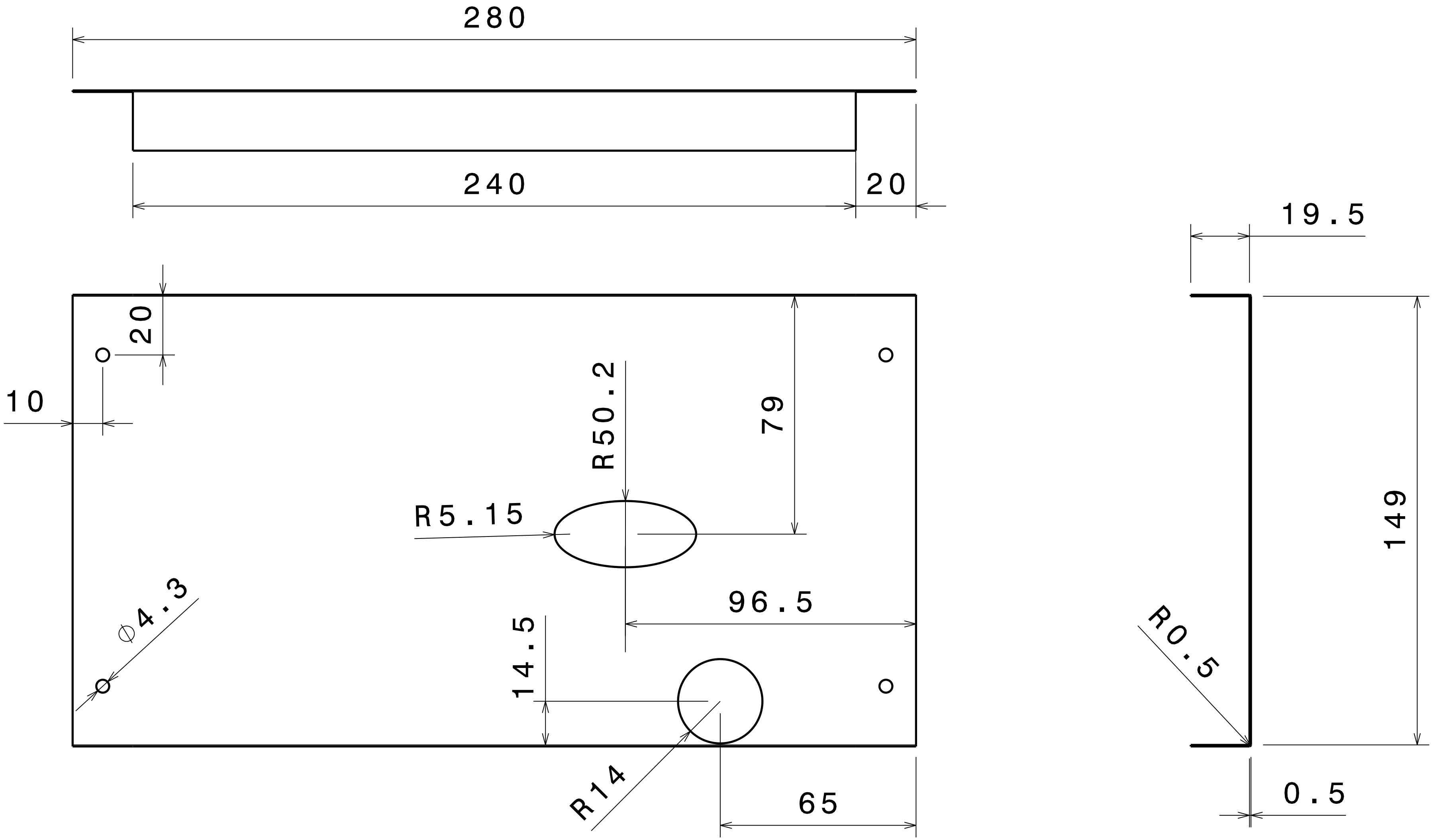
DESIGNED BY: Emily Chen	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M16.20	PART NAME: CAC Styrofoam Cross	
DATE: 02/10/2018	MATERIAL: Styrofoam 250 SL-A-N		AMOUNT: 1
SIZE A4 / SCALE 1:2	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



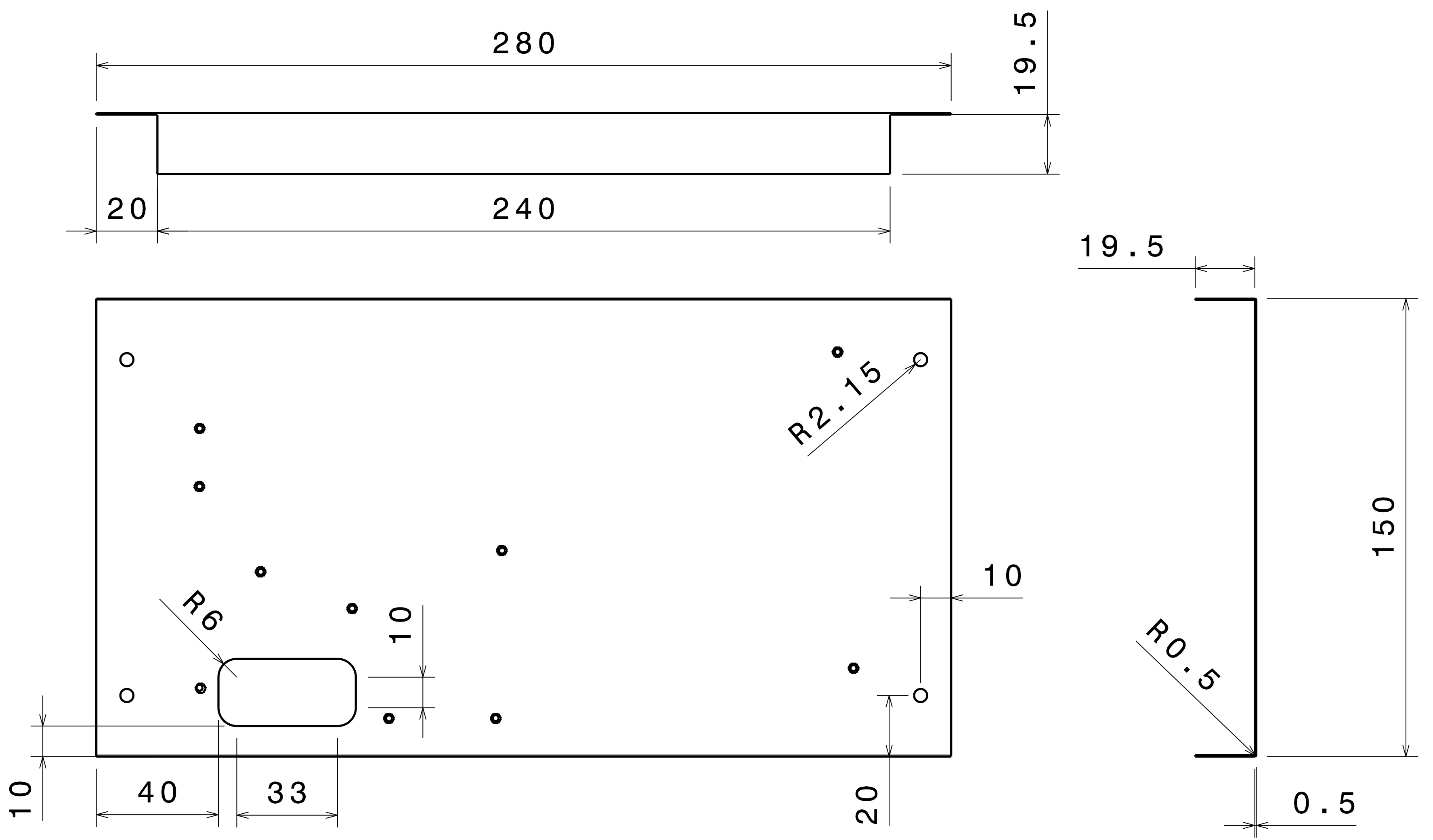
DESIGNED BY: Emily Chen	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M20.1	PART NAME: Gondola Interface L-shape	
DATE: 02/10/2018	MATERIAL: Stainless Steel 304		AMOUNT: 2
SIZE A4 / SCALE 1:1	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



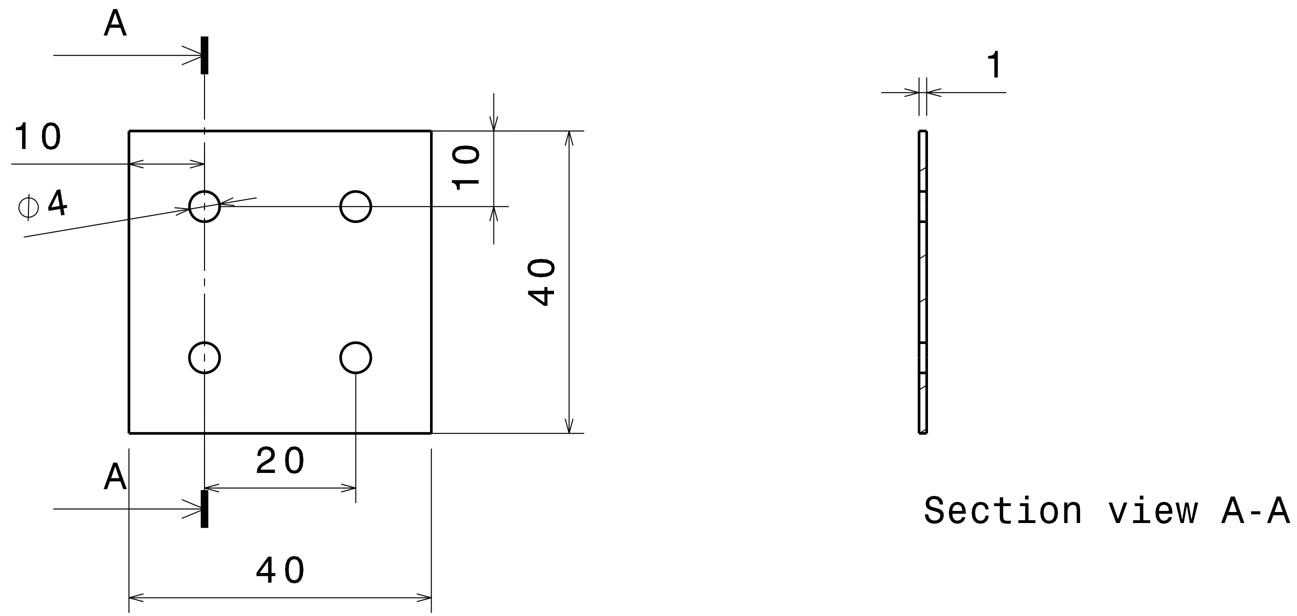
DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 30/09/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M20.2	PART NAME: Level 1 Plate - The Brain	
DATE: 01/10/2018	MATERIAL: Steel Sheet		AMOUNT: 1
SIZE: A4 / SCALE: 1:2	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 30/09/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M20.3	PART NAME: Level 2 Plate - The Brain	
DATE: 01/10/2018	MATERIAL: Steel Sheet		AMOUNT: 1
SIZE A4 / SCALE 1:2	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



DESIGNED BY: Pau Molas Roca	TEAM: TUBULAR - BEXUS 26		
DATE: 30/09/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M20.4	PART NAME: Level 3 Plate - The Brain	
DATE: 01/10/2018	MATERIAL: Steel Sheet		AMOUNT: 1
SIZE A4 / SCALE 1:2	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		



DESIGNED BY: Emily Chen	TEAM: TUBULAR - BEXUS 26		
DATE: 01/10/2018	UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY		
CHECKED BY: Jordi Coll Ortega	PART ID: M20.5	PART NAME: CAC-AAC Fixing Plate	
DATE: 02/10/2018	MATERIAL: Stainless Steel 304		AMOUNT: 6
SIZE A4 / SCALE 1:1	VERSION: EXPERIMENT ACCEPTANCE REVIEW - SEDv4.0		

C.7 Software Sequence Diagram

C.7.1 Air Sampling Control Object Sequence diagrams

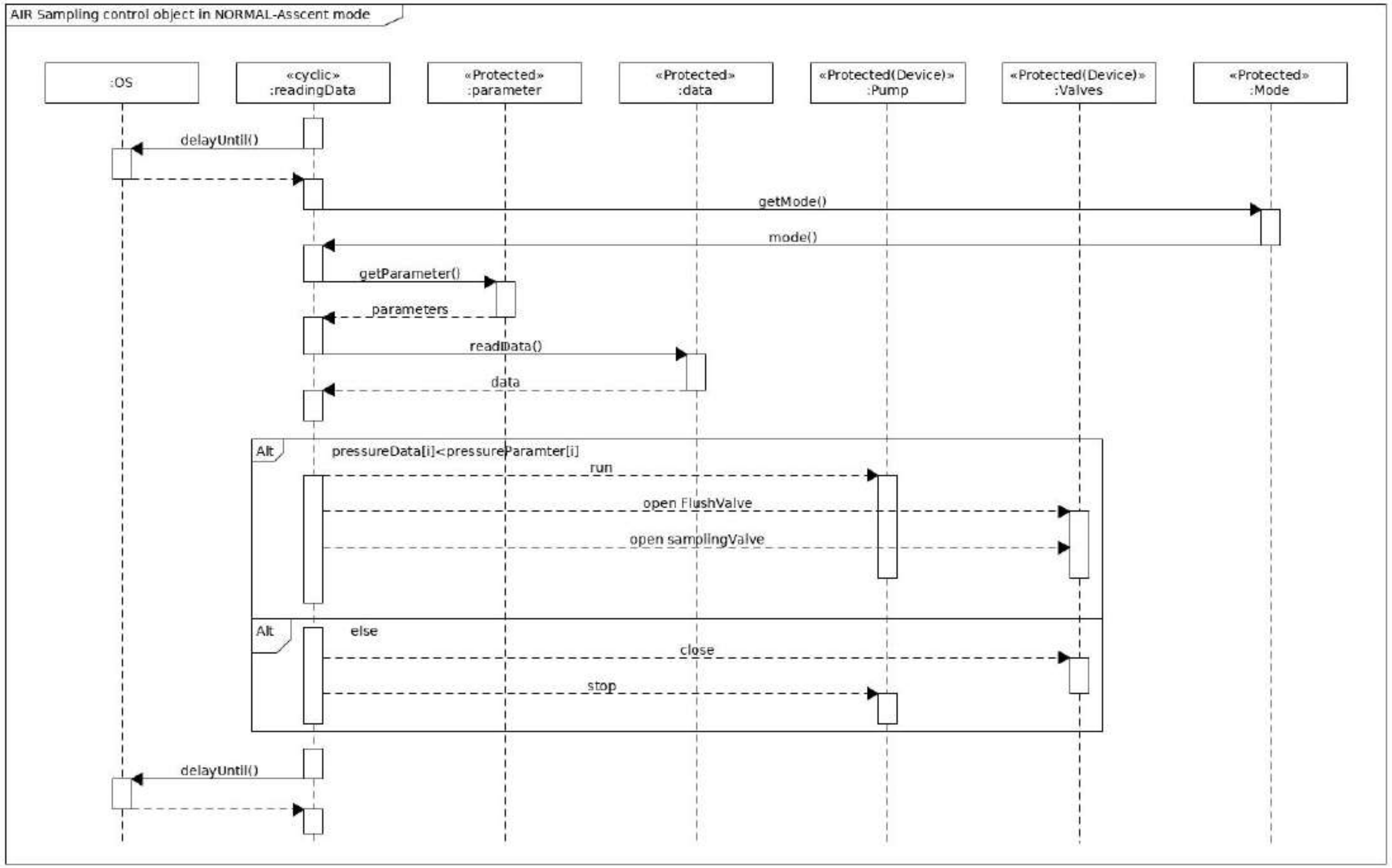


Figure 91: ASC Object in Normal Mode - Ascent.

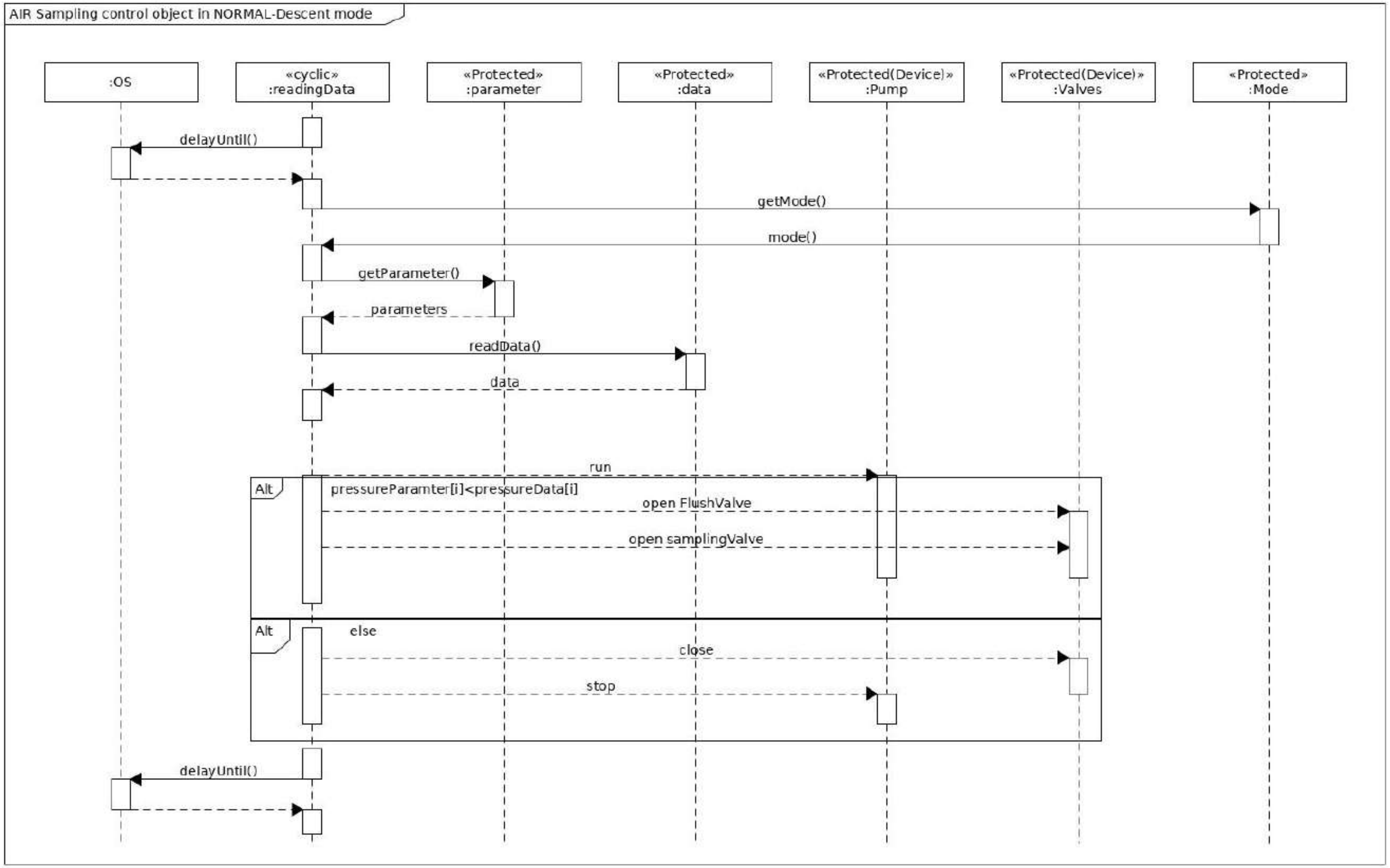


Figure 92: ASC Object in Normal Mode - Descent.

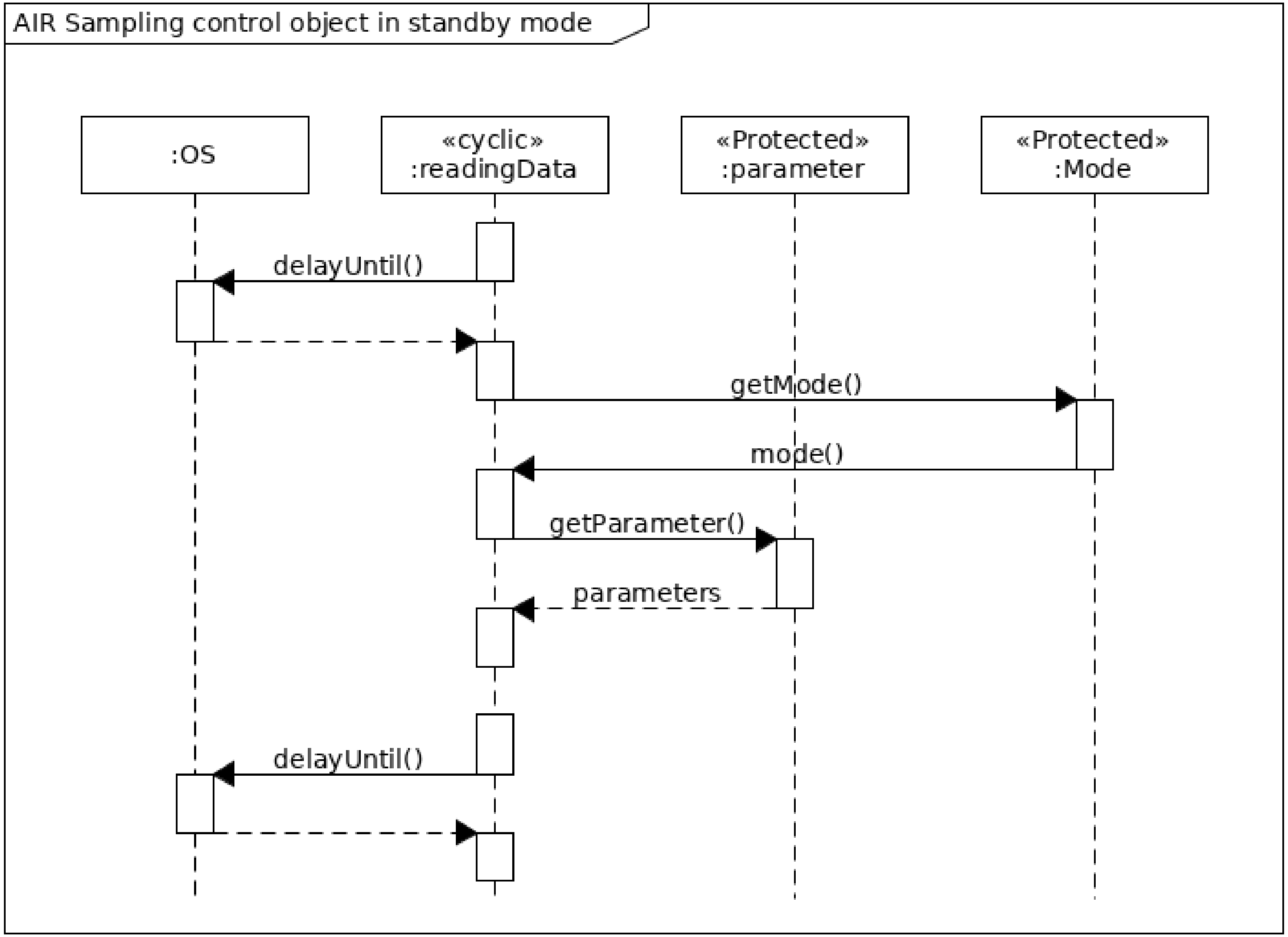


Figure 93: ASC Object in Standby Mode.

C.8 Heating Object Sequence Diagrams

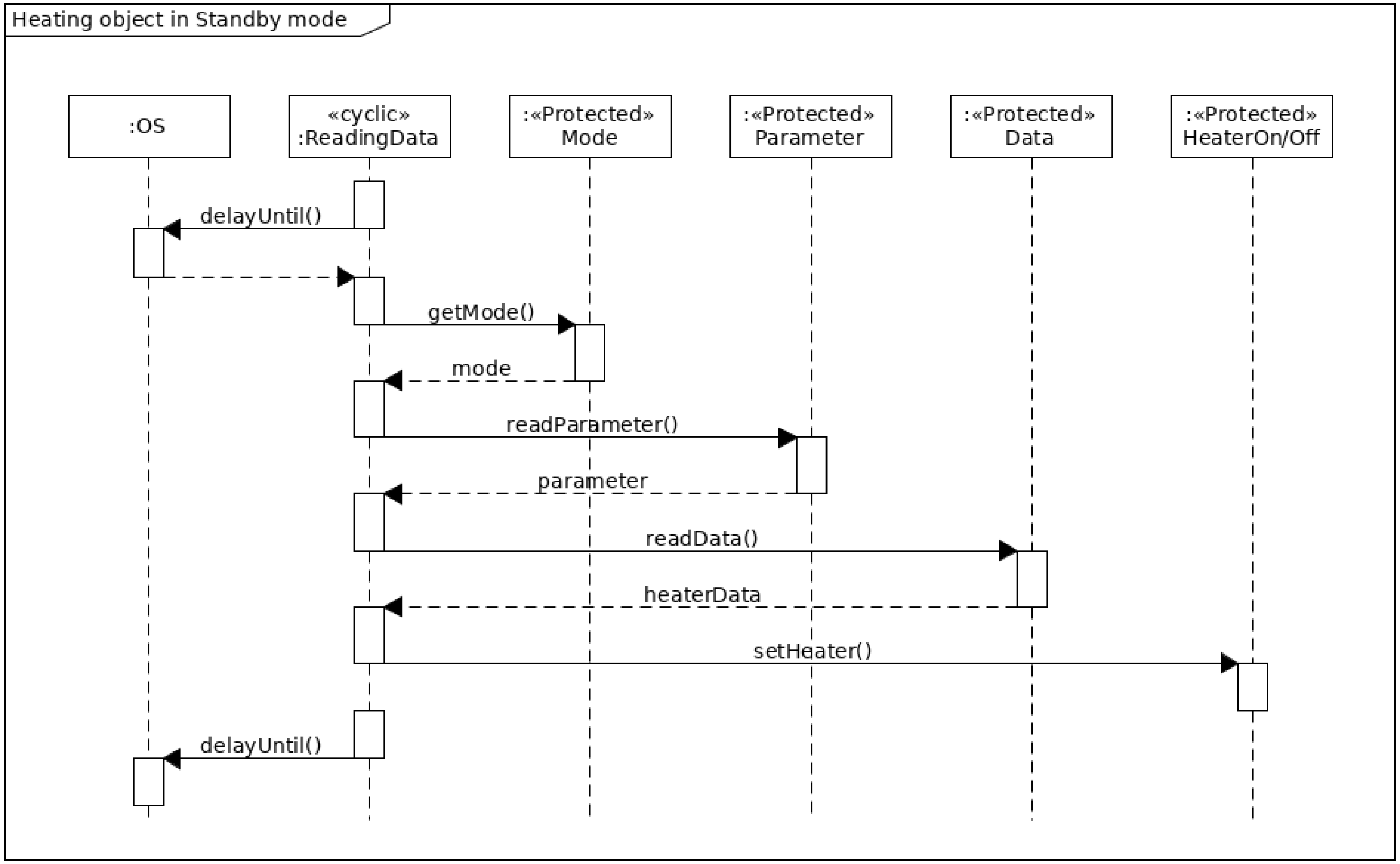


Figure 94: Heating Object in Standby Mode.

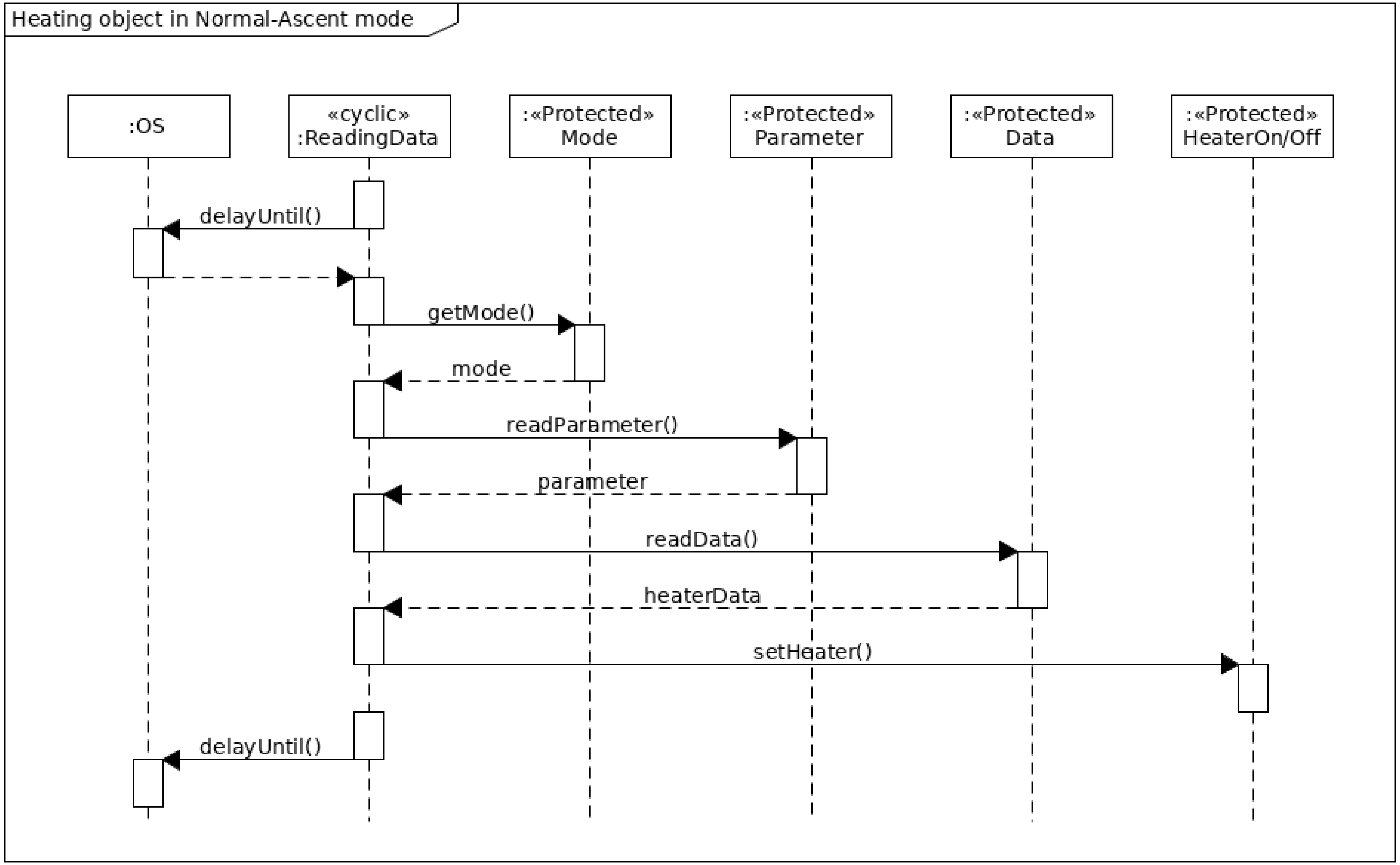


Figure 95: Heating Object in Normal Mode - Ascent.

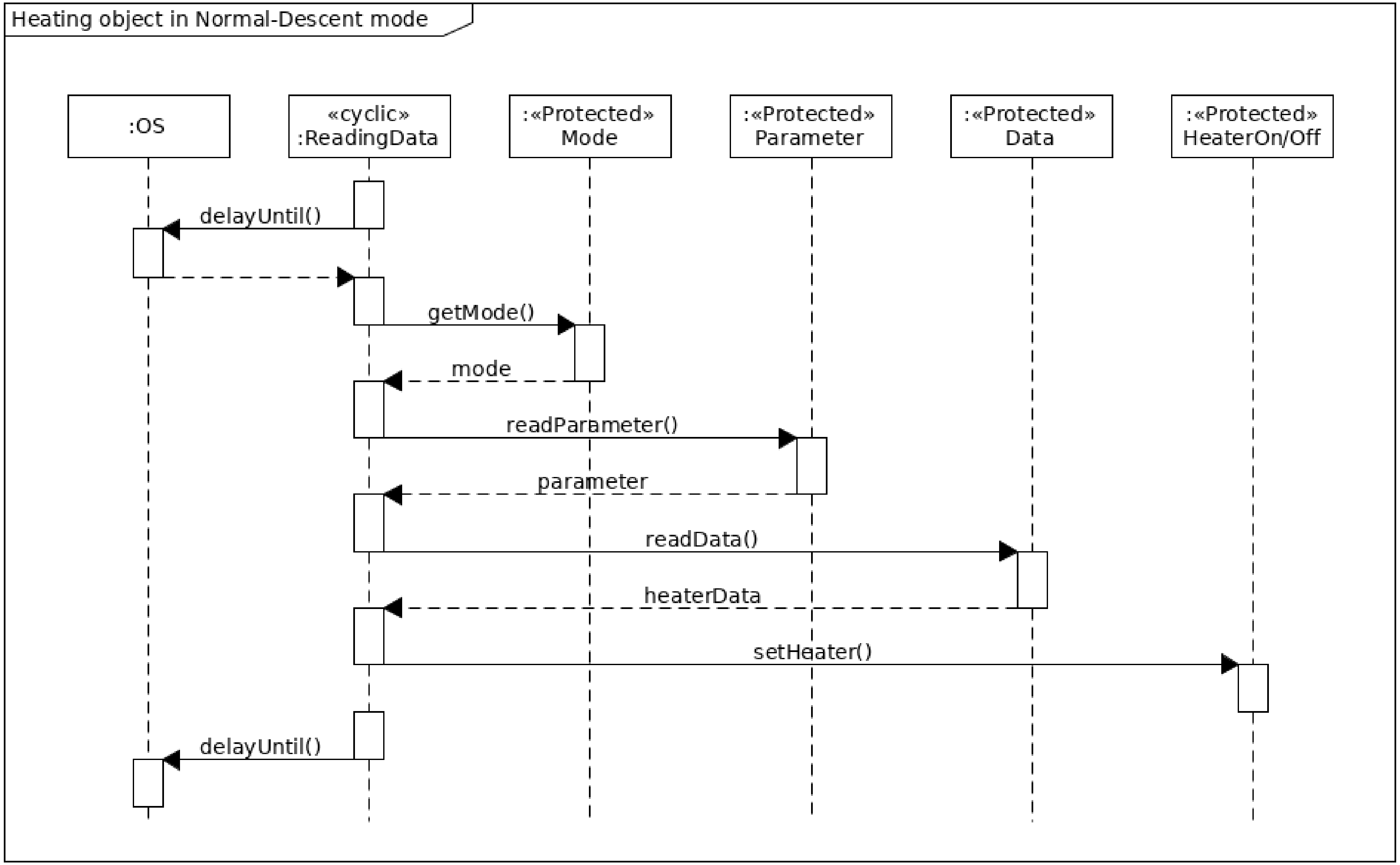


Figure 96: Heating Object in Normal Mode - Descent.

C.9 Sensor Object Sequence Diagrams

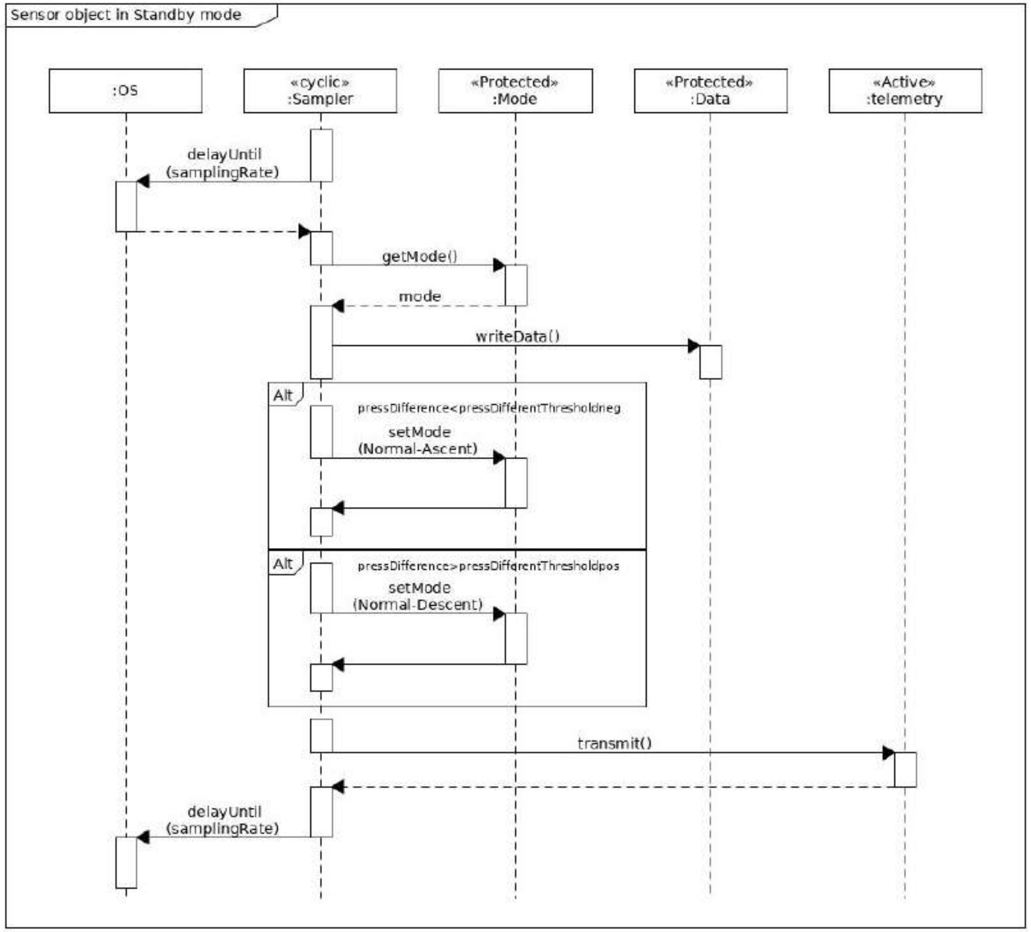
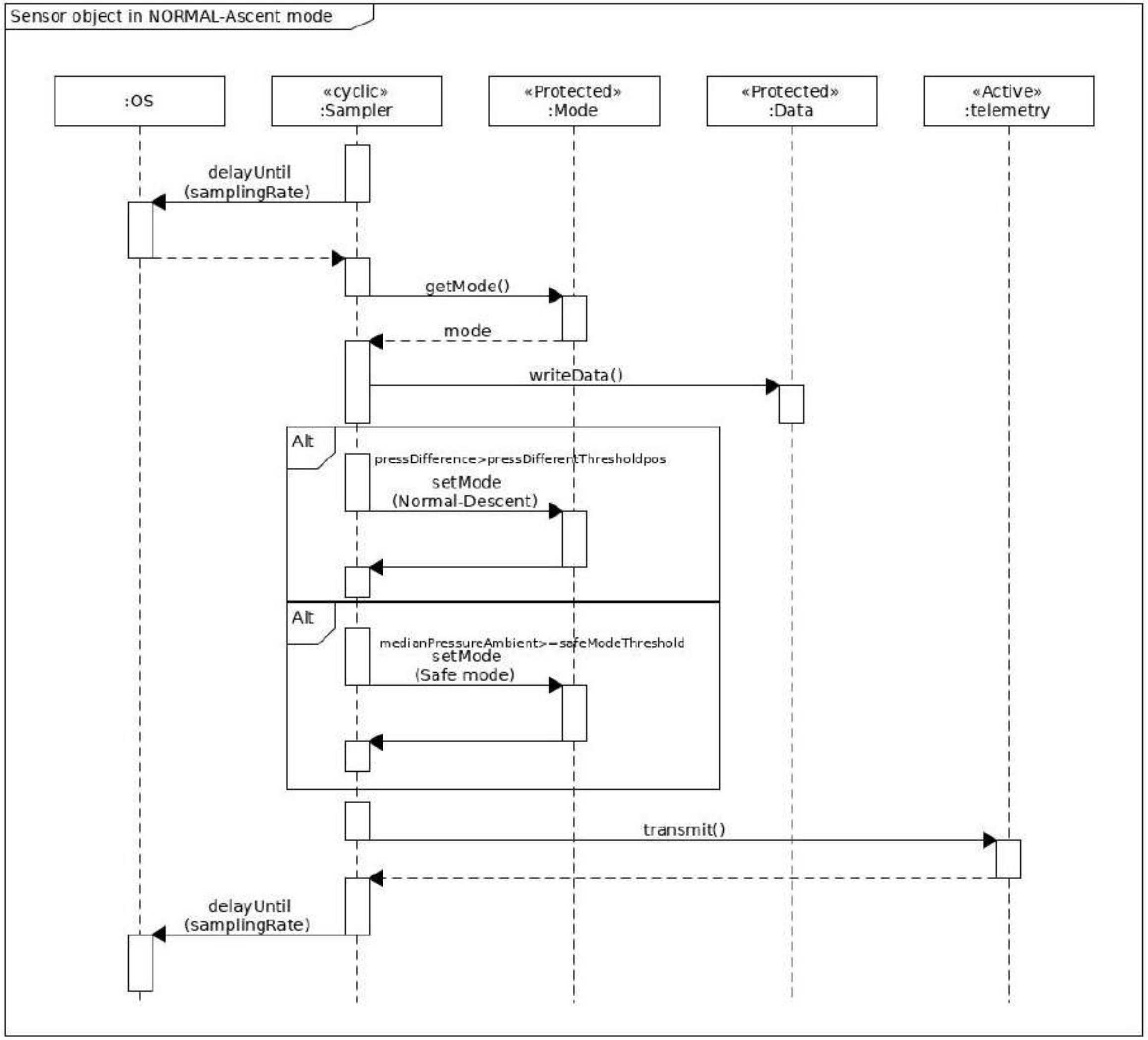


Figure 97: Sensor Object in Standby Mode.



ascent-Mode.jpg

Figure 98: Sensor Object in Normal - Ascent Mode.

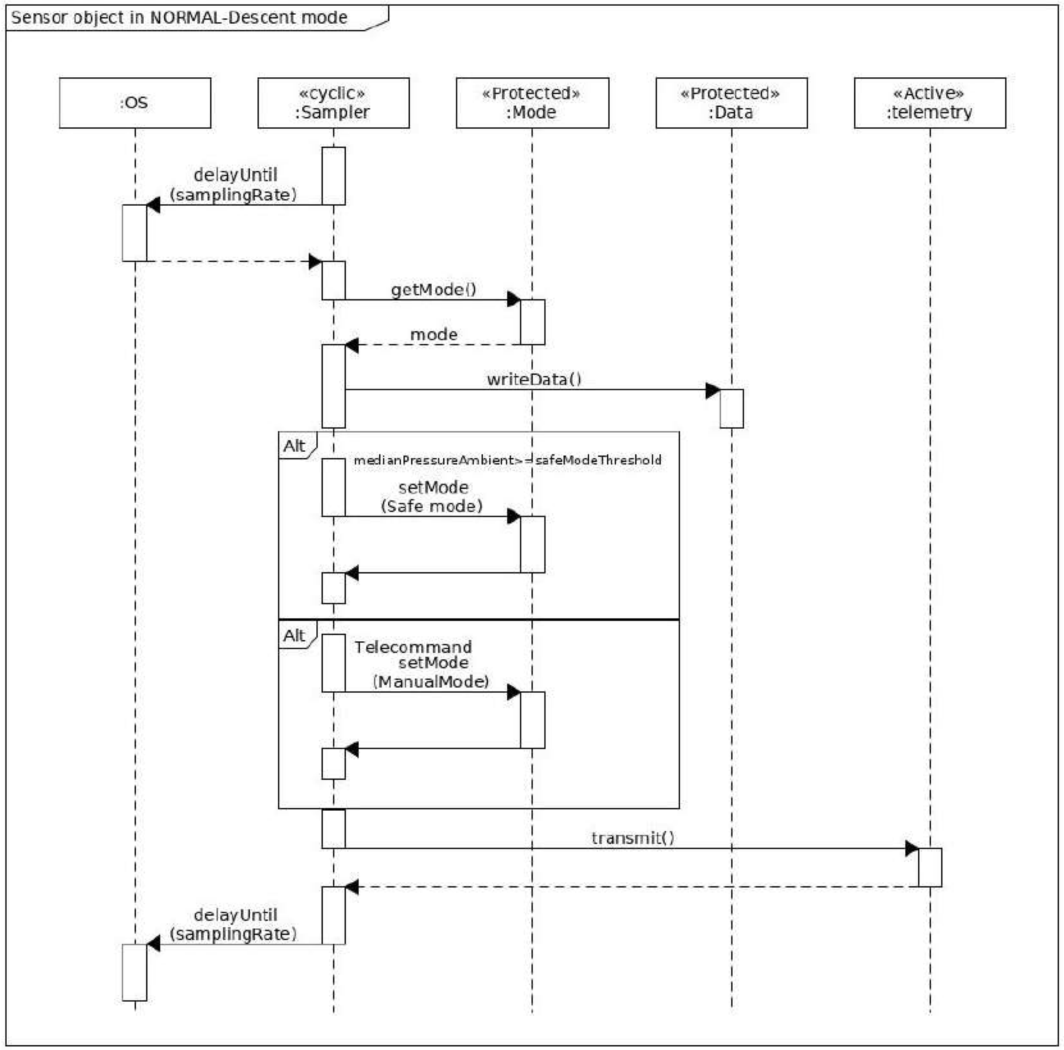


Figure 99: Sensor Object in Normal - Descent Mode.

C.10 Software Interface Diagram

C.10.1 Sensor Object Interface Diagram

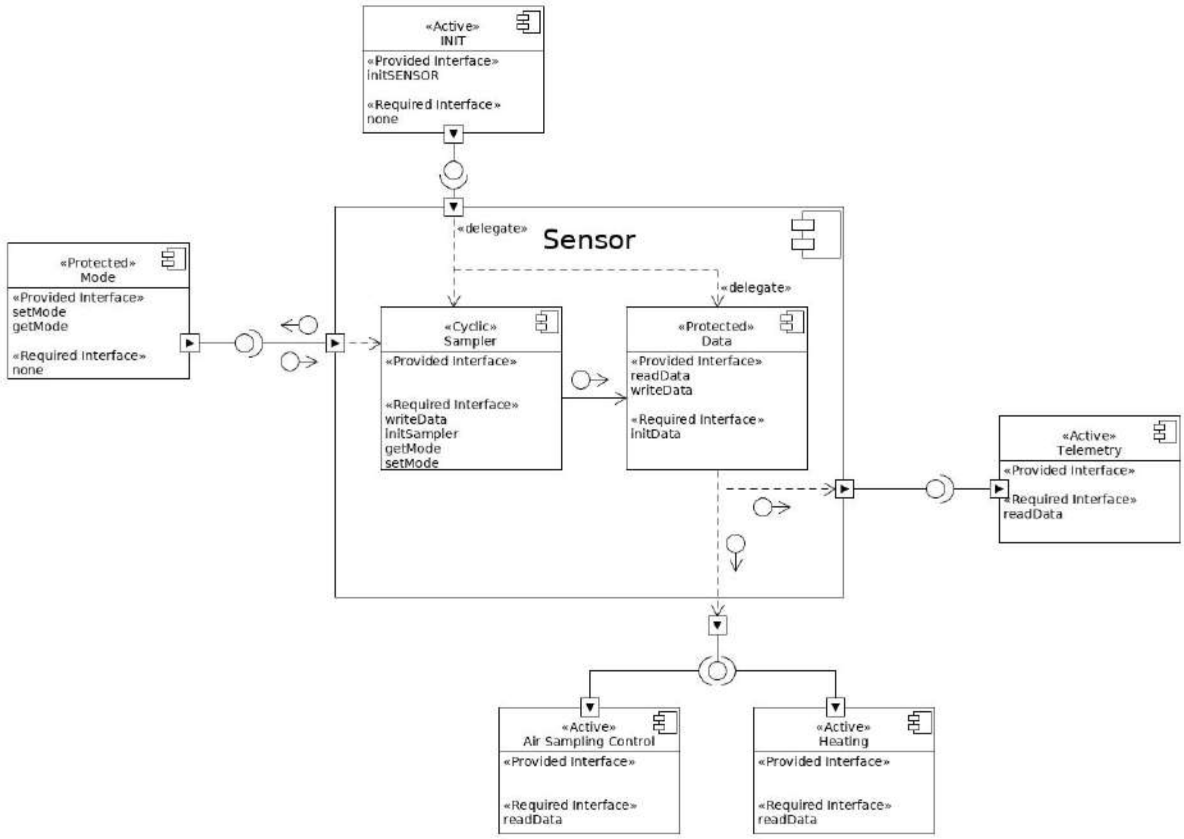


Figure 100: Sensor Object Interface Diagram.

C.10.2 Air Sampling Control Object Interface Diagram

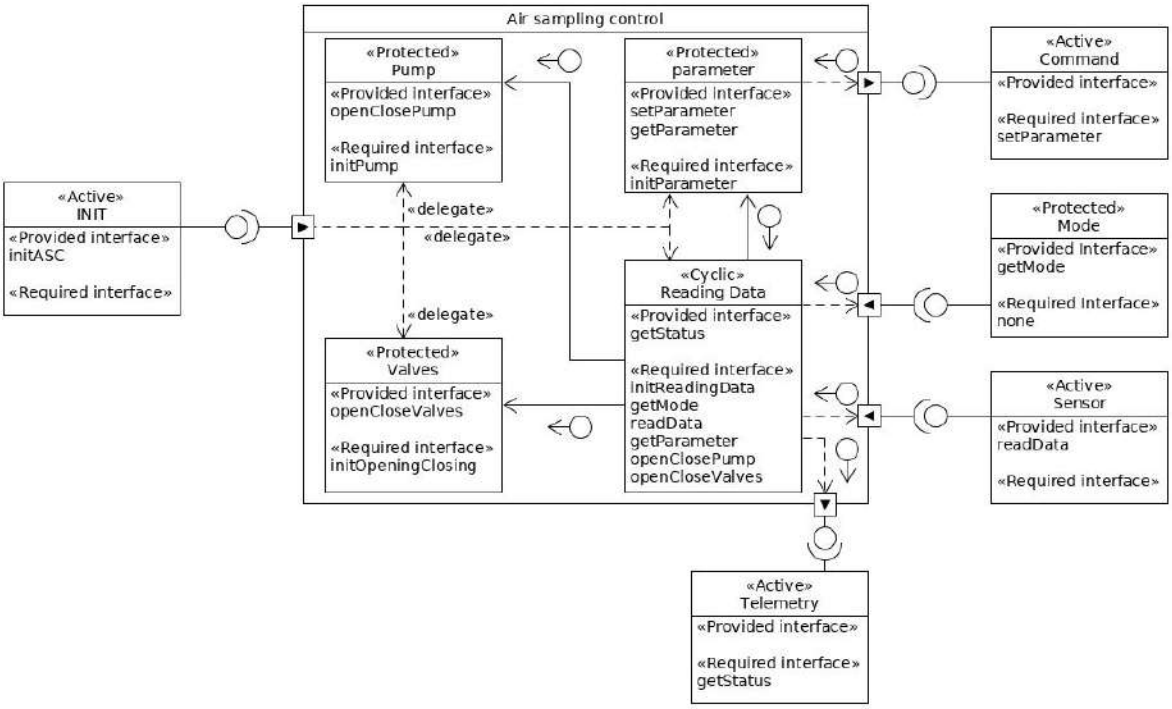


Figure 101: Air Sampling Control Object Interface Diagram.

C.10.3 Heating Object Interface Diagram

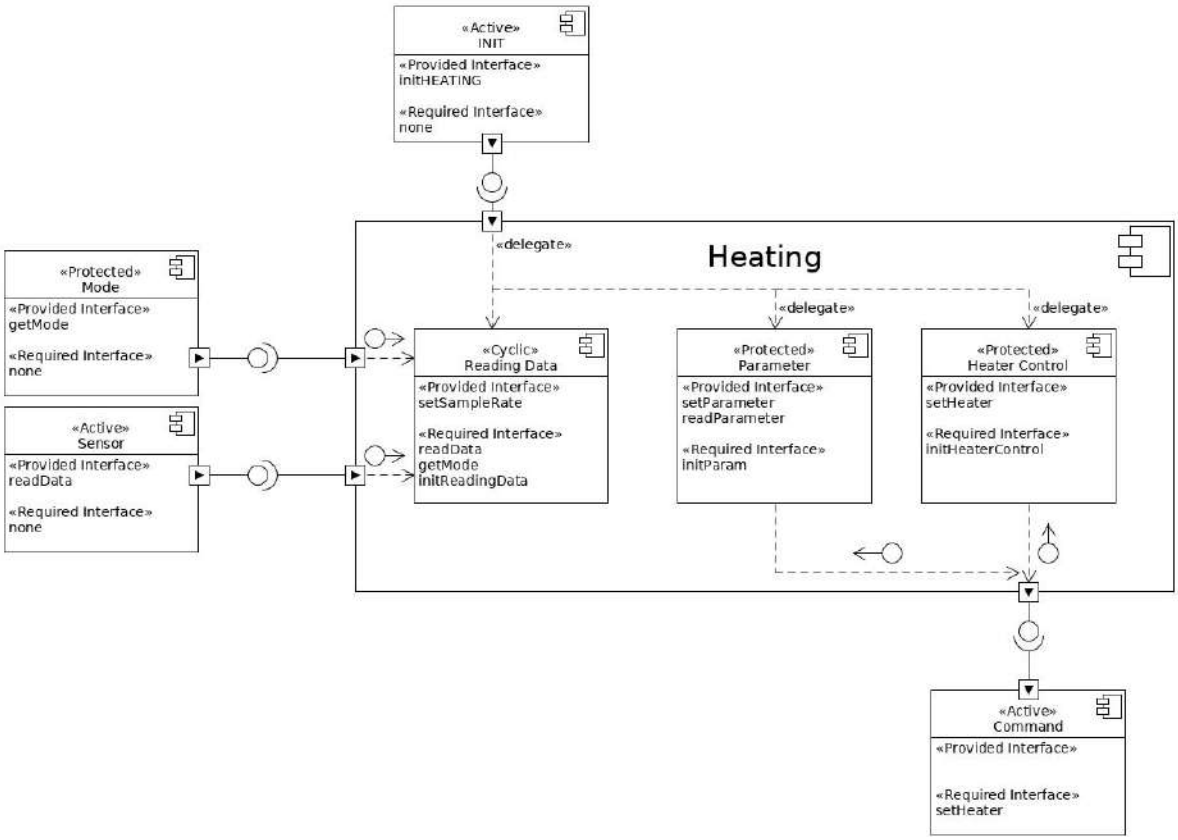


Figure 102: Heating Object Interface Diagram.

C.11 PCB Schematics

Red is traces pulled on the top layer and blue are the traces on the bottom layer.

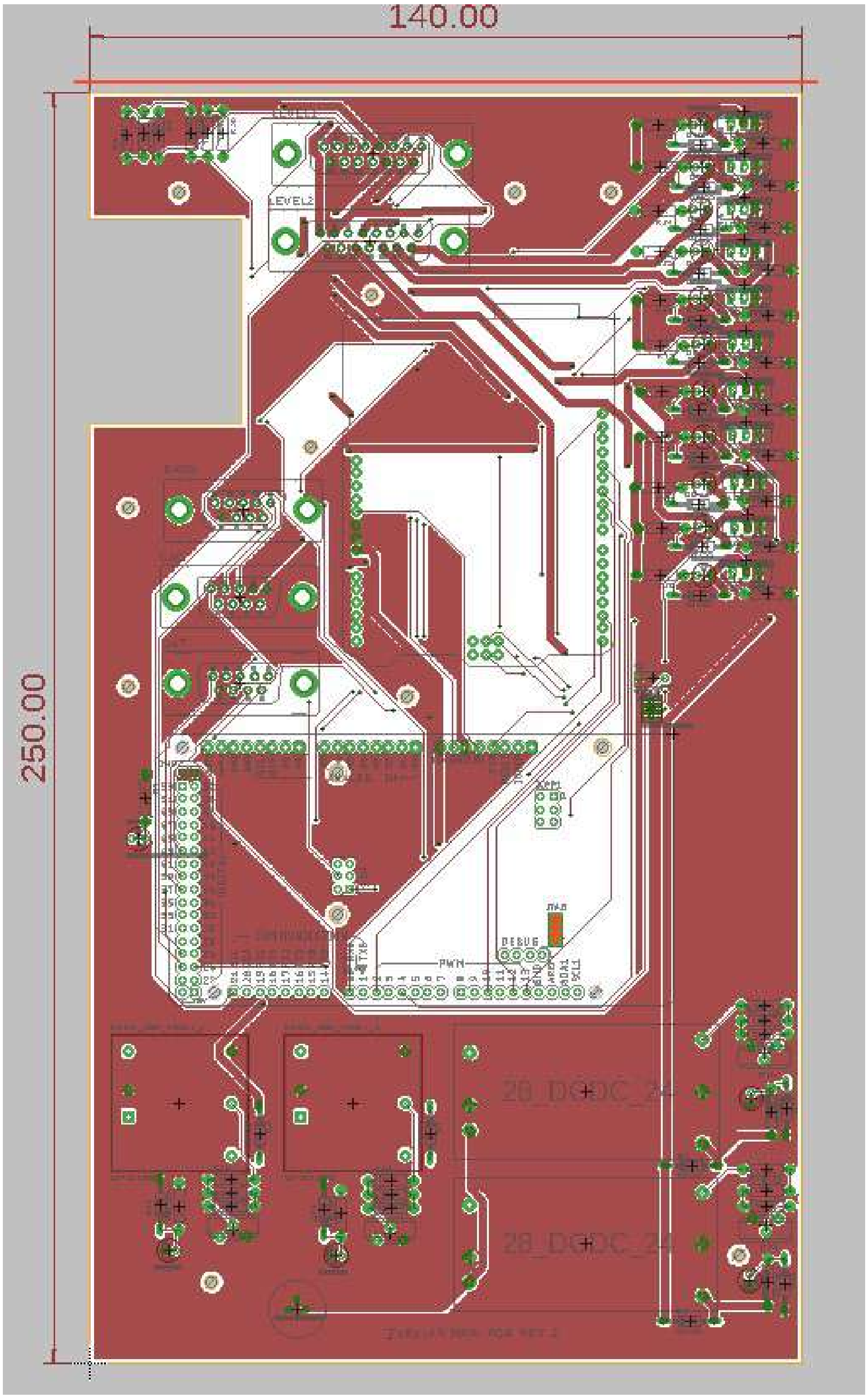


Figure 103: Main PCB Top layer Layout in Eagle.

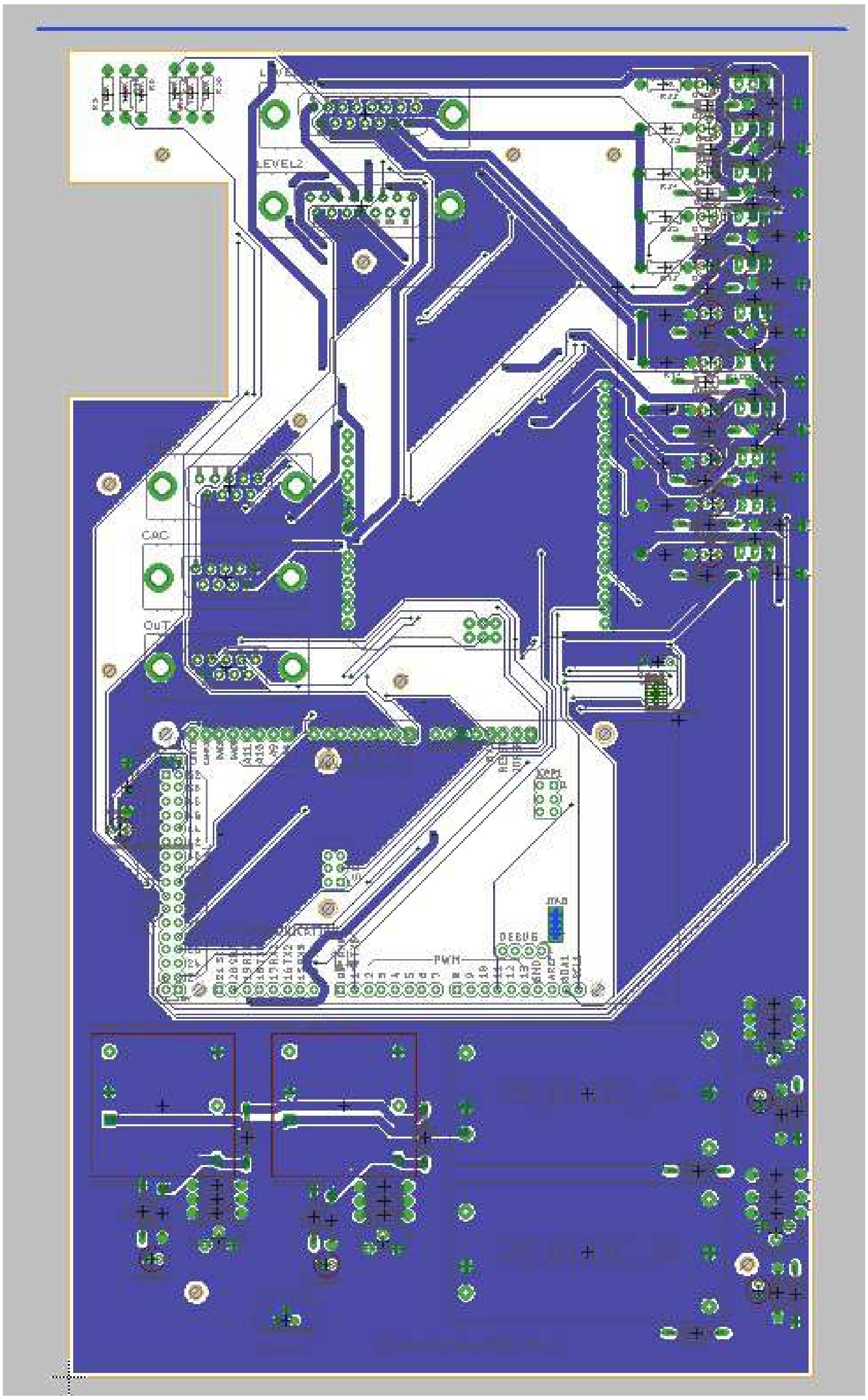


Figure 104: Main PCB bottom layer Layout in Eagle.

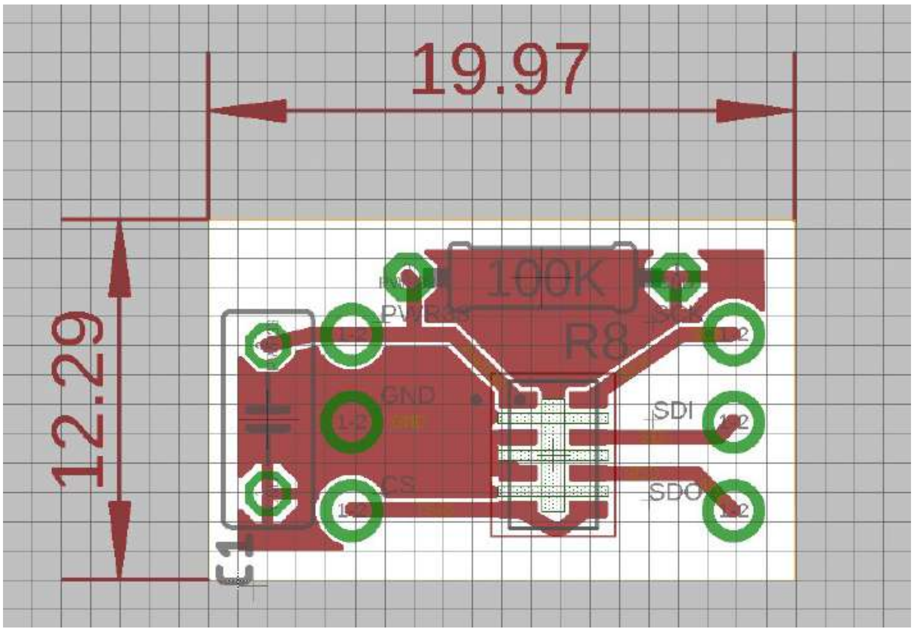


Figure 105: Barometric pressure sensor PCB top layer Layout in Eagle.

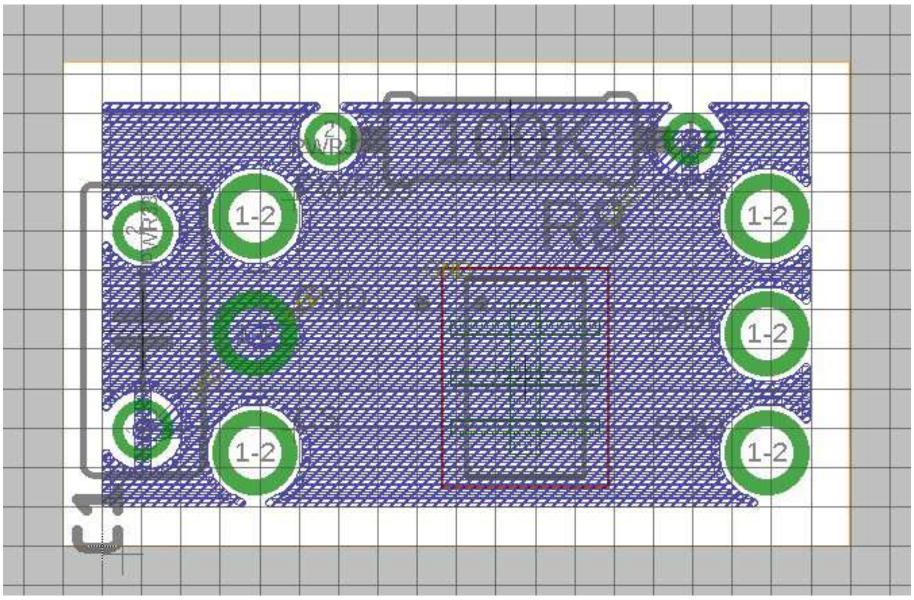


Figure 106: Barometric pressure sensor PCB bottom layer Layout in Eagle.

C.12 Tube

GC ACCESSORIES | GAS MANAGEMENT

Tubing

An extra charge is applied for cutting Sulfinert® or Silcosteel®-CR tubing. The charge is calculated from the total number of pieces produced for each line item

Treated Welded/Drawn 304 Grade Stainless Steel Tubing

Our most popular grade of tubing. Recommended for:

- Chromatography applications.
- Gas delivery systems.
- Lower pressures.
- Inert applications.

Maximum temperature of 450 °C in an inert atmosphere.

			Length							
ID	OD	Wall Thickness	6 Feet cat.#	10 Feet cat.#	15 Feet cat.#	20 Feet cat.#	25 Feet cat.#	50 Feet cat.#	100 Feet cat.#	>100 Feet cat.#*
Sulfinert® Treated (Coiled)										
0.011" (0.28 mm)	0.022" (0.56 mm)		29194	29195	29196	29197	29198	29199	29200	29201
0.021" (0.53 mm)	0.029" (0.74 mm)		29202	29203	29204	29205	29206	29207	29208	29209
0.010" (0.25 mm)	1/16" (1.59 mm)		29210	29211	29212	29213	29214	29215	29216	29217
0.020" (0.51 mm)	1/16" (1.59 mm)		29218	29219	29220	29221	29222	29223	29224	29225
0.030" (0.76 mm)	1/16" (1.59 mm)		29226	29227	29228	29229	29230	29231	29232	29233
0.040" (1.02 mm)	1/16" (1.59 mm)		29234	29235	29236	29237	29238	29239	29240	29241
0.085" (2.16 mm)	1/8" (3.18 mm)	0.020"	29242	29243	29244	29245	29246	29247	29248	29249
0.210" (5.33 mm)	1/4" (6.35 mm)	0.020"	29250	29251	29252	29253	29254	29255	29256	29257

*The availability of long lengths is subject to inventory constraints. Lead times may vary depending on the continuous length needed. Please inquire before ordering. Maximum continuous lengths are: 200** ft (cat.# 29201, 29209), 2,000 ft (cat.# 29217, 29225, 29233, 29241), 1,150 ft (cat.# 29249), and 750 ft (cat.# 29257). Pricing for lengths of 101 ft or more is on a per foot basis.
**Contact us if longer length is needed for cat.# 29201 or 29209.

ordering note

Required length in meters x 3.2808 = length in feet.

Treated Seamless 316L Grade Stainless Steel Tubing

High durability tubing. Recommended for:

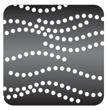
- Inert applications.
- High temperatures.
- High pressures.
- Corrosive environments.
- Zero bleed.

			Length							
ID	OD	Wall Thickness	6 Feet cat.#	10 Feet cat.#	15 Feet cat.#	20 Feet cat.#	25 Feet cat.#	50 Feet cat.#	100 Feet cat.#	>100 Feet cat.#*
Silcosteel®-CR Treated (Coiled)										
0.055" (1.40 mm)	1/8" (3.18 mm)	0.035"	29091	29092	29093	29094	29095	29096	29097	29098
0.180" (4.57 mm)	1/4" (6.35 mm)	0.035"	29099	29100	29101	29102	29103	29104	29105	29106
0.277" (7.04 mm)	3/8" (9.52 mm)	0.049"	29107	29108	29109	29110	29111	29112	29113	29114
Sulfinert® Treated (Coiled)										
0.055" (1.40 mm)	1/8" (3.18 mm)	0.035"	29067	29068	29069	29070	29071	29072	29073	29074
0.180" (4.57 mm)	1/4" (6.35 mm)	0.035"	29075	29076	29077	29078	29079	29080	29081	29082
0.277" (7.04 mm)	3/8" (9.52 mm)	0.049"	29083	29084	29085	29086	29087	29088	29089	29090

*The availability of long lengths is subject to inventory constraints. Lead times may vary depending on the continuous length needed. Please inquire before ordering. 1/8" OD: 1,500 ft in one continuous coil; 1/4" OD: 750 ft in one continuous coil; 3/8" OD: 250 ft in one continuous coil. Longer lengths will be more than one coil. Pricing for lengths of 101 ft or more is on a per foot basis.

C.13 AAC Manifold Valve

Series VDW

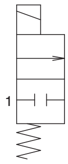


For Air **Single Unit**

Model/Valve Specifications

N.C.

Configuration symbol



Note) The configuration symbol shows ports 1 and 2 as blocked, but there is actually a limit to the blocking capability when the pressure of port 2 is greater than the pressure of port 1. Please contact SMC when low leakage performance is required.

Normally Closed (N.C.)
Aluminium Body Type

Size	Port size	Orifice diameter [mmø]	Model	Flow-rate characteristics			Maximum operating pressure differential [MPa]	Weight [g]
				C [dm^3/(s·bar)]	b	Cv	Pressurized port 1	
2	M5, 1/8	1.6	**VDW20**	0.30	0.45	0.07	0.7	80
		2.3		0.58	0.45	0.18	0.4	
		3.2		1.10	0.38	0.30	0.2	

Resin Body Type (Built-in One-touch Fittings)

Size	Port size	Orifice diameter [mmø]	Model	Flow-rate characteristics			Maximum operating pressure differential [MPa]	Weight [g]
				C [dm^3/(s·bar)]	b	Cv	Pressurized port 1	
1	M5 ø3.2 One-touch fitting ø4 One-touch fitting	1.0	**VDW10**	0.14	0.40	0.04	0.9	45
		1.6		0.30	0.25	0.07	0.4	
2	M5 ø4 One-touch fitting ø6 One-touch fitting	1.6	**VDW20**	0.30	0.45	0.07	0.7	80
		2.3		0.58	0.45	0.18	0.4	
		3.2		1.10	0.38	0.30	0.2	

Refer to “Glossary of Terms” on page 11 for details on the maximum operating pressure differential.

Fluid and Ambient Temperature

Fluid temperature [°C]	Ambient temperature [°C]
–10 Note) to 50	–10 to 50

Note) Dew point temperature: –10°C or less

Valve Leakage

Internal Leakage

Seal material	Leakage rate (Air) Note)
NBR	1 cm^3/min or less (Aluminium body type)
	15 cm^3/min or less (Resin body type)

External Leakage

Seal material	Leakage rate (Air) Note)
NBR	1 cm^3/min or less (Aluminium body type)
	15 cm^3/min or less (Resin body type)

Note) Leakage is the value at ambient temperature 20°C.

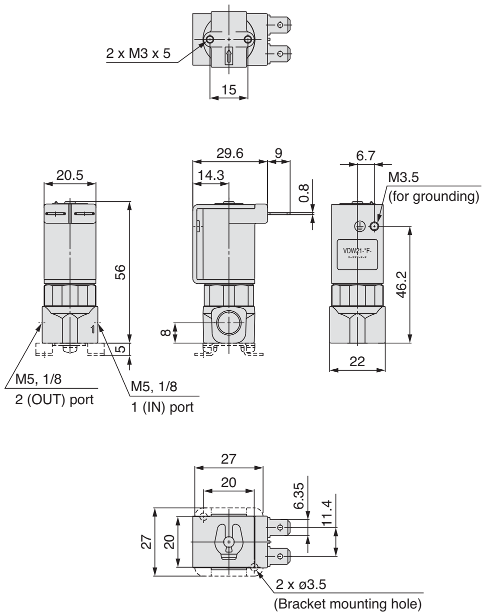
C.14 AAC Flushing Valve and CAC Valve

Compact Direct Operated
2 Port Solenoid Valve For Water and Air ***Series VDW10/20/30***

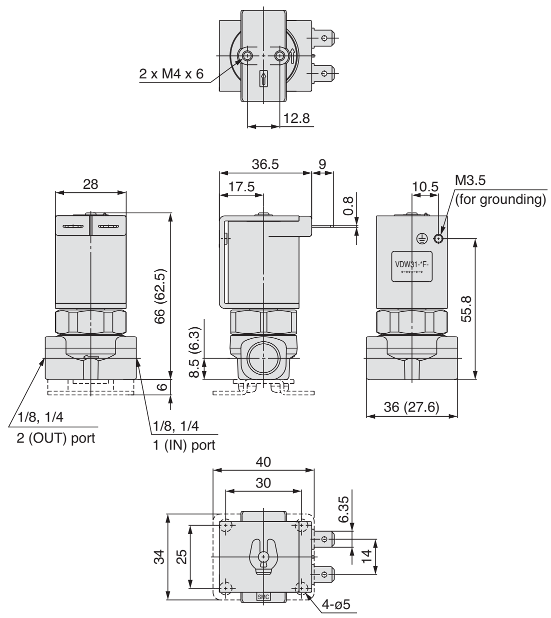
Series VDW10/20/30 2-port type has been remodeled to new compact and lightweight series.
For details about new series, refer to New VDW for VDW10/20 and to Series VX21 for VDW30, respectively.

Dimensions

VDW21-□F



VDW31-□F



Bracket assembly part no.

・Series 20

VDW20－15A－1

・Series 30

VCW20－12－01A

How to Order Manifold

VV2DW 2 – □ 05 01 □ – □ – Q

Series

1	10
2	20
3	30

Material

Symbol	Manifold material	Seal material
-	Brass (C37)	NBR
A		FKM
B		EPDM
G	Stainless steel	NBR
H		FKM
J		EPDM

Stations

02	2 stations
⋮	⋮
10	10 stations

OUT port size

Symbol	Port size	Series 10	Series 20	Series 30
M5	M5	○	○	–
01	1/8 (6A)	–	○	○
02	1/4 (8A)	–	–	○

Note) IN port sizes are as follows.
10: 1/8 (6A)
20: 1/4 (8A)
30: 3/8 (10A)

Thread type

-	Rc
F	G
N	NPT

Option

-	None
F	With bracket

Note) Series 30 is available with bracket only.

How to Order Manifold Assembly

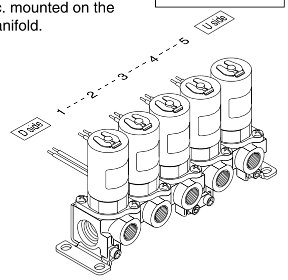
Enter the mounting valve and option part numbers under the manifold base part number.

<Ordering example>

VV2DW2-0501 ········ **1 set** **Manifold part no.**
∗**VDW23-5G-2** ········· **5 sets** **Valve part no. (Stations 1 to 5)**

"∗" is the symbol for assembly. Add an "∗" in front of the part numbers to have solenoid valves, etc. mounted on the manifold.

Enter together in order, counting from station 1 on the D side.



How to Order Valves (For manifold)

VDW 2 3 – 5 G – 2 – □ – Q

Series

1	10
2	20
3	30

Valve type

3	N.C. for manifold

Voltage

Symbol	Voltage	Grommet / Tape winding	Faston™ terminal, Molded	Grommet / Molded
1	100 VAC (50/60 Hz)	●	—	●
2	200 VAC (50/60 Hz)	●	—	●
3	110 VAC (50/60 Hz)	●	—	●
4	220 VAC (50/60 Hz)	●	—	●
5	24 VDC	●	●	●
6	12 VDC	●	●	●
V	6 VDC	●	●	●
S	5 VDC	●	●	●
R	3 VDC	●	●	●

∗ Please consult with SMC regarding other voltages.

Coil type Note)

G	Grommet / Tape winding
F	Faston™ terminal / Molded
W	Grommet / Molded

Note) For series and coil type combinations, refer to page 1.

Material and insulation type

Symbol	Body material	Seal material	Coil insulation
-	Brass (C37)	NBR	Class B
A		FKM	
B		EPDM	
G	Stainless steel	NBR	
H		FKM	
J		EPDM	
L Note)		FKM	

Note) For deionized water: the armature assembly is a corrosion resistant construction.

Orifice size

Symbol	Orifice diameter (mmø)	Series
1	1	10
2	1.6	
1	1.6	20
2	2.3	
3	3.2	
2	2	30
3	3	
4	4	

Manifold Options

Blanking plate assembly

- **Series 10, 20**

VVDW 2 0 – 3A – □

Series

1	10
2	20

Material

Symbol	Plate material	Seal material
G	Stainless steel	NBR
H		FKM
J		EPDM

∗ Plate material is stainless steel only.

- **Series 30**

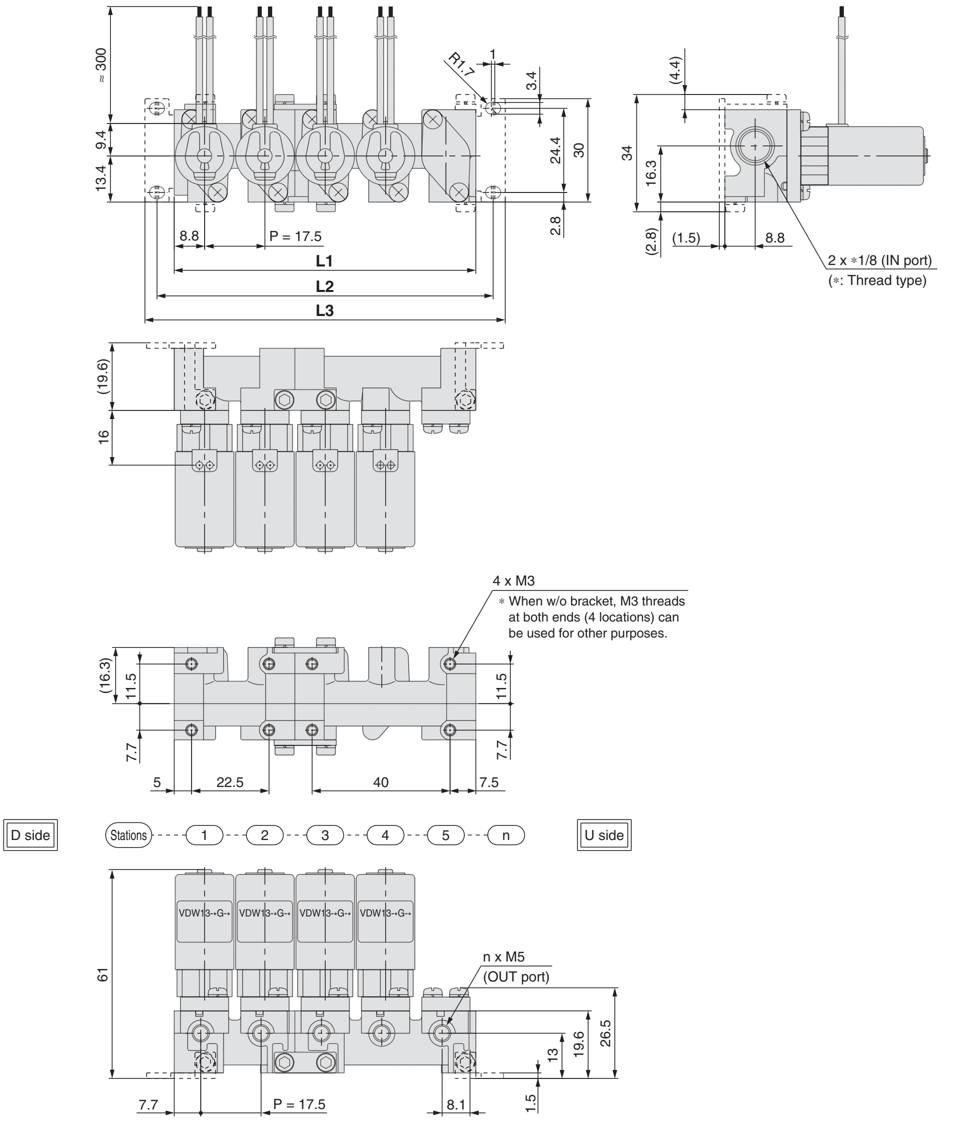
VVCW20 – 3A – □

Material

Symbol	Plate material	Seal material
G	Stainless steel	NBR
H		FKM
J		EPDM

Dimensions

VV2DW1



L Dimension

(mm)

Dimension	n (stations)								
	2	3	4	5	6	7	8	9	10
L1	35	52.5	70	87.5	105	122.5	140	157.5	175
L2	45	62.5	80	97.5	115	132.5	150	167.5	185
L3	52	69.5	87	104.5	122	139.5	157	174.5	192
Manifold composition	2 stns. x 1	3 stns. x 1	2 stns. x 2	2 stns. + 3 stns.	3 stns. x 2	2 stns. x 2 + 3 stns.	2 stns. + 3 stns. x 2	3 stns. x 3	2 stns. x 2 + 3 stns. x 2

Note) The manifold base consists of a junction of 2 and 3 station bases.
Refer to page 10 and 11 regarding manifold additions.

C.15 Pump

NMP850K_DC-B

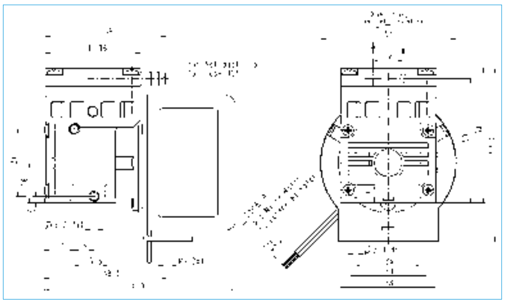
PERFORMANCE DATA

Type	KNF DC motor, brushless (V)	Delivery at atm. pressure (l/min)[1]	Max. operating pressure (bar)	Ultimate vacuum (mbar abs.)
NMP850KPDC-B	12	4.2	1.5	230
NMP850KTDC-B	12	3.5	1.5	300
NMP850KPDC-B	24	4.2	1.5	230
NMP850KTDC-B	24	3.5	1.5	300

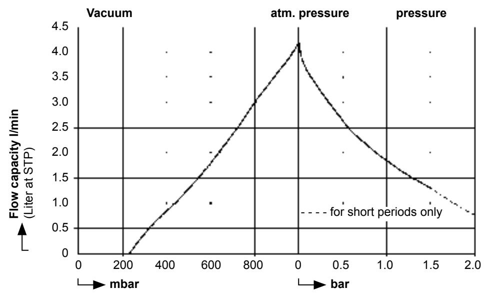
[1] Liter at STP

PUMP MATERIAL

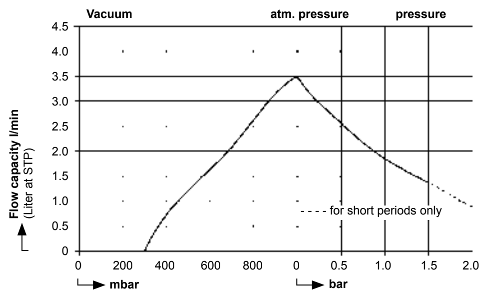
Type	Pump head	Diaphragm	Valves
NMP850KPDC-B	PPS	EPDM	EPDM
Chemically resistant version			
NMP850KTDC-B	PPS	PTFE-coated	FFPM



NMP850KPDC-B



NMP850KTDC-B



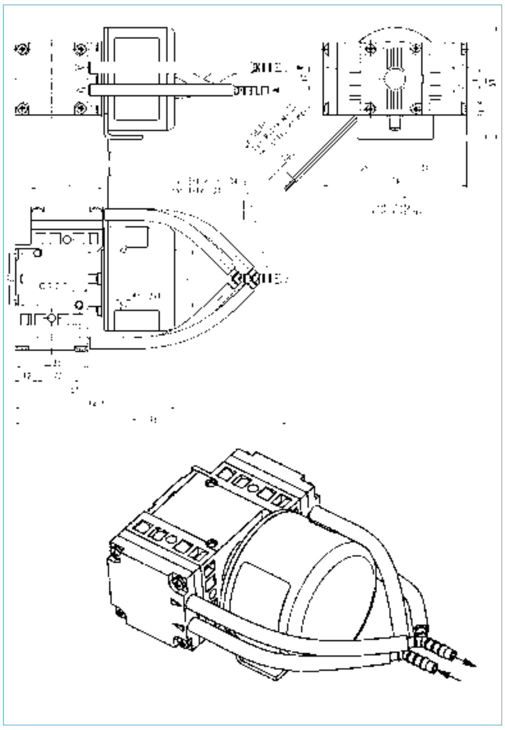
NMP850.1.2KPDC-B

PERFORMANCE DATA

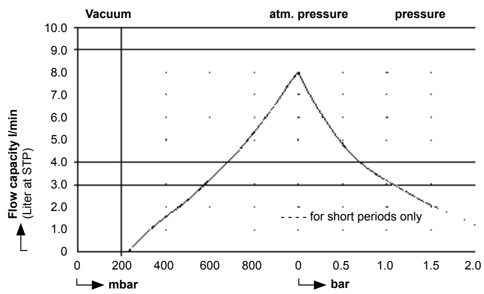
Type	KNF DC motor, brushless (V)	Delivery at atm. pressure (l/min)[1]	Max. operating pressure (bar)	Ultimate vacuum (mbar abs.)
NMP850.1.2KPDC-B	12	8.0	1.5	230
NMP850.1.2KPDC-B	24	8.0	1.5	230

PUMP MATERIAL

Type	Pump head	Diaphragm	Valves
NMP850.1.2KPDC-B	PPS	EPDM	EPDM



NMP850.1.2KPDC-B

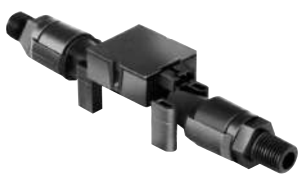


C.16 Airflow Sensor

Airflow Sensors

High Flow Mass Airflow/Amplified

AWM5000 Series



FEATURES
- Linear voltage output
- Venturi design
- Remote mounting capability
- Active laser trimming improves interchange ability
- Separate gas calibration types:
  - Ar (argon)
  - N_2 (nitrogen) or
  - CO_2 (carbon dioxide)

In-Line Flow Measurement
AWM5000 Series Microbridge Mass Airflow Sensors feature a venturi type flow housing. They measure flow as high as 20 standard liters per minute (SLPM) while inducing a maximum pressure drop of 2.25″ H_2O. The microbridge chip is in direct contact with the flow stream, greatly reducing error possibilities due to orifice or bypass channel clogging.

Rugged, Versatile Package
The rugged plastic package has been designed to withstand common mode pressures up to 50 psi, and the small sensing element allows 100 gs of shock without compromising performance. The included ''AMP'' compatible connector provides reliable connection in demanding applications.

On-board Signal Conditioning
Each AWM5000 sensor contains circuitry which performs amplification, linearization, temperature compensation, and gas calibration. Figure 1 (Heater Control Circuit) and Figure 2 (Sensor Bridge Circuit and Amplification Linearization Circuit) illustrate the on-board electrical circuitry for the AWM5000 Series. A 1 to 5 VDC linear output is possible for all listings regardless of flow range (5, 10, 15, or 20 SLPM) or calibration gas (nitrogen, carbon dioxide, nitrous oxide, or argon). All calibration is performed by active laser trimming.

Figure 1

Heater Control Circuit

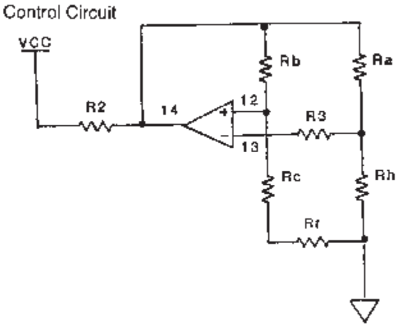
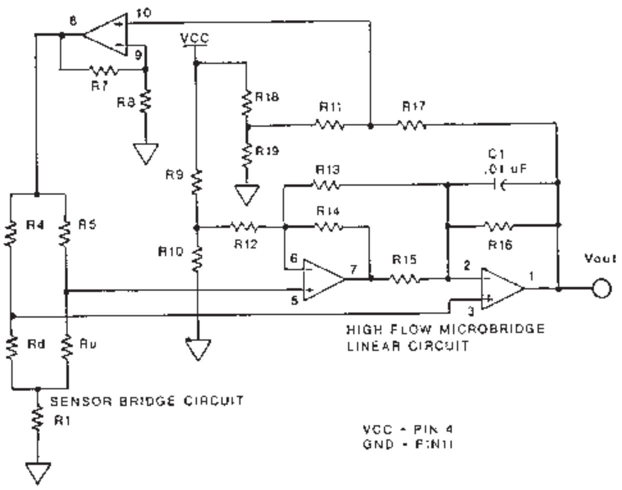


Figure 2

Sensor Bridge Circuit and Amplification Linearization Circuit



SPECIFICATIONS (Performance Characteristics @ 10.0 ±0.01 VDC, 25°C)

	AWM5101	AWM5102	AWM5103	AWM5104
Flow Range (Note 3)	0-5 SLPM	0-10 SLPM	0-15 SLPM	0-20 SLPM

Suffix - Calibration gas	**VA** - Argon (Ar)	**VC** - Carbon dioxide (CO_2)	**VN** - Nitrogen (N_2)
	Min.	**Typ.**	**Max.**
Excitation VDC	8	10±0.01	15
Power consumption (mW)	—	—	100
Response time (msec)	—	—	60
Null output VDC	0.95	1	1.05
Null output shift −20° to 70°C	—	±0.050 VDC	±.200 VDC
Common Mode Pressure (psi)	—	—	50
Temperature range	−20° to +70°C, (−4° to 158°F)		
Weight	60 grams (2.12 oz.)		
Shock ratings	100 g peak, 6 msec half-sine (3 drops, each direction of 3 axes)		
Output @ laser trim point	5 VDC @ Full Scale Flow		
Output voltage shift +20° to −25°C, +20° to 70°C	Suffix VA or VN ±7.0% Reading, Suffix VC ±10.0% Reading		
Linearity error (2)	±3.0% Reading (max.)		
Repeatability & Hysteresis	±0.5% Reading (max.)		
Connector (Included) —Four pin receptacle	MICRO SWITCH (SS12143)/AMP (103956-3)		
Leak rate, max	0.1 psi/min. at static condition, (Note 2)		

Notes:
1. Linearity specification applies from 2 to 100% full scale of gas flow range, and does not apply to null output at 0 SLPM.
2. The AWM5000 series product has a leakage spec of less than 0.1 psi per minute at 50 psi common mode pressure. If during installation, the end adapters are twisted with respect to the flowtube, this may compromise the seal between the o-ring and the flowtube and may cause a temporary leak. This leak might be as high as 1 psi or might remain in specification. It will self-reseal as the o-ring takes a new set. Approximately 85% of the leakage will dissipate in 24 hours. Within 48 hours, complete recovery will take place.
3. SLPM denotes standard liters per minute, which is a flow measurement referenced to standard conditions of 0°C/1 bar (sea level), 50% RH.

NOTICE

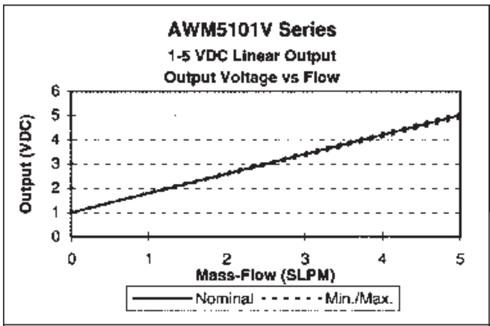
AWM5000—Chimney Effect

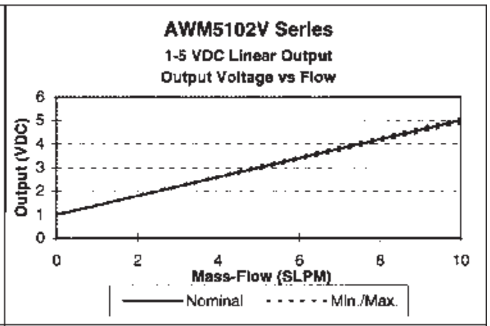
AWM microbridge mass airflow sensors detect mass airflow caused by heat transfer. The thermally isolated microbridge structure consists of a heater resistor positioned between two temperature sensing resistors.

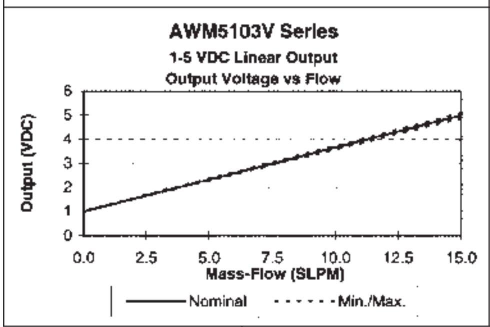
The heater resistor maintains a constant temperature, 160°C above ambient, during sensor operation. Airflow moving past the chip transfers heat from the heater resistor. This airflow warms the downstream resistor and cools the upstream resistor. The temperature change and the resulting change in resistance of the temperature resistors is proportional to the mass airflow across the sensing element.

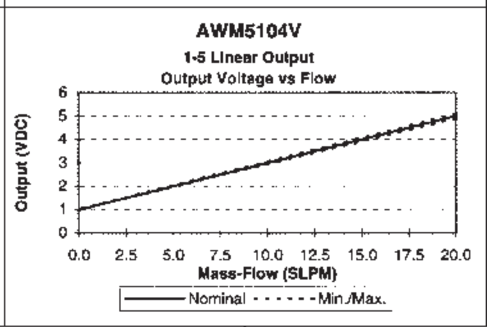
When the sensor is mounted in a vertical position, under zero flow conditions, the sensor may produce an output that is the result of thermally induced convection current. This occurrence is measurable in the AWM5000 Series, particularly in the 5 SLPM versions. When designing the sensor into applications where null stability is critical, avoid mounting the sensor in a vertical position.

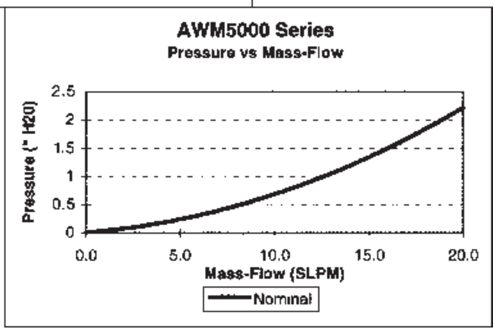
OUTPUT CURVES (Performance Characteristics @ 10.0 ±0.01 VDC, 25°C)











Airflow

Highflow Mass Airflow/Amplified

AWM5000 ORDER GUIDE

Catalog Listing	Flow Range
AWM5101VA	5 SLPM, Argon calibration
AWM5101VC	5 SLPM, CO_2 calibration (2)
AWM5101VN	5 SLPM, N_2 calibration (1)
AWM5102VA	10 SLPM, Argon calibration
AWM5102VC	10 SLPM, CO_2 calibration (2)
AWM5102VN	10 SLPM, N_2 calibration (1)
AWM5103VA	15 SLPM, Argon calibration
AWM5103VC	15 SLPM, CO_2 calibration (2)
AWM5103VN	15 SLPM, N_2 calibration (1)
AWM5104VA	20 SLPM, Argon calibration
AWM5104VC	20 SLPM, CO_2 calibration (2)
AWM5104VN	20 SLPM, N_2 calibration (1)

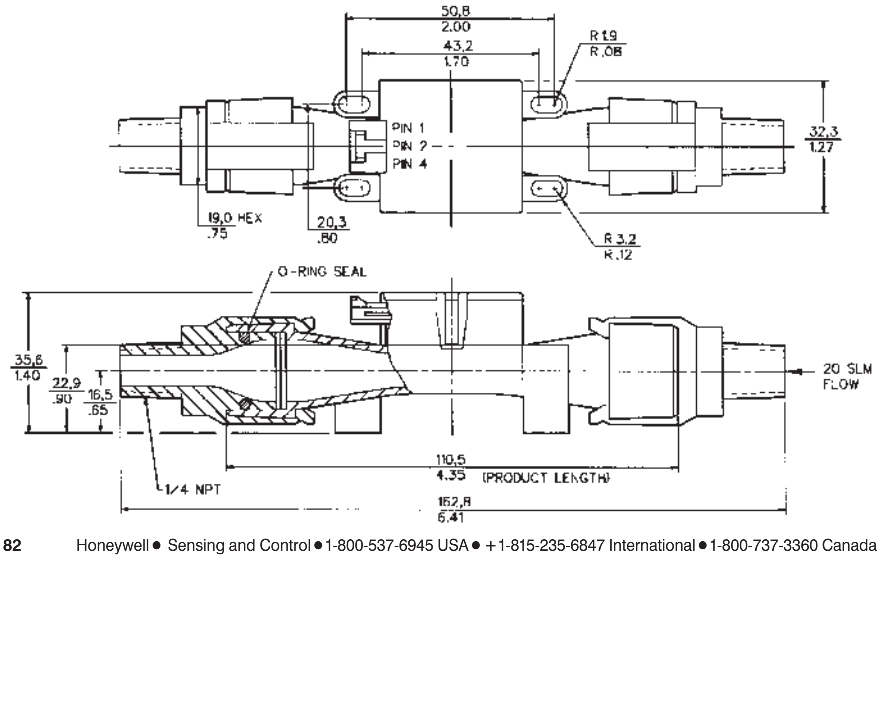
CONNECTOR ORDER GUIDE

Catalog Listing	Description
SS12143	Four pin Electrical connector Connectors use Amp 103956-3

Note: All listings have 1 - 5 VDC linear output with 10 VDC supply over given flow range for a specific calibration gas.
1. N_2 calibration is identical to 0_2 and air calibration.
2. CO_2 calibration is identical to N_2O calibration.
3. For additional gas correction factors, see Application Note 3.

OUTPUT CONNECTIONS
Pin 1 + Supply voltage
Pin 2 Ground
Pin 3 No connection
Pin 4 Output voltage
Arrow on bottom of housing indicates direction of flow.

MOUNTING DIMENSIONS (for reference only)



C.17 Static Pressure Sensor

Gems Sensors & Controls

3500 Series

Compact Low Pressure OEM Pressure Transmitters

- 5 to 600 psi pressure ranges (0.35 to 40 bar)
- Choice of outputs, electrical connections and pressure ports
- Operating temperature up to 257°F (125°C)

For OEMs that need consistent high levels of performance, reliability and stability the 3500 Series units offer a small package size with all stainless steel wetted parts at an unbeatable price performance ratio. A wide choice of electrical outputs as well as both electrical and pressure connections means the unit is suitable for most applications without modification. The compact construction of the 3500 Series makes it ideal for installation where space is at a premium.

Specifications

Input	
Pressure Range	5-600 psi (0.35-40 bar)
Proof Pressure	2x
Burst Pressure	3X
Performance	
Long Term Drift	<0.2% FS/YR
Accuracy	0.25% FS
Thermal Error, Max.	±1% / 176°F (80°C)
Compensated Temperatures	-4°F to +212°F (-20°C to +100°C)
Operating Temperatures	-40°F to +257°F (-40°C to +125°C)
Zero Tolerance, Max.	±0.5% of span
Span Tolerance, Max.	±0.5% of span
Fatigue Life	Designed for more than 100 M cycles
Mechanical Configuration	
Pressure Port	See under "How to Order," last page
Wetted Parts	316L Stainless Steel
Electrical Connection	See under "How to Order," last page
Enclosure	IP67
Vibration	BSEN 60068-2-6 (FC) BSEN 60068-2-64 (FH)
Shock	BSEN 60068-2-27 (Ea)
Approvals	CE, RoHS
Weight	1.23 to 1.9 ounces (35-53 grams). Configuration dependant

Individual Specifications

Voltage	
Output	0V min. to 10V max. See under "How to Order," last page
Supply Voltage (Vs)	2 Volts above full scale to 30 Vdc (24 Vdc, max. above 230°F (110°C) applications)
Source and Sinks	8 mA
Current	
Output	4-20 mA
Supply Voltage (Vs)	10-30 Vdc (24 Vdc, max. above 230°F (110°C) applications)
Maximum Load Resistance	(Supply Voltage -10) x 50ohms
Ratiometric	
Output	0.5 to 4.5V
Supply Voltage (Vs)	5 Vdc ±10%

EMC Specifications

Emissions Tests: EN61326-1:2006 and EN61326-2-3:2006

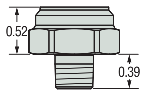
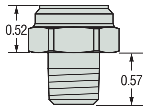
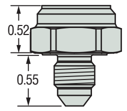
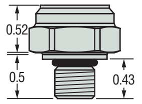
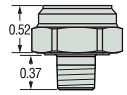
EN55011:2009 + A1	Radiated Emissions

Immunity Tests: EN61326-1:2006 and EN61326-2-3:2006

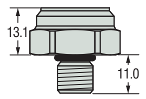
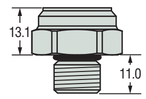
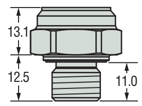
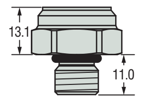
EN61000-4-2:2009	Electrostatic Discharge
EN61000-4-3:2006 + A2	Radiated Immunity
EN61000-4-4:2012	Fast Burst Transients
EN61000-4-6:2009	Conducted RF Immunity

Pressure Ports

SAE

	1/8˝-27 NPT	1/4˝-18 NPT	7/16˝-20 UNF with 37° Flare	7/16˝-20 UNF	1/8˝-27 NPTF
Dimensions in Inches					
Fitting Code	**08**	**02**	**04**	**1J**	**4D**
Torque	2-3 TFFT*	2-3 TFFT*	15-16 NM	18-20 NM	2-3 TFFT*

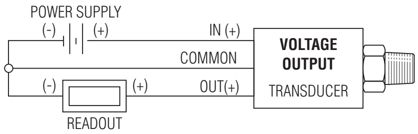
BSP & Metric

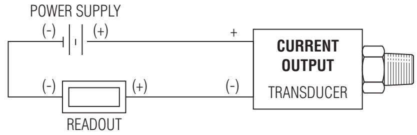
	G1/8˝ External	G1/4˝-19 External w/O-Ring	G1/4˝-19 A Integral Face Seal	M12 x 1.5 w/O-Ring
Dimensions in MM				
Fitting Code	**OS**	**01**	**05**	**OL**
Torque	22-25 NM	30-35 NM	30-35 NM	28-30 NM

* NPT Threads 2-3 turns from finger tight. Wrench tighten 2-3 turns.

General Notes:
1. The diameter of all cans is 19 mm (0.748˝)
2. Hex is 22 mm (0.886˝) Across Flats (A/F) for deep socket mounting

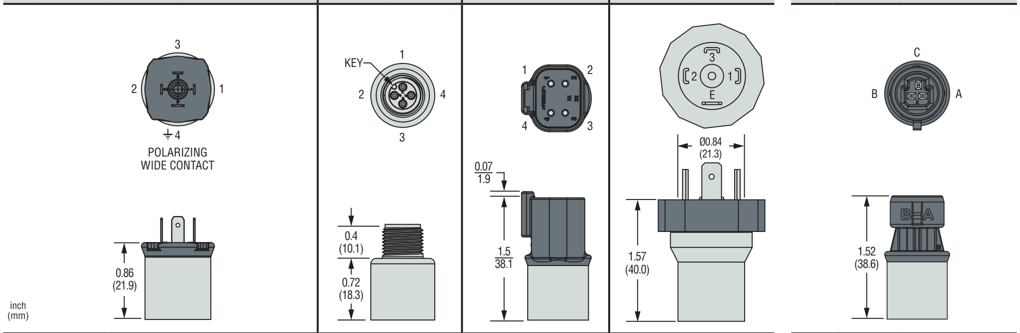
Wiring Diagram





Gems Sensors & Controls

Electrical Connector



	DIN 9.4 mm				M12 x 1P		Deutsch DT04-4P		DIN 43650A	
	Code B		Code K		Code E		Code 8		Code G	
Pin #	**Voltage Mode**	**Current Mode**	**Voltage Mode**	**Current Mode**	**Voltage Mode**	**Current Mode**	**Voltage Mode**	**Current Mode**	**Voltage Mode**	**Current Mode**
1	V_{out} (pressure)	No Connect	V_{supply}	Supply	V_{supply}	Supply	Ground	Return	V_{supply}	Supply
2	V_{supply}	Supply	Ground	Return	V_{out} (pressure)	No Connect	V_{supply}	Supply	Ground	Return
3	No Connect	No Connect	V_{out}	No Connect	Ground	Return	No Connect	No Connect	V_{out}	No Connect
4	Ground	Return	No Connect	No Connect	No Connect	No Connect	V_{out} (pressure)	No Connect	No Connect	No Connect

Packard MetriPack		
Code 9		
Pin ID	**Voltage Mode**	**Note**
C	V_{out} (pressure)	MetriPack connectors may be used with 0.5-4.5V Ratiometric and 4-20 mA only.
A	Ground	
B	V_{supply}	
—	—	

Mating Connectors

Part Number	Description	For Use on Elect. Code #
557230	MINI DIN Connector, Strain Relief (with drive screw & gasket)	B and K
557254	Large DIN 43650A	G
557703-01M0	M12 Cord Set – 1 Meter (Red 1, Green 2, Blue 3, Yellow 4)	E
557703-03M0	M12 Cord Set – 3 Meters (Red 1, Green 2, Blue 3, Yellow 4)	E
557703-04M0	M12 Cord Set – 4 Meters (Red 1, Green 2, Blue 3, Yellow 4)	E
557703-05M0	M12 Cord Set – 5 Meters (Red 1, Green 2, Blue 3, Yellow 4)	E
	Recommended Mating Parts (Deutsch p/n: Housing Plug DT064S-P012; Wedge W4S-P012; Sockets 4X 0462-201-1631)	8
224153	Deutsch Cord Set 3´ Long (18 AWG PVC Cable – Black 1, Red 2, Green 3, White 4)	8
	Recommended Mating Parts (Delphi Packard MetriPack p/n: Body 12065286; Seal 12052893. Consult Delphi for Contacts)	9
218760	Packard Mate Kit	9
223974	Packard Cord Set 3´ Long (24 AWG PVC Cable – White 1, Black 2, Red 3)	9
223975	Packard Cord Set 6´ Long (24 AWG PVC Cable – White 1, Black 2, Red 3)	9
227987	Packard Cord Set 14.75' Long (22 AWG PVC Cable - White 1, Black 2, Red 3)	9
220492	Packard Mate - 12˝ Flying Leads – 3 Conductor PVC 18 AWG	9
222976	Packard Mate - 18˝ Flying Leads – 3 Conductor PVC 18 AWG	9
220797	Packard Mate - 24˝ Flying Leads – 3 Conductor PVC 18 AWG	9

Appendix D Checklists

The Pre-Launch Checklist will be taken care of by two team members. One of them will be responsible of reading out loud each item and marking them when they are done. The other one will be responsible for performing the stated actions. At the same time, the one reading will check that the actions are properly conducted.

For three key actions (M5, M9 and M13), a third team member will be responsible of asking and, when possible, checking, that they have been properly conducted.

D.1 Pre-Launch Checklist

ID	**ITEM**	**CHECK**
SCIENCE		
	CAC	
S1	Remove the CAC wall with the D-SUB connector, if it's not removed already.	
S2	Connect picarro to quick connector stem at No 10.	
S3	Attach the fill gas bottle's quick connector stem to quick connector body No 1.	
S4	Let the fill gas run through the AirCore at a flow rate of 40ml/min.	
S5	Leave it flushing over night.	
S6	Detach quick connector stem at No 1.	
S7	Detach the quick connector stem at No 10.	
S8	Disconnect the picarro analyser.	
S9	Connect the dryer tube No 14 to No 13.	
S10	Connect parts 11 to 21.	
S11	Check all connections are tighten.	
S12	Close the CAC's solenoid valve No 17.	
S13	Connect quick connector stem No 10 to No 9.	
S14	Connect No 10 with No 11.	
S15	Check all connections are tighten.	
S16	Put the CAC wall with the D-SUB connector back.	
	AAC/MANIFOLD	
S17	Unscrew the plug from the inlet (1) and outlet tube (29).	
S18	Screw in the male threaded quick connector to the inlet tube (1).	
S19	Connect the vacuum pump and the dry gas bottle through a central valve to the AAC's inlet tube (1).	
S20	Open flushing valve (27).	
S21	Turn central valve on so that is open to dry gas.	
S22	Let the dry gas run through the AAC's manifold for 10 minutes.	
S23	Close flushing valve (27)	
S24	Turn central valve off so that is close to dry gas.	
S25	Disconnect the vacuum pump and the dry gas bottle through a central valve from the AAC's inlet tube (1).	

S26	Screw in the plug to the AAC inlet tube (1).	
	AAC/TUBES/BAGS	
S27	Connect the vacuum pump and the dry gas bottle through a central valve to the AAC's outlet tube (29).	
S28	Make sure the AAC's inlet tube (1) is shielded.	
S29	Open 1st bag's manual valve.	
S30	Open flushing valve (27).	
S31	Open 1st bag's solenoid valve in the manifold (23)	
S32	Open central valve so that is open to dry gas.	
S33	Start filling the bag with 3L of dry gas with a flow rate of 2L/min for 1.5 minutes.	
S34	After 1.5 mins, when the bag is full, turn the central valve open to the vacuum , allowing the bag to empty.	
S35	Empty the bag with controlled vacuum only 1-2 mbar below ambient pressure.	
S36	Turn the central valve open to dry gas.	
S37	Start filling the bag with 3L of dry gas with a flow rate of 2L/min for 1.5 minutes.	
S38	After 1.5 mins, when the bag is full, turn the central valve open to the vacuum , allowing the bag to empty.	
S39	Empty the bag with controlled vacuum only 1-2 mbar below ambient pressure.	
S40	Repeat steps S36 to S39 one more time.	
S41	Close 1st bag's solenoid valve in the manifold (23).	
S42	Disconnect the vacuum pump and the dry gas bottle through a central valve from the AAC's outlet tube (29).	
S43	Unscrew the plug from the AAC inlet tube (1).	
S44	Connect the vacuum pump and the dry gas bottle through a central valve to the AAC's inlet tube (1).	
S45	Turn central valve on so that is open to dry gas.	
S46	Let the dry gas run through the AAC's manifold for 2 minutes.	
S47	Close flushing valve (27)	
S48	Turn central valve off so that is close to dry gas.	
S49	Disconnect the vacuum pump and the dry gas bottle through a central valve from the AAC's inlet tube (1).	
S50	Screw in the plug to the AAC inlet tube (1).	
S51	Connect the vacuum pump and the dry gas bottle through a central valve to the AAC's outlet tube (29).	
S52	Make sure the AAC's inlet tube (1) is shielded.	
S53	Open 2nd bag's manual valve.	
S54	Open flushing valve (27).	
S55	Open 2nd bag's solenoid valve in the manifold (23)	
S56	Open central valve so that is open to dry gas.	
S57	Start filling the bag with 3L of dry gas with a flow rate of 2L/min for 1.5 minutes.	

S58	After 1.5 mins, when the bag is full, turn the central valve open to the vacuum , allowing the bag to empty.	
S59	Empty the bag with controlled vacuum only 1-2 mbar below ambient pressure.	
S60	Turn the central valve open to dry gas.	
S61	Start filling the bag with 3L of dry gas with a flow rate of 2L/min for 1.5 minutes.	
S62	After 1.5 mins, when the bag is full, turn the central valve open to the vacuum , allowing the bag to empty.	
S63	Empty the bag with controlled vacuum only 1-2 mbar below ambient pressure.	
S64	Repeat steps S60 to S63 one more time.	
S65	Close 2nd bag's solenoid valve in the manifold (23).	
S66	Disconnect the vacuum pump and the dry gas bottle through a central valve from the AAC's outlet tube (29).	
S67	Unscrew the plug from the AAC inlet tube (1).	
S68	Connect the vacuum pump and the dry gas bottle through a central valve to the AAC's inlet tube (1).	
S69	Turn central valve on so that is open to dry gas.	
S70	Let the dry gas run through the AAC's manifold for 2 minutes.	
S71	Close flushing valve (27)	
S72	Turn central valve off so that is close to dry gas.	
S73	Disconnect the vacuum pump and the dry gas bottle through a central valve from the AAC's inlet tube (1).	
S74	Screw in the plug to the AAC inlet tube (1).	
S75	Connect the vacuum pump and the dry gas bottle through a central valve to the AAC's outlet tube (29).	
S76	Make sure the AAC's inlet tube (1) is shielded.	
S77	Open 3rd bag's manual valve.	
S78	Open flushing valve (27).	
S79	Open 3rd bag's solenoid valve in the manifold (23)	
S80	Open central valve so that is open to dry gas.	
S81	Start filling the bag with 3L of dry gas with a flow rate of 2L/min for 1.5 minutes.	
S82	After 1.5 mins, when the bag is full, turn the central valve open to the vacuum , allowing the bag to empty.	
S83	Empty the bag with controlled vacuum only 1-2 mbar below ambient pressure.	
S84	Turn the central valve open to dry gas.	
S85	Start filling the bag with 3L of dry gas with a flow rate of 2L/min for 1.5 minutes.	
S86	After 1.5 mins, when the bag is full, turn the central valve open to the vacuum , allowing the bag to empty.	
S87	Empty the bag with controlled vacuum only 1-2 mbar below ambient pressure.	

S88	Repeat steps S84 to S87 one more time.	
S89	Close 3rd bag's solenoid valve in the manifold (23).	
S90	Disconnect the vacuum pump and the dry gas bottle through a central valve from the AAC's outlet tube (29).	
S91	Unscrew the plug from the AAC inlet tube (1).	
S92	Connect the vacuum pump and the dry gas bottle through a central valve to the AAC's inlet tube (1).	
S93	Turn central valve on so that is open to dry gas.	
S94	Let the dry gas run through the AAC's manifold for 2 minutes.	
S95	Close flushing valve (27)	
S96	Turn central valve off so that is close to dry gas.	
S97	Disconnect the vacuum pump and the dry gas bottle through a central valve from the AAC's inlet tube (1).	
S98	Screw in the plug to the AAC inlet tube (1).	
S99	Connect the vacuum pump and the dry gas bottle through a central valve to the AAC's outlet tube (29).	
S100	Make sure the AAC's inlet tube (1) is shielded.	
S101	Open 4th bag's manual valve.	
S102	Open flushing valve (27).	
S103	Open 4th bag's solenoid valve in the manifold (23)	
S104	Open central valve so that is open to dry gas.	
S105	Start filling the bag with 3L of dry gas with a flow rate of 2L/min for 1.5 minutes.	
S106	After 1.5 mins, when the bag is full, turn the central valve open to the vacuum , allowing the bag to empty.	
S107	Empty the bag with controlled vacuum only 1-2 mbar below ambient pressure.	
S108	Turn the central valve open to dry gas.	
S109	Start filling the bag with 3L of dry gas with a flow rate of 2L/min for 1.5 minutes.	
S110	After 1.5 mins, when the bag is full, turn the central valve open to the vacuum , allowing the bag to empty.	
S111	Empty the bag with controlled vacuum only 1-2 mbar below ambient pressure.	
S112	Repeat steps S108 to S111 one more time.	
S113	Close 4th bag's solenoid valve in the manifold (23).	
S114	Disconnect the vacuum pump and the dry gas bottle through a central valve from the AAC's outlet tube (29).	
S115	Unscrew the plug from the AAC inlet tube (1).	
S116	Connect the vacuum pump and the dry gas bottle through a central valve to the AAC's inlet tube (1).	
S117	Turn central valve on so that is open to dry gas.	
S118	Let the dry gas run through the AAC's manifold for 2 minutes.	
S119	Close flushing valve (27)	
S120	Turn central valve off so that is close to dry gas.	

S121	Disconnect the vacuum pump and the dry gas bottle through a central valve from the AAC's inlet tube (1).	
S122	Screw in the plug to the AAC inlet tube (1).	
S123	Connect the vacuum pump and the dry gas bottle through a central valve to the AAC's outlet tube (29).	
S124	Make sure the AAC's inlet tube (1) is shielded.	
S125	Open 5th bag's manual valve.	
S126	Open flushing valve (27).	
S127	Open 5th bag's solenoid valve in the manifold (23)	
S128	Open central valve so that is open to dry gas.	
S129	Start filling the bag with 3L of dry gas with a flow rate of 2L/min for 1.5 minutes.	
S130	After 1.5 mins, when the bag is full, turn the central valve open to the vacuum , allowing the bag to empty.	
S131	Empty the bag with controlled vacuum only 1-2 mbar below ambient pressure.	
S132	Turn the central valve open to dry gas.	
S133	Start filling the bag with 3L of dry gas with a flow rate of 2L/min for 1.5 minutes.	
S134	After 1.5 mins, when the bag is full, turn the central valve open to the vacuum , allowing the bag to empty.	
S135	Empty the bag with controlled vacuum only 1-2 mbar below ambient pressure.	
S136	Repeat steps S132 to S135 one more time.	
S137	Close 5th bag's solenoid valve in the manifold (23).	
S138	Disconnect the vacuum pump and the dry gas bottle through a central valve from the AAC's outlet tube (29).	
S139	Unscrew the plug from the AAC inlet tube (1).	
S140	Connect the vacuum pump and the dry gas bottle through a central valve to the AAC's inlet tube (1).	
S141	Turn central valve on so that is open to dry gas.	
S142	Let the dry gas run through the AAC's manifold for 2 minutes.	
S143	Close flushing valve (27)	
S144	Turn central valve off so that is close to dry gas.	
S145	Disconnect the vacuum pump and the dry gas bottle through a central valve from the AAC's inlet tube (1).	
S146	Screw in the plug to the AAC inlet tube (1).	
S147	Connect the vacuum pump and the dry gas bottle through a central valve to the AAC's outlet tube (29).	
S148	Make sure the AAC's inlet tube (1) is shielded.	
S149	Open 6th bag's manual valve.	
S150	Open flushing valve (27).	
S151	Open 6th bag's solenoid valve in the manifold (23)	
S152	Open central valve so that is open to dry gas.	

S153	Start filling the bag with 3L of dry gas with a flow rate of 2L/min for 1.5 minutes.	
S154	After 1.5 mins, when the bag is full, turn the central valve open to the vacuum , allowing the bag to empty.	
S155	Empty the bag with controlled vacuum only 1-2 mbar below ambient pressure.	
S156	Turn the central valve open to dry gas.	
S157	Start filling the bag with 3L of dry gas with a flow rate of 2L/min for 1.5 minutes.	
S158	After 1.5 mins, when the bag is full, turn the central valve open to the vacuum , allowing the bag to empty.	
S159	Empty the bag with controlled vacuum only 1-2 mbar below ambient pressure.	
S160	Repeat steps S156 to S159 one more time.	
S161	Close 6th bag's solenoid valve in the manifold (23).	
S162	Disconnect the vacuum pump and the dry gas bottle through a central valve from the AAC's outlet tube (29).	
S163	Unscrew the plug from the AAC inlet tube (1).	
S164	Connect the vacuum pump and the dry gas bottle through a central valve to the AAC's inlet tube (1).	
S165	Turn central valve on so that is open to dry gas.	
S166	Let the dry gas run through the AAC's manifold for 2 minutes.	
S167	Close flushing valve (27)	
S168	Turn central valve off so that is close to dry gas.	
S169	Disconnect the vacuum pump and the dry gas bottle through a central valve from the AAC's inlet tube (1).	
S170	Screw in the plug to the AAC inlet tube (1).	
ELECTRICAL		
E1	Check that all (3 9-Pin, Bags, Out, CAC, and 2 15-pin, Level 1 and 2) D-subs are connected and screwed in on the PCB (hand tight, DO NOT TIGHTEN TO HARD).	
E2	Check that plastic 28.8V power is connected to level 1 and 2 connectors (Red wire, plastic connector, Male on wires going to each level, female is underneath the PCB.).	
E3	Check that the plastic 28.8V power cable from the PCB is secured with zip tie to one of the standoffs.	
E4	Check that power is plugged in on the PCB.	
E5	Check that Ethernet is connected form PCB to wall. (should hear click)	
E6	Check that outside pressure sensors are connected to the outside upper (furthest from frame) 9-pin D-sub wall connector (hand tight, DO NOT TIGHTEN TO HARD).	
E7	Check that CAC is connected on the outside lower (closest to frame) 9-pin D-sub wall connector (hand tight, DO NOT TIGHTEN TOO HARD).	

E8	Check that power is connected on the outside wall.	
E9	Check that the Ethernet is connected on the outside wall (should hear click).	
E10	Check main PCB board is secure (Locking nuts where possible and no nut for the rest).	
E11	Check that pressure sensors are secure on the outside (Bolted down with locking nuts).	
E12	Check output voltage from DCDC's and make sure they are used equally (after diode).	
E13	Verify sensors give data to ground station.	
E14	Verify that all valves open and close as expected (listen and check PCB lights).	
E15	Verify that heaters get warm when they are turned on (Check temp data, feel, and check lights)	
SOFTWARE		
SW1	The ground station laptop PC will need to be put in place and operational.	
SW2	The correct version of the onboard software have been uploaded to the OBC.	
SW3	The communication through E-link with the experiment shall be tested.	
SW4	Verify that the data from sensors are realistic.	
SW5	The air sampling itinerary is checked.	
SW6	SD card contents are checked.	
MECHANICAL		
M1	Check that the frame structure is properly fixed.	
M2	Check that the handles of both boxes are properly fixed.	
	AAC BOX	
M3	Check that The Brain is properly attached to the structure of the AAC Box.	
M4	Check that all the pneumatic connections are set (interfaces, valves, bags): use the manufactured tool for this matter.	
M5	Check that the bags valve are open.	
M6	Check that the bags are properly fixed with the circular bar.	
M7	Check that the electronic interfaces panel is properly fixed to the top wall.	
M8	Close all the open walls and check that they are all properly fixed and closed.	
M9	Unscrew the plugs from the inlet and the outlet tube.	
	CAC BOX	
M10	Check that the AirCore is properly placed.	
M11	Check that all the pneumatic connections are set (interfaces, valves)	
M12	Close all the open walls and check that they are all properly fixed and closed.	

M13	Unscrew the plug from the inlet/outlet tube.	
	GONDOLA	
M14	Attach both boxes one to the other.	
M15	Introduce both boxes inside the gondola.	
M16	Check that the experiment box is fixed to the gondola rails (10 anchor points).	
M17	Check that the electronic connectors are properly fixed to both electronic panels (D-sub, power, E-link)	

D.2 Cleaning Checklist

Why Cleaning is Important	
Grease on pipe and fittings will outgas and contaminate samples	
Dust increases the risk of condensation which destroys samples	
Organic material can outgas and contaminate samples	

DO NOT	
Blow into tubes or fittings	
Handle the pneumatic system without gloves	
Leave clean items unsealed on the bench	

Before you begin	
Workspace clear of debris	
Signage up that this area is clean so no touching	
Wearing gloves	
Workspace cleaned with IPA	
Tools cleaned with IPA	
Tupperware storage cleaned with IPA	

Working Procedure	
Cutting	
Use pipe cutter	
Ensure debris does not fall onto workspace	
Cut one piece at a time	
Reeming	
Use the reeming tool	
Reemer must be lower than pipe	
Ensure debris does not fall onto workspace	
Minimise debris falling further into pipe	
Use oil free compressed air to clear pipe of debris	
DO NOT BLOW INTO PIPE	
Bending	

Use the bending tool	
Clamp one end of bending tool to bench if possible	
Bend slowly	
Bend slightly further (1 or 2 degrees) more than the target	
Check bend with protractor BEFORE removing it	
If bend not correct rebend	
If bend correct remove pipe	
Cleaning after	
Place Kapton tape (or equivalent) over both pipe ends	
Place pipe into clean tupperware box	
Place tools into clean tupperware box	
Fittings	
Use IPA to clean vigorously before attachment	
AVOID touching with bare hands	
Always follow correct Swagelok procedure when attaching	

Table 69: Table Containing the Cleaning Checklist for use During Manufacture.

D.3 Recovery Team Checklist

FAST RECOVERY OF CAC

- Check no damage exists to outer structure and no white paste seen in inlet tubes, this confirms no leak and chemicals are SAFE.
- Screw on the three metal plugs provided to the inlet and outlet tubes.
- Unplug the gondola power cord from the AAC box. Circled with RED paint. See Figure 107.
- Unplug the E-Link connection from the AAC box. Circled with RED paint. See Figure 107.
- Unplug the D-Sub connector from the CAC Box. Circled with RED paint. See Figure 107.
- Unscrew 6 screws vertically aligned in the CAC frame in the outside face of the experiment. Painted in RED. Allen key #3. See Figure 108.
- Unscrew 6 screws vertically aligned in the CAC frame in the inside face of the experiment (opposite to outside). Painted in RED. Allen key #3.
- Unscrew 2 gondola attachment points from the CAC, L-shape anchor, 4 screws in total. Allen key #3. See Figure 109.
- Loosen the gondola's safety wire (on the CAC side), use a thick Allen key (i.e. Allen key #5) and a clamp.
- Remove the CAC Box from the gondola from the lateral side. Handles located at the top of the box. First lift it up, then drag it out. Take care with the outlet tube not to hit the gondola structure.

- Tighten the gondola's safety wire (on the CAC side), use a thick Allen key (i.e. Allen key #5) and a clamp.

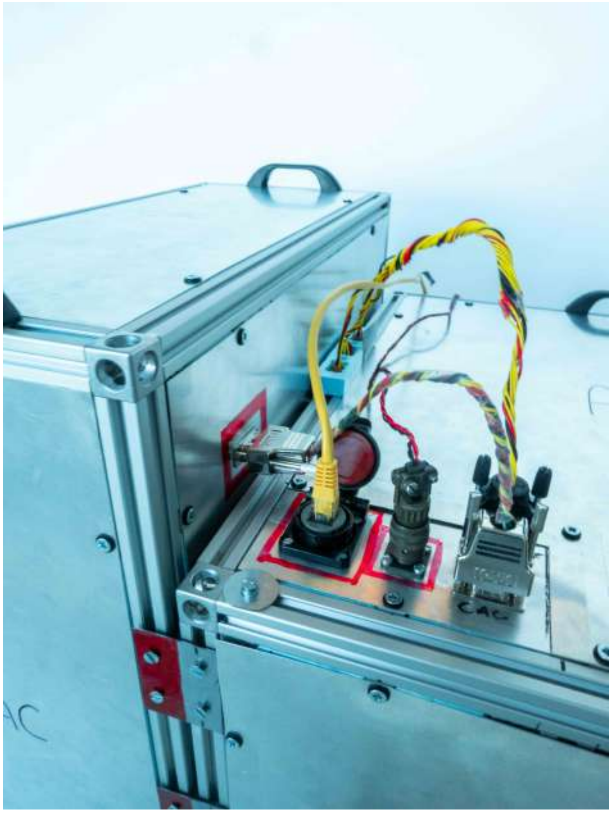


Figure 107: Electrical Interfaces detail.

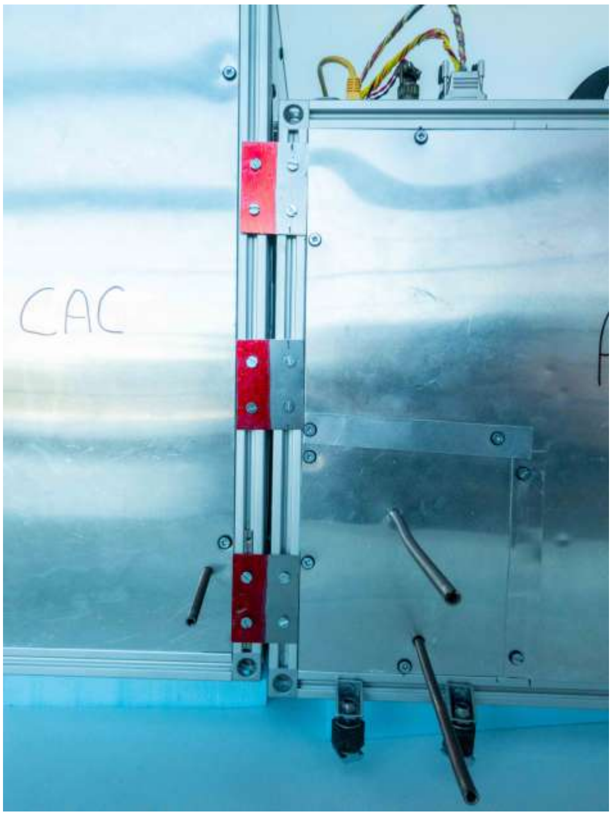


Figure 108: Fast Recovery Interfaces detail, boxes attachment.

Figure 109: Fast Recovery Interfaces detail.

REGULAR RECOVERY OF AAC

- Unscrew 8 gondola attachment points from the AAC.
- Remove the AAC Box from the gondola. Handles located at the top of the box.

If the recovery is not nominal the following instructions should be followed. It should be noted that the chemical on-board, magnesium perchlorate, has the appearance of white powdery stones when dry and a white paste when wet.

- If outer structure is damaged or white paste is seen in inlet tubes put on provided gloves before proceeding. Assume possibility chemicals are UNSAFE.
- If white paste is seen wipe with provided cloth and seal the end of tube with the provided plugs. Put any contaminated items into a bag which is then sealed.
- In event magnesium perchlorate comes into contact with skin wash immediately with water (following the MSDS procedure).
- In the event magnesium perchlorate comes into contact with clothes remove clothes as soon as possible and wash before wearing again.
- Even if no contact was made with the magnesium perchlorate it is recommended to wash hands after as a preventative measure.
- In the event that magnesium perchlorate is seen on the ground or inside the gondola, the appearance is a white paste or white stone, it should be recovered with gloves and wiped and placed into a sealed bag.

Provided material

- Gloves
- Piece of cloth
- Plastic bag
- Three plugs
- Allen key set (at least #3 and #5)
- Clamp

Appendix E Team Availability

E.1 Team availability from February 2018 to July 2018

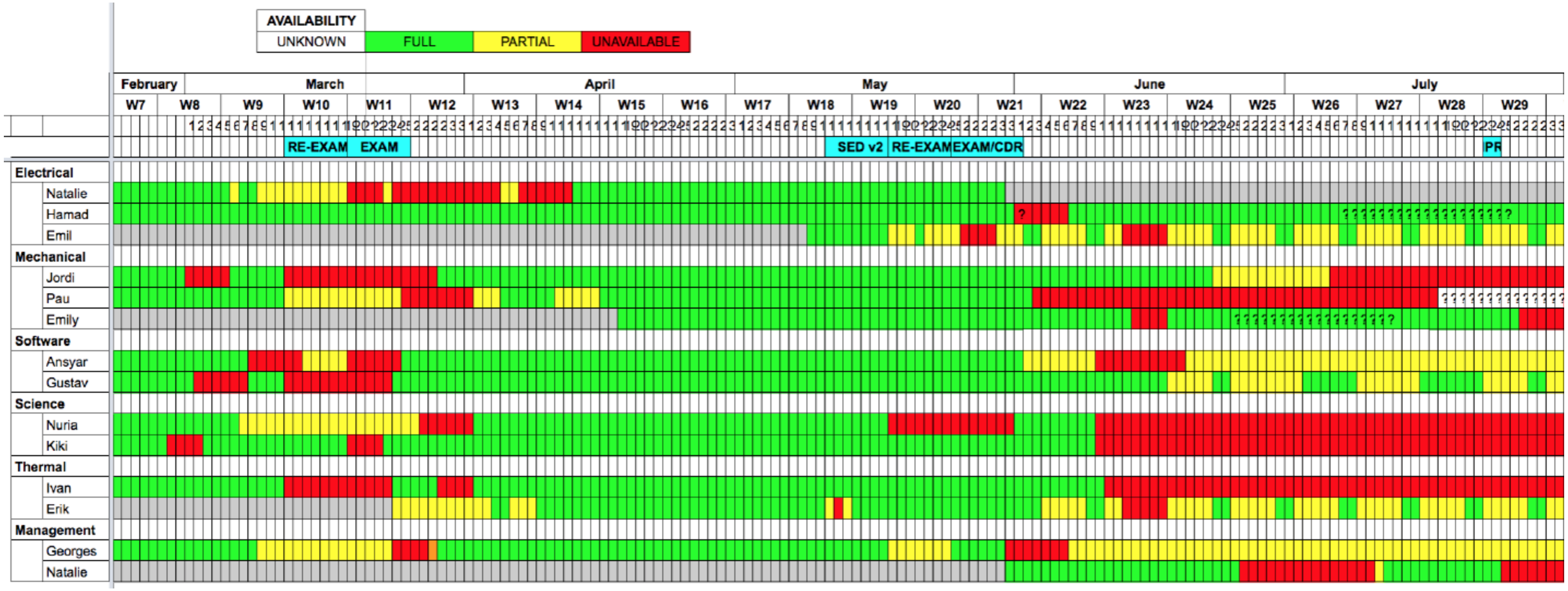


Figure 110: Team Availability From February 2018 to July 2018.

E.2 Team availability from August 2018 to January 2019

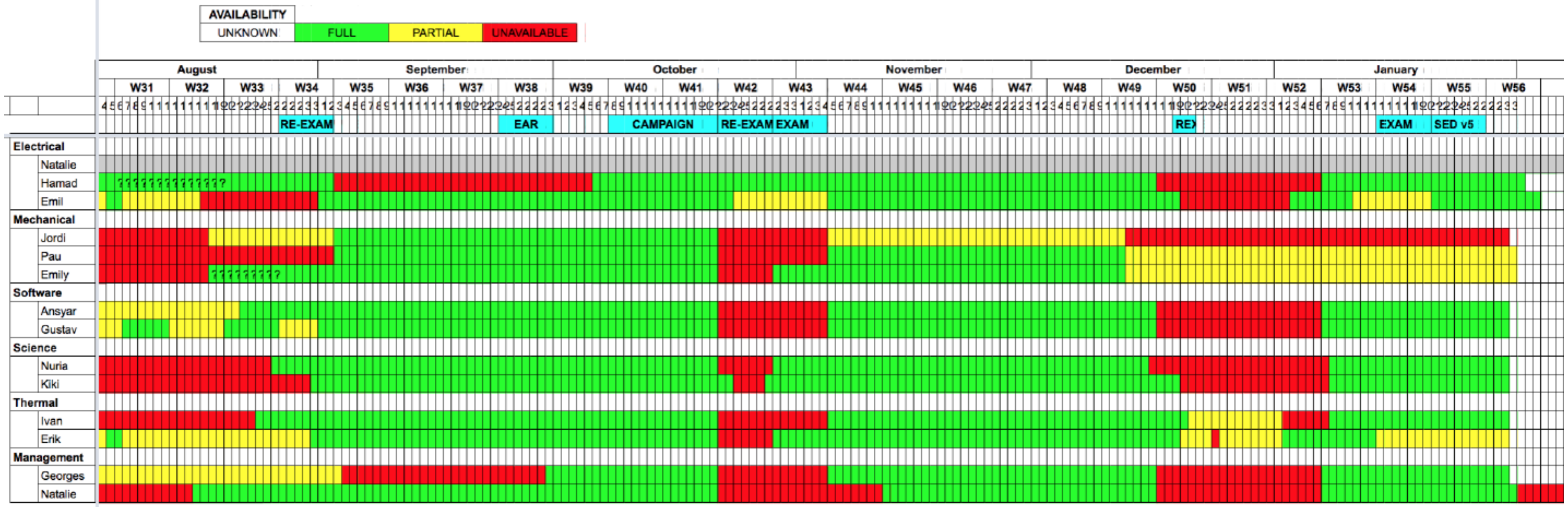


Figure 111: Team Availability From August 2018 to January 2019.

E.3 Graph Showing Team availability Over Summer

Green squares with question marks indicate uncertainty over whether someone will be available in Kiruna at that time.

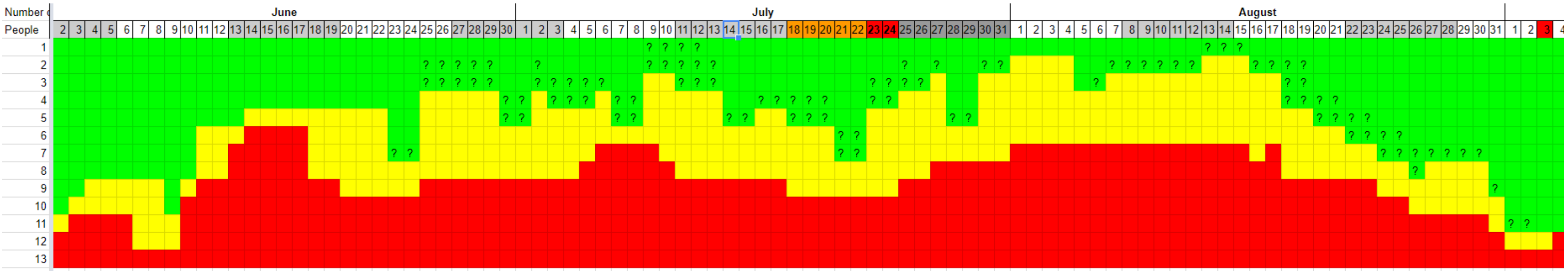
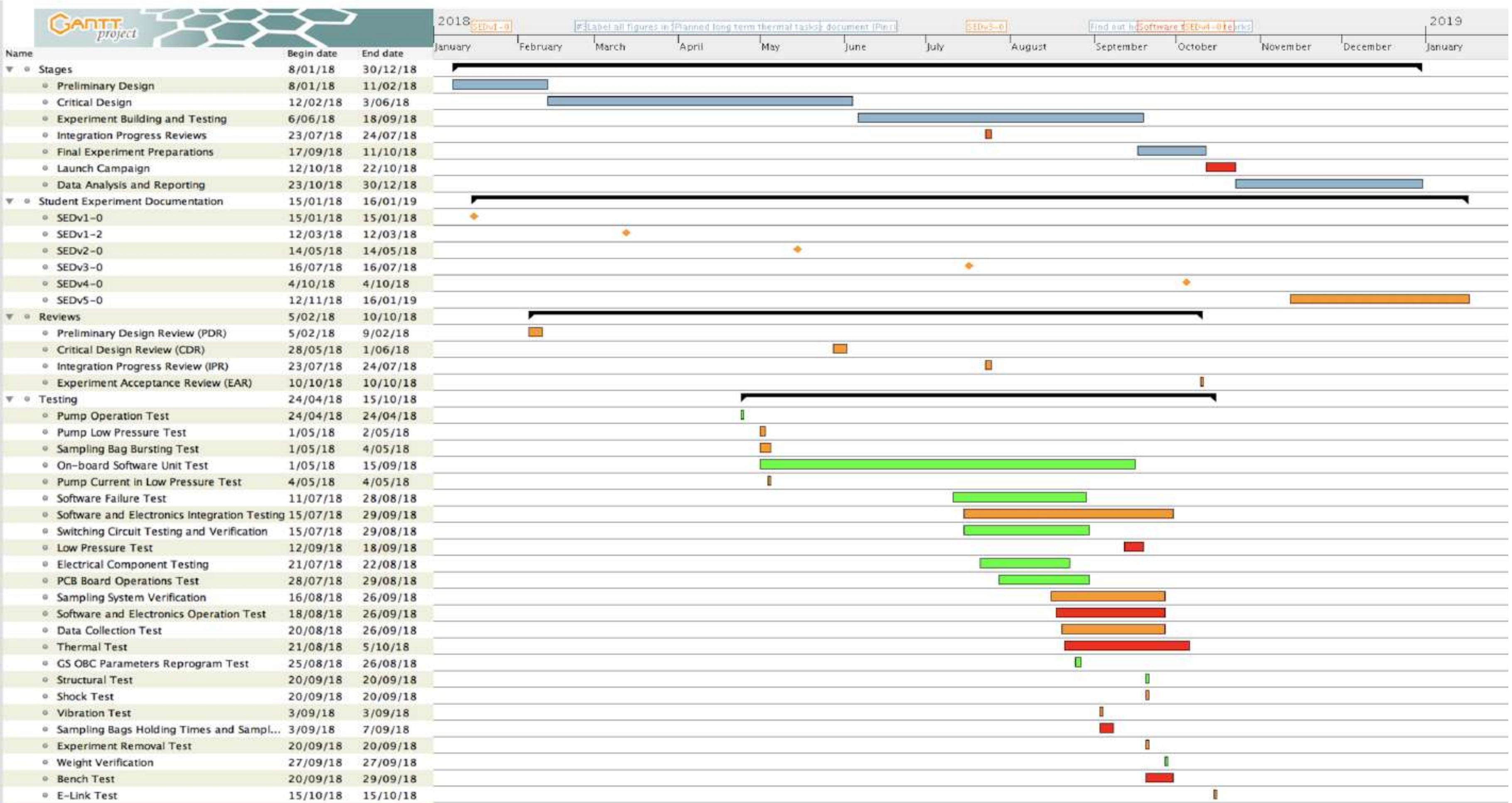


Figure 112: Graph Showing Team Avaliability Over the Summer Period.

Appendix F Gantt Chart

The current critical path starts with ordering and receiving parts, until this is done building cannot take place. The key components are the pump, valves, tubing, fittings and Arduino. Once orders have been received building can take place and then testing can begin. All remaining tests require some degree of building to be completed. Certain tests such as Test 17 in Table 34 require the entire pneumatic system to be completed and others such as Test 2 in Table 23 require just the electronics and software.

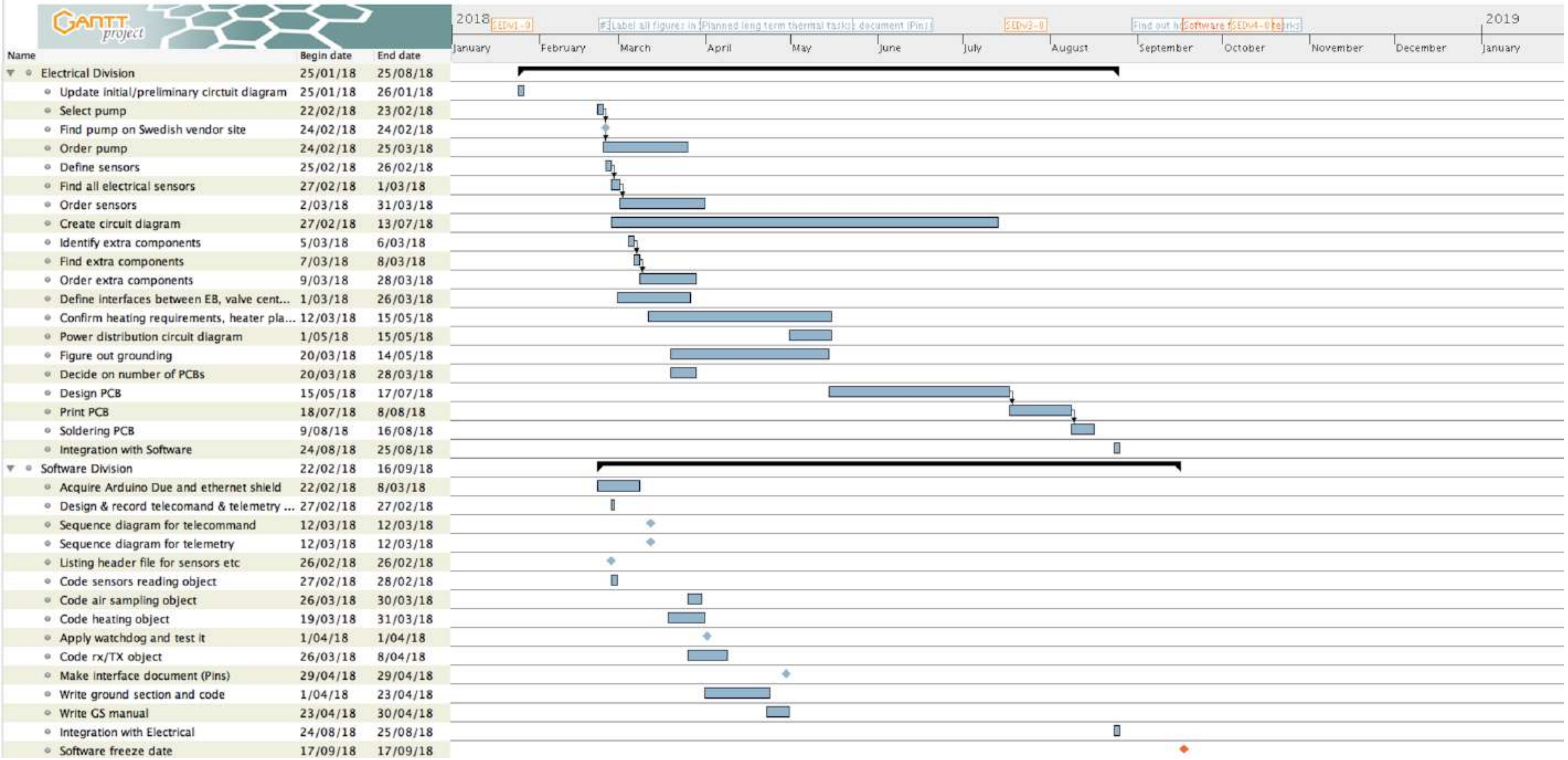
F.1 Gantt Chart (1/4)



Name	Begin date	End date
Stages	8/01/18	30/12/18
Preliminary Design	8/01/18	11/02/18
Critical Design	12/02/18	3/06/18
Experiment Building and Testing	6/06/18	18/09/18
Integration Progress Reviews	23/07/18	24/07/18
Final Experiment Preparations	17/09/18	11/10/18
Launch Campaign	12/10/18	22/10/18
Data Analysis and Reporting	23/10/18	30/12/18
Student Experiment Documentation	15/01/18	16/01/19
SEDv1-0	15/01/18	15/01/18
SEDv1-2	12/03/18	12/03/18
SEDv2-0	14/05/18	14/05/18
SEDv3-0	16/07/18	16/07/18
SEDv4-0	4/10/18	4/10/18
SEDv5-0	12/11/18	16/01/19
Reviews	5/02/18	10/10/18
Preliminary Design Review (PDR)	5/02/18	9/02/18
Critical Design Review (CDR)	28/05/18	1/06/18
Integration Progress Review (IPR)	23/07/18	24/07/18
Experiment Acceptance Review (EAR)	10/10/18	10/10/18
Testing	24/04/18	15/10/18
Pump Operation Test	24/04/18	24/04/18
Pump Low Pressure Test	1/05/18	2/05/18
Sampling Bag Bursting Test	1/05/18	4/05/18
On-board Software Unit Test	1/05/18	15/09/18
Pump Current in Low Pressure Test	4/05/18	4/05/18
Software Failure Test	11/07/18	28/08/18
Software and Electronics Integration Testing	15/07/18	29/09/18
Switching Circuit Testing and Verification	15/07/18	29/08/18
Low Pressure Test	12/09/18	18/09/18
Electrical Component Testing	21/07/18	22/08/18
PCB Board Operations Test	28/07/18	29/08/18
Sampling System Verification	16/08/18	26/09/18
Software and Electronics Operation Test	18/08/18	26/09/18
Data Collection Test	20/08/18	26/09/18
Thermal Test	21/08/18	5/10/18
GS OBC Parameters Reprogram Test	25/08/18	26/08/18
Structural Test	20/09/18	20/09/18
Shock Test	20/09/18	20/09/18
Vibration Test	3/09/18	3/09/18
Sampling Bags Holding Times and Sampl...	3/09/18	7/09/18
Experiment Removal Test	20/09/18	20/09/18
Weight Verification	27/09/18	27/09/18
Bench Test	20/09/18	29/09/18
E-Link Test	15/10/18	15/10/18

Figure 113: Gantt Chart (1/4).

F.2 Gantt Chart (2/4)



Name	Begin date	End date
Electrical Division	25/01/18	25/08/18
Update initial/preliminary circuit diagram	25/01/18	26/01/18
Select pump	22/02/18	23/02/18
Find pump on Swedish vendor site	24/02/18	24/02/18
Order pump	24/02/18	25/03/18
Define sensors	25/02/18	26/02/18
Find all electrical sensors	27/02/18	1/03/18
Order sensors	2/03/18	31/03/18
Create circuit diagram	27/02/18	13/07/18
Identify extra components	5/03/18	6/03/18
Find extra components	7/03/18	8/03/18
Order extra components	9/03/18	28/03/18
Define interfaces between EB, valve cent...	1/03/18	26/03/18
Confirm heating requirements, heater pla...	12/03/18	15/05/18
Power distribution circuit diagram	1/05/18	15/05/18
Figure out grounding	20/03/18	14/05/18
Decide on number of PCBs	20/03/18	28/03/18
Design PCB	15/05/18	17/07/18
Print PCB	18/07/18	8/08/18
Soldering PCB	9/08/18	16/08/18
Integration with Software	24/08/18	25/08/18
Software Division	22/02/18	16/09/18
Acquire Arduino Due and ethernet shield	22/02/18	8/03/18
Design & record telecomand & telemetry ...	27/02/18	27/02/18
Sequence diagram for telecommand	12/03/18	12/03/18
Sequence diagram for telemetry	12/03/18	12/03/18
Listing header file for sensors etc	26/02/18	26/02/18
Code sensors reading object	27/02/18	28/02/18
Code air sampling object	26/03/18	30/03/18
Code heating object	19/03/18	31/03/18
Apply watchdog and test it	1/04/18	1/04/18
Code rx/TX object	26/03/18	8/04/18
Make interface document (Pins)	29/04/18	29/04/18
Write ground section and code	1/04/18	23/04/18
Write GS manual	23/04/18	30/04/18
Integration with Electrical	24/08/18	25/08/18
Software freeze date	17/09/18	17/09/18

Figure 114: Gantt Chart (2/4).

F.3 Gantt Chart (3/4)

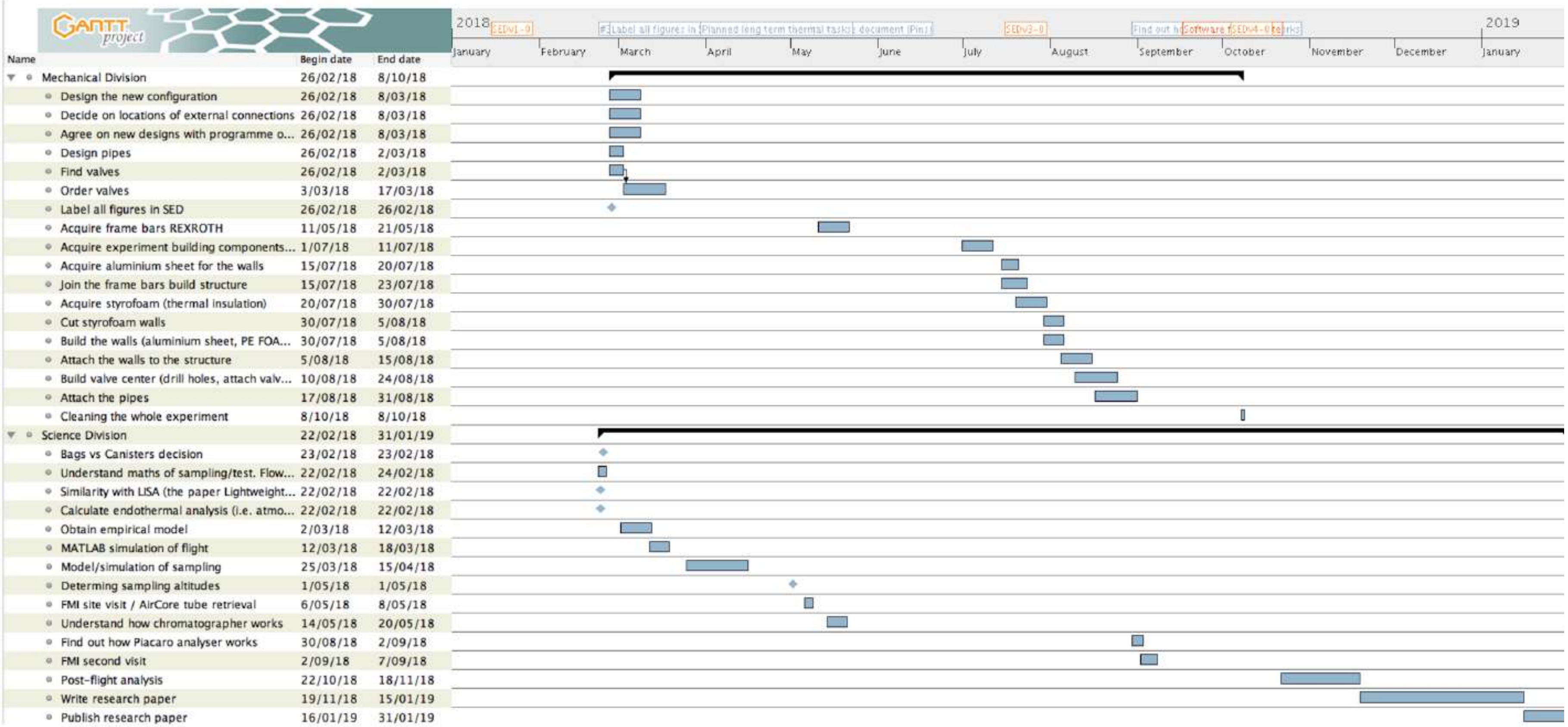


Figure 115: Gantt Chart (3/4).

F.4 Gantt Chart (4/4)

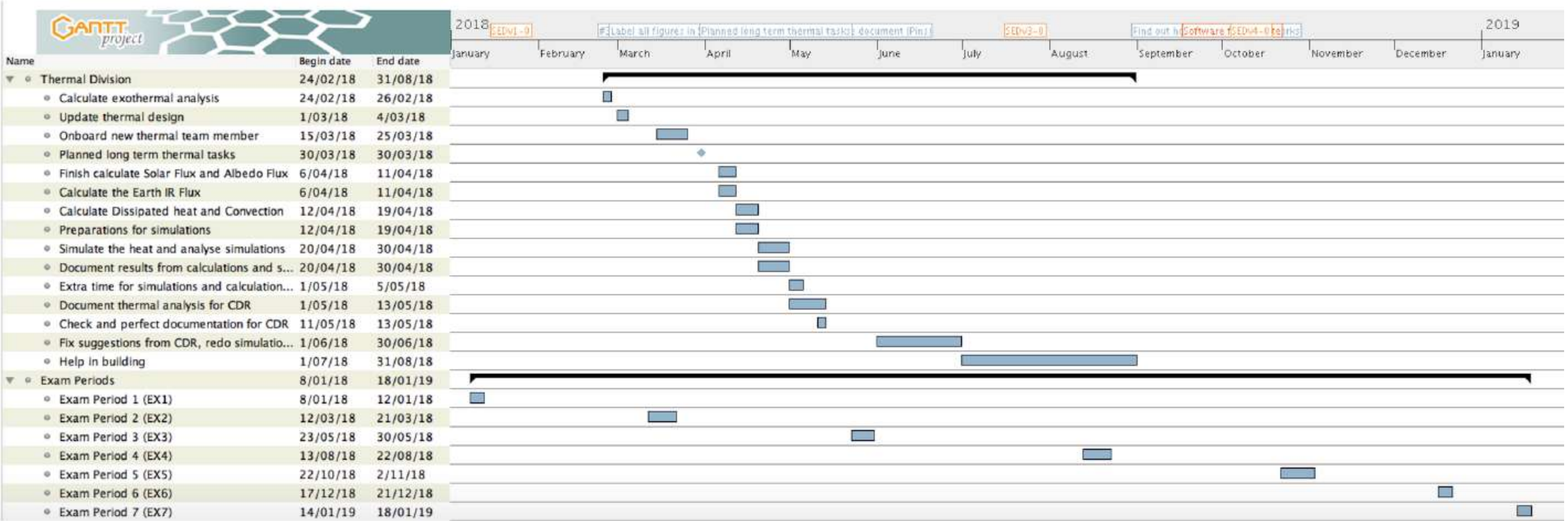


Figure 116: Gantt Chart (4/4).

By comparing the team availability in Appendix E to the Gantt chart it can be seen that across the summer there is lower team availability. In this time frame there are two periods with particularly low team availability; The early summer and early August. The work has been planned so that the critical work will be completed in the periods with higher availability. In the event that the work takes longer than expected the question marks can become green.

Appendix G Equipment Loan Agreement

Equipment Loan Agreement

I. Lender Information
Institution: Finnish Meteorological Institute (FMI)
Address: Tähteläntie 62, 99600 Sodankylä, Finland
Representative: Dr. Rigel Kivi
E-Mail: rigel.kivi@fmi.fi
Telephone Number: +358 405 424 543

Hereinafter referred to as "the Lender."

II. Borrower Information
Group: Team TUBULAR (BEXUS 26/27)
Address: Luleå University of Technology, Rymdcampus, 981 28, Kiruna, Sweden.
Representative: Georges L. J. Labrèche
E-Mail: geolab-7@student.ltu.se
Telephone Number: +4670 577 23 87

Hereinafter referred to as "the Borrower."

III. Equipment Information
The borrowed Equipment, hereinafter referred to as "the Equipment," is a coiled 300 meters long stainless steel tube. The tube is coated and has wall thickness of 0.005 inches. The coil can be damaged if not packed properly, using some kind of shock absorbing material, for example soft styrofoam material. The Borrower is to use the Equipment as part of an AirCore experimental setup that will collect air samples during a high altitude balloon flight under the REXUS/BEXUS programme[1] scheduled to launch in October, 2018. After the payload landing and gas analysis the Equipment will be returned to the Lender.

[1] REXUS/BEXUS – Rocket and Balloon Experiments for University Students, http://rexusbexus.net/.

1

IV. Borrower Responsibilities

This Agreement and the responsibilities as outlined hereunder are not transferable without the written approval of the Lender. By executing this Agreement, the Borrower agrees to comply with the terms set forth below:

1. *Use/Disclaimer*

1.1. The Borrower is responsible for the proper use and deployment of the Equipment.

1.2. The Borrower is responsible for training anyone using the Equipment on the proper use of the Equipment in accordance with any Equipment use procedures.

1.3. The Borrower agrees to use the Equipment for academic or research use only and not for any commercial use of application.

1.4. If the Equipment is lost, stolen, or damaged, the Borrower agrees to promptly notify the Lender Representative designated above.

2. *Proper Care and Protection*

2.1. The Borrower is responsible for proper care, maintenance, and protection of the Equipment.

2.2. The Borrower is responsible for designing experiments using the Equipment with protection of the Equipment as the primary requirement.

2.3. The Borrower is responsible for testing the designed Equipment protection measures.

2.4. The Borrower is responsible for communicating the Equipment protection test results to the Lender Representative designated above.

2.5. The Borrower is not responsible for Equipment damage related to hard landings. Nominally, the landing is gentle with no damage to the experiments however, on rare occasions, landing shocks up to 35g have been recorded when landing in rocky terrain.

2.6. The Borrower is not responsible for Equipment damage related to the unlikely event of a water landing since the experiment gondola is not watertight.

3. *Delivery and Return*

3.1. Title to the Equipment is to remain with the Lender.

3.2. The Borrower is responsible for the safe packaging, proper import, export, and receiving of the Equipment.

3.3. The Equipment is to be returned within a reasonable amount of time after the Loan Period end date agreed between the Lender and the Borrower.

3.4. The Equipment shall be returned to the Lender in as good a condition as when received by the Borrower.

4. *Indemnification*

4.1. In consideration for the Equipment loan, the Borrower agrees to indemnify, defend, and hold Lender harmless from any and all damages, losses, claims, causes of actions, expenses, and liability of any nature whatsoever associated with its use of the Equipment while under care, custody, and control of the Borrower unless due to the negligence of Lender.

5. *Amendment/Modification*
   5.1. This Agreement cannot be amended or modified except by an instrument in writing signed by both parties. Any attempt to do so except in accordance with this paragraph shall be void.

6. *Force Majeure*
   6.1. The Borrower is not responsible to Lender for any loss, damage, or failure to perform if occasioned by fire, flood, explosion, windstorm, riot, war, transportation difficulty, or any other cause beyond the reasonable control of the Borrower.

In witness whereof, the parties have executed this Agreement effective as of the date of the last party to sign this Agreement below.

Authorized Borrower Representative

Signature: DocuSigned by: Georges L. J. Labrèche 6326A4DA9B2F4D0...

Name: Georges L. J. Labrèche

Title: Project Manager (Team TUBULAR)

Date: 3/12/2018

Authorized Lender Representative

Signature: Rigel Kivi

Name: Dr. Rigel Kivi

Title: Senior Scientist

Date: March 12, 2018

Appendix H Air Sampling Model for BEXUS Flight

H.1 Introduction

H.1.1 Objectives

The purpose of this is to theoretically simulate the experiment; its preparation, the sampling methodology, and the expected results.

H.1.2 Justification

This theoretical model will give an estimation of the time needed to fill the bags in order to achieve the best resolution, the required volume of the samples at the different altitudes, to make sure that there is enough sample left for analysis, the sampling altitudes and the number of the bags.

H.1.3 Methodology

For this purpose, a mathematical model was created using MATLAB. In order to make sure that this model is reliable, it is going to be tested for the atmospheric conditions in the Arctic, and then compared with the 1976 US Standard atmosphere model that is used for this region. What is more, the model will be compared with past BEXUS flight data. The goal of the model is to be as close as possible with these past data. After the tests, and making sure that the mathematical model is accurate, it will be adjusted with the TUBULAR's experiment requirements. In this way, the TUBULAR Team will get a general picture of the experiment's layout. Hence, the results of the experiment will be more or less expected, and in the case of complications, the mathematical model will be used as a reference of understanding what went wrong.

H.2 Scientific and Empirical Background

H.2.1 Study of Previous BEXUS Flights

This section has been elaborated based on the flight data files located in the previous BEXUS flights folders in the REXUS/BEXUS teamsite. This data was recorded by the Esrange Balloon Service System (EBASS).

This unit is responsible of the piloting of the balloon is done by Esrange. It provides the communication link between the gondola and the ground station. The EBASS airborne unit, receives the data from the on board sensors, and then it sends them to the EBASS ground unit. It is also responsible for the payload control, providing functions like the altitude control, by valve and ballast release or the flight termination. What is more, EBASS keeps track of the filght trajectory with an on-board GPS system.

Tables 70 and 71 below gather some general information before and after the BEXUS flights. The pre-flight and the post-flight data are more or less in agreement in estimating for example, the ascent/descent time, the cut-off altitude and the float time. Knowing those information and that the estimations are close enough to the real data, will help the TUBULAR Team to define the experiment's parameters with higher accuracy.

It is worth mentioning that the ascent speed in Table 71 is lower than the predicted $5 \sim 6m/s$ which is mentioned in the BEXUS manual. That is because it is the average velocity value of all the data points.

	BEXUS 20	**BEXUS 21**	**BEXUS 22**	**BEXUS 23**	**BEXUS 24**	**BEXUS 25**
Main Balloon	Zodiac 12SF	Zodiac 12SF	Zodiac 35SF	Zodiac 35SF	Zodiac 12SF	Zodiac 12SF
Balloon mass [kg]	101.4	101.4	-	-	101.4	101.4
Parachute $[m^2]$	80	80	80	80	80	80
Vehicle mass Launch [kg]	256.8	287.8	-	-	300.6	321.15
Vehicle mass Descent [kg]	155.4	186.4	189.58	181.5	199.2	219.75
Float altitude estimation [km]	28.2	27.5	-	-	27	26.6
Float pressure estimation [hPa]	15.38	17.11	-	-	18.5	19.6
Float temperature estimation $[^{\circ}C]$	- 48	- 48	-	-	- 49.5	- 49.9
Estimated ascent time	1h 33min	1h 31min	-	-	1h 29min	1h 27min

Table 70: Pre-flight Information Available in Previous BEXUS Campaigns.

	BEXUS 20	**BEXUS 21**	**BEXUS 22**	**BEXUS 23**	**BEXUS 24**	**BEXUS 25**
Ascent time	1h 37min	1h 37min	1h 51min	1h 51min	1h 55min	3h 45min
Average ascent speed [m/s]	4.78	4.59	4.52	4.79	3.79	1.86
Floating altitude [km]	28	27	32	32	26.5	25.8
Floating time	2h 10min	1h 46min	2h 34min	2h 42min	2h 9min	2h 36min
Cut-off altitude [km]	27.7	20.5	28	32	25.7	25.2
Ending altitude [m]	648	723	3380	1630	1050	-
Descent time	36 min	31 min	29 min	31 min	30 min	-

Table 71: Post-flight Information Regarding the Flight Profile for Previous BEXUS Campaings.

In order to find out how many bags it is possible to sample during Ascent and Descent Phase it is important to know the time duration of each phase i.e Ascent, Floating and Descent. For that reason, Figure 117 provides some sights on how previous BEXUS flights perform and what we can expect from BEXUS 26.

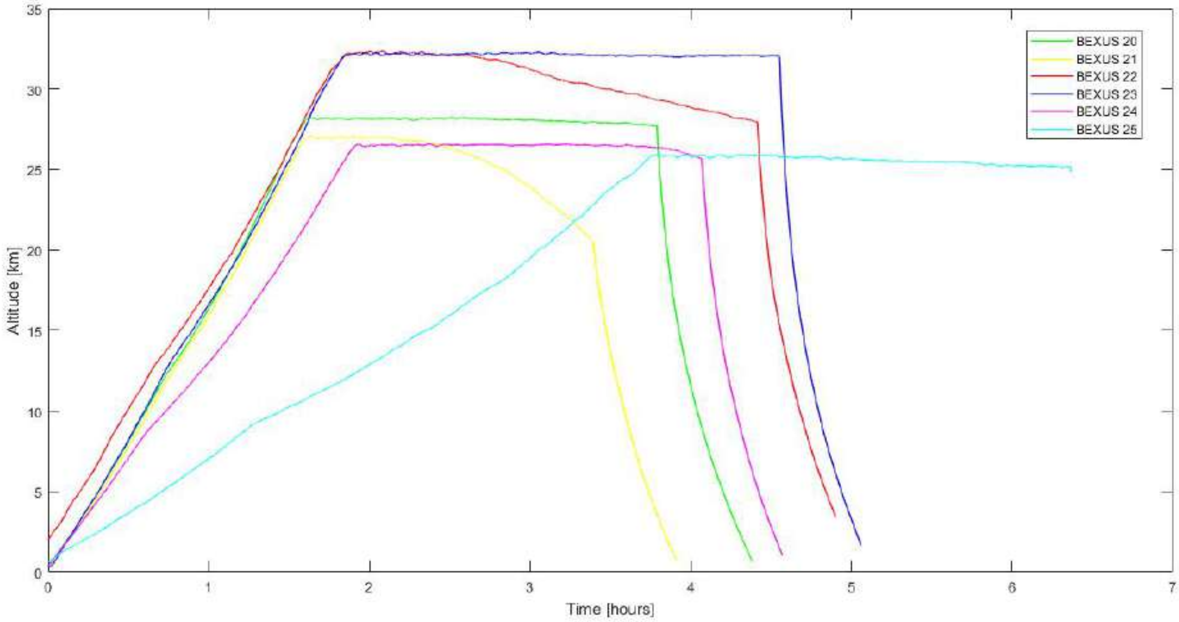


Figure 117: Altitude Over Flight Time for BEXUS Flights 20,21,22,23,24 and 25.

Gondola Dynamics

The velocity of the gondola at each phase can give us information about its dynamics. For example, the data from the BEXUS flight 22 was chosen for analysis in order to get an idea of the velocity values and fluctuations throughout the flight. The obtained diagrams, with some marked points showing the time it takes for the gondola to reach a certain altitude, or the velocity of the gondola at a specific altitude, are shown below.

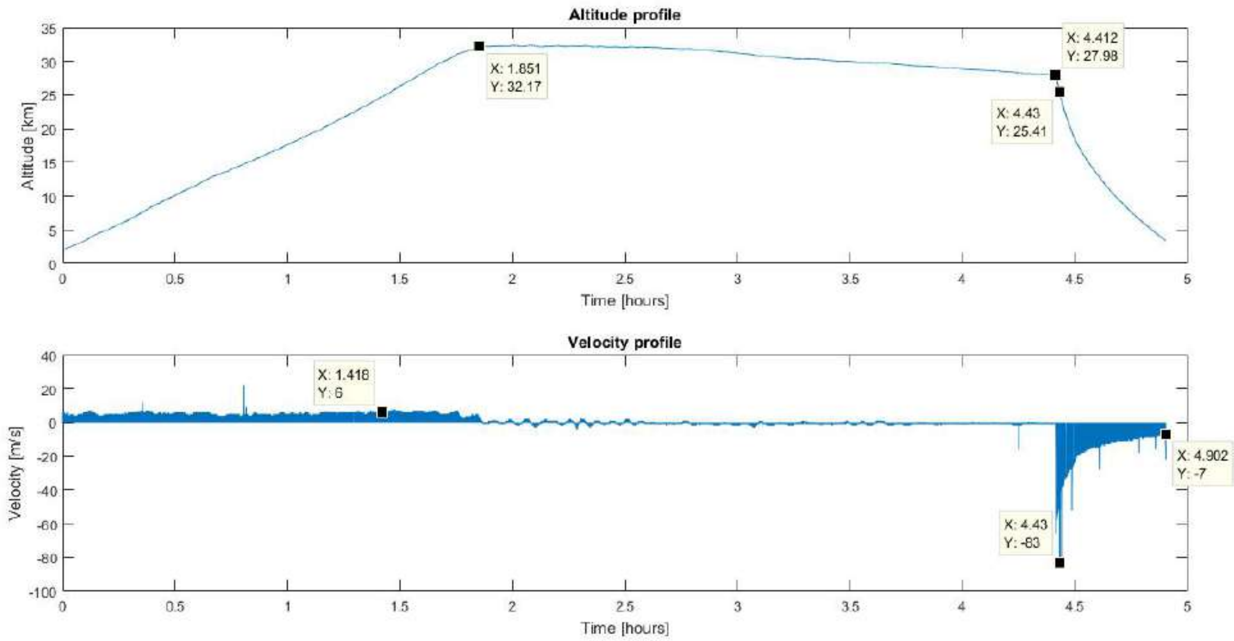


Figure 118: Altitude Profile [Up] and Vertical Velocity Profile [Down] Over the Flight Time During BEXUS 22 Flight.

Figure 119 below, illustrates the velocity changes throughout the different phases.It works like a combination of both graphics form previous Figure 118, however it provides a better representation of the velocity values at each phase. Especially during the Descent Phase, which is the most determinant for the air sampling process.

For each altitude, there are two velocity values, one for the Ascent and one for the Descent Phase. Constant and positive velocities indicate the Ascent Phase. During Ascent Phase the velocity is 6 m/s and almost constant, in agreement with the ascent speed value in the BEXUS manual. A zero velocity value indicates the Float Phase. Then the velocity becomes negative which indicates the Descent Phase. Once again, the velocity value close to the ground is 8 m/s as mentioned in the BEXUS manual[8].

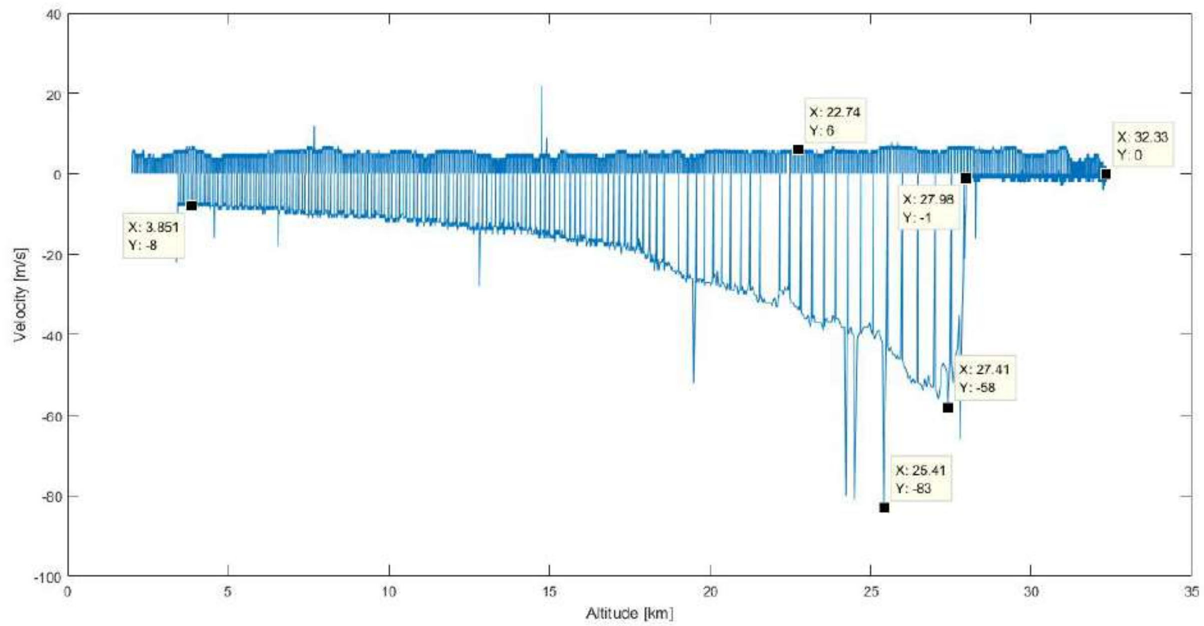


Figure 119: Vertical Velocity of the Gondola Over the Altitude During BEXUS 22 Flight.

Atmospheric Conditions

In order to see how the atmospheric conditions change during a BEXUS flight, the data from the BEXUS flight 22 was chosen for analysis. Figure 120 below shows which kind of information is available for different parameters such as the temperature, the pressure and the air density with altitude.

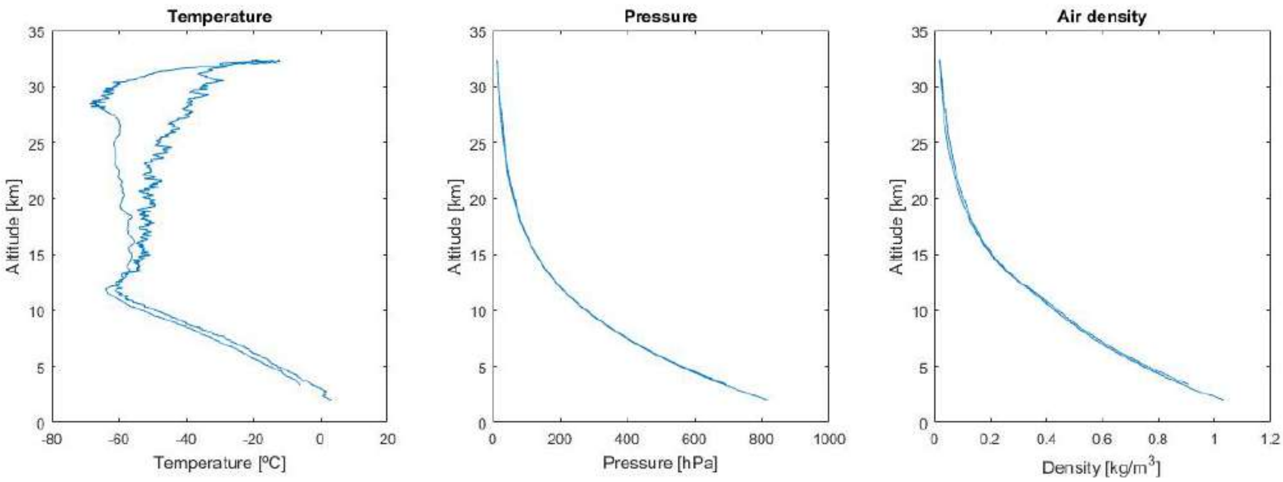


Figure 120: Variations in Temperature, Pressure and Air Density During the Ascent and Descent Phase for BEXUS Flight 22.

H.2.2 Trace Gases Distribution

Atmospheric greenhouse gases are mostly concentrated in the upper troposphere and lower stratosphere. The Arctic region is of significant importance since there is where the maximum concentration of greenhouse gases is found due to meridional circulation (temperature differences) that pushes the gases from the equatorial to higher latitudes. Figures 121 and 122 are showing the concentration over latitude of two of the main greenhouse gases, CO_2 and CH_4 respectively.

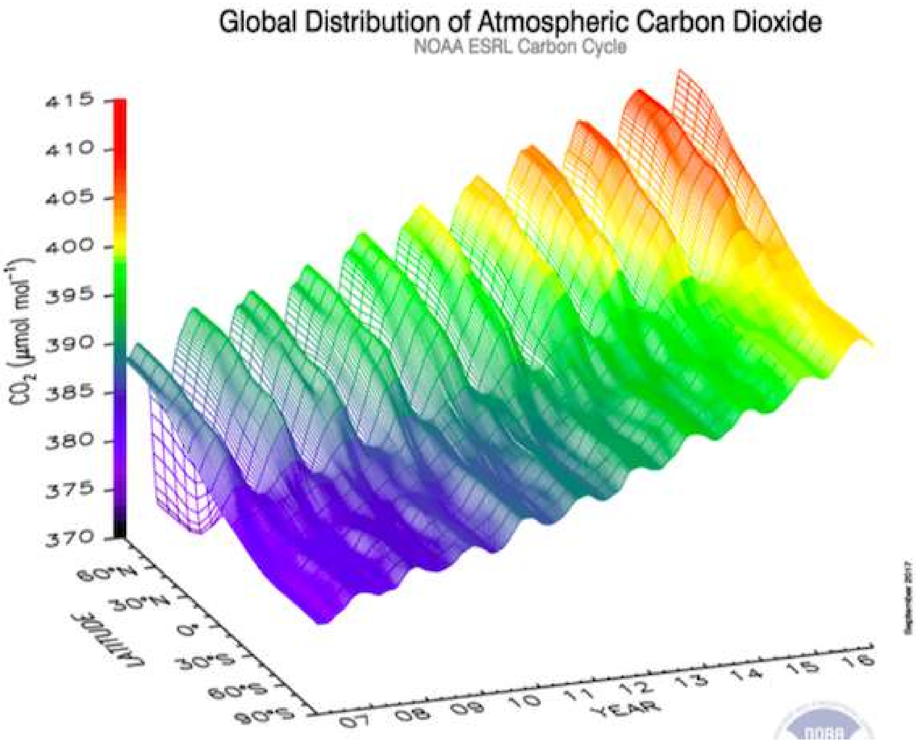


Figure 121: Global Distribution of Atmospheric Carbon Dioxide[18].

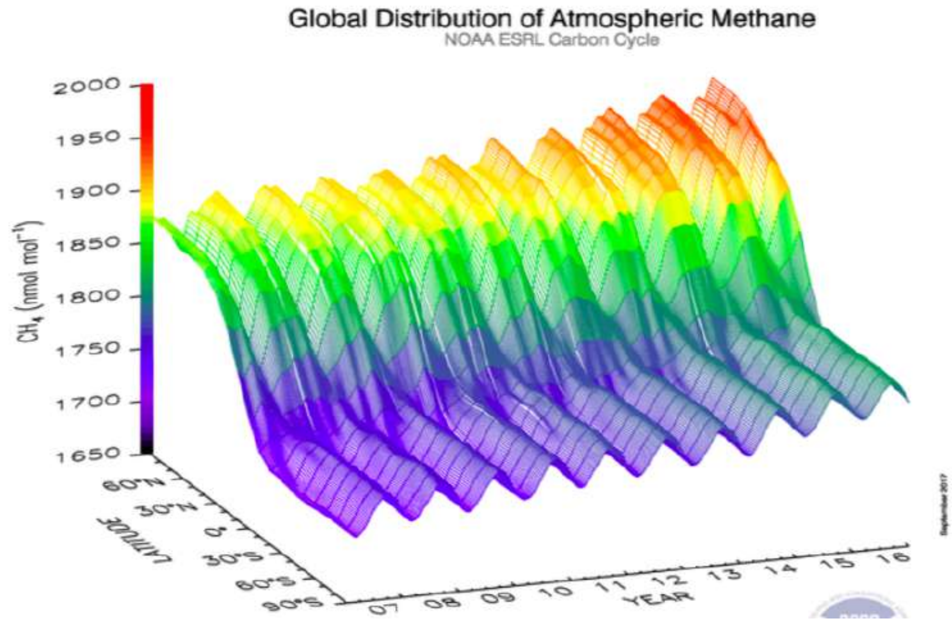


Figure 122: Global Distribution of Atmospheric Methane[18].

The same applies for the vertical distribution of atmospheric greenhouse gases. The favoured altitudes for higher concentrations are the upper troposphere and the lower stratosphere due to gravity waves and the vertical wind, which carry the trace gases at higher altitudes. What is more, CO_2 has longer lifetime in the troposphere and stratosphere, where it has essentially no sources or sinks since it is basically chemically inert in the free troposphere.

Figure 123 shows the global distribution of carbon dioxide in the upper troposphere-stratosphere, at 50-60°N for the time period 2000-2010.

Figure 124 shows the global distribution of the seasonal cycle of the monthly mean CO_2 (in ppmv) in the upper troposphere and the lower stratosphere for the even months of 2010 and the altitude range from 5-45 Km.

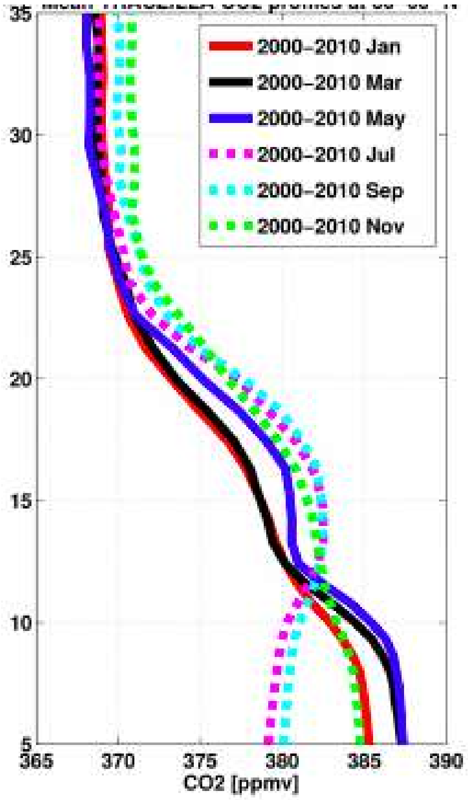


Figure 123: Global Distribution of CO_2 in the Upper Troposphere-Stratosphere[7].

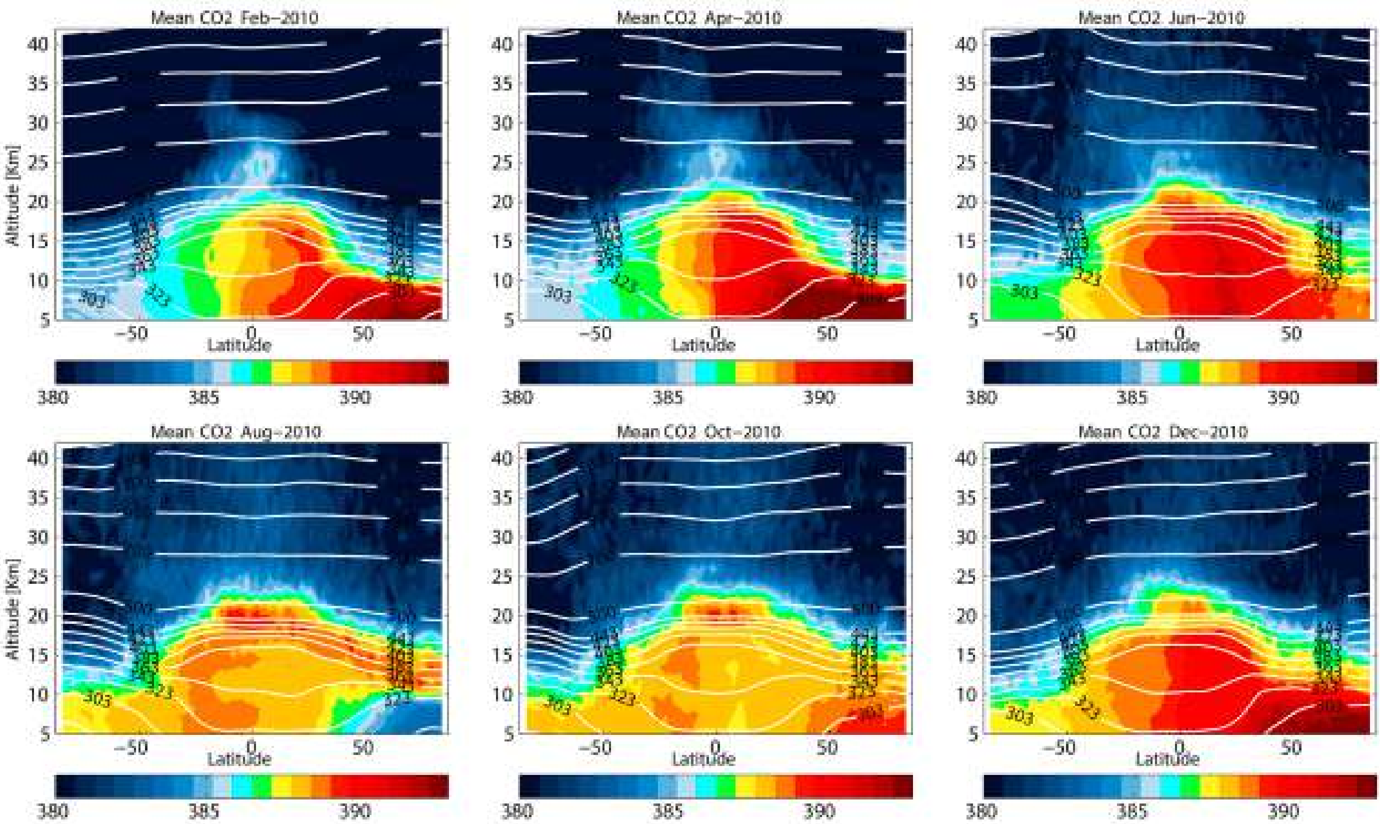


Figure 124: Global Distribution of the Seasonal Cycle of the Monthly Mean CO_2 (in ppm) in the Upper Troposphere and the Lower Stratosphere for the Even Months of 2010[7].

Figures 123, and 124, indicate that the higher CO_2 concentrations are found between 5 and 25 km with peaks around 10 to 15 km (figure 123) and 20 km for October (figure 124).

Figures 125 and 126 focus more on the region near the Arctic Circle. These figures represent vertical profiles distribution of CO, CO_2 and CH_4 extracted from past research papers [5] [17]. The range of altitudes that will be compared is the one between 10 and 25 km. Since Figure 125 vertical axis is in pressure, the equivalent pressures for these altitudes will be from approximately 200 hPa to 20 hPa.

- CH_4 distribution: There is a good agreement between both researches that the concentration around 10 km of altitude is about 1800 ppb and then it starts decreasing gradually with altitude. This decrease seems to be faster above 17 km (70 hPa) which would make this the region of major interest.
- CO_2 distribution: The concentration around 10 km is approximately 390-400 ppm in both researches. The biggest variation in concentration can be found between 10-17 km. The concentration of CO_2 seems to have an increase and then decrease again so this would be the most interesting range to sample.
- CO distribution: Only one research with CO profiles has been presented here so it cannot be compared with other researches. Analysing the only CO profile, it seems that the

largest variation lays on the range 10-15 km, which should be the area of interest.

Based on the vertical distribution profiles obtained from past researches, seems that our experiment should focus on sampling between 10-15 km for CO and CO_2 but above 17 km for CH_4.

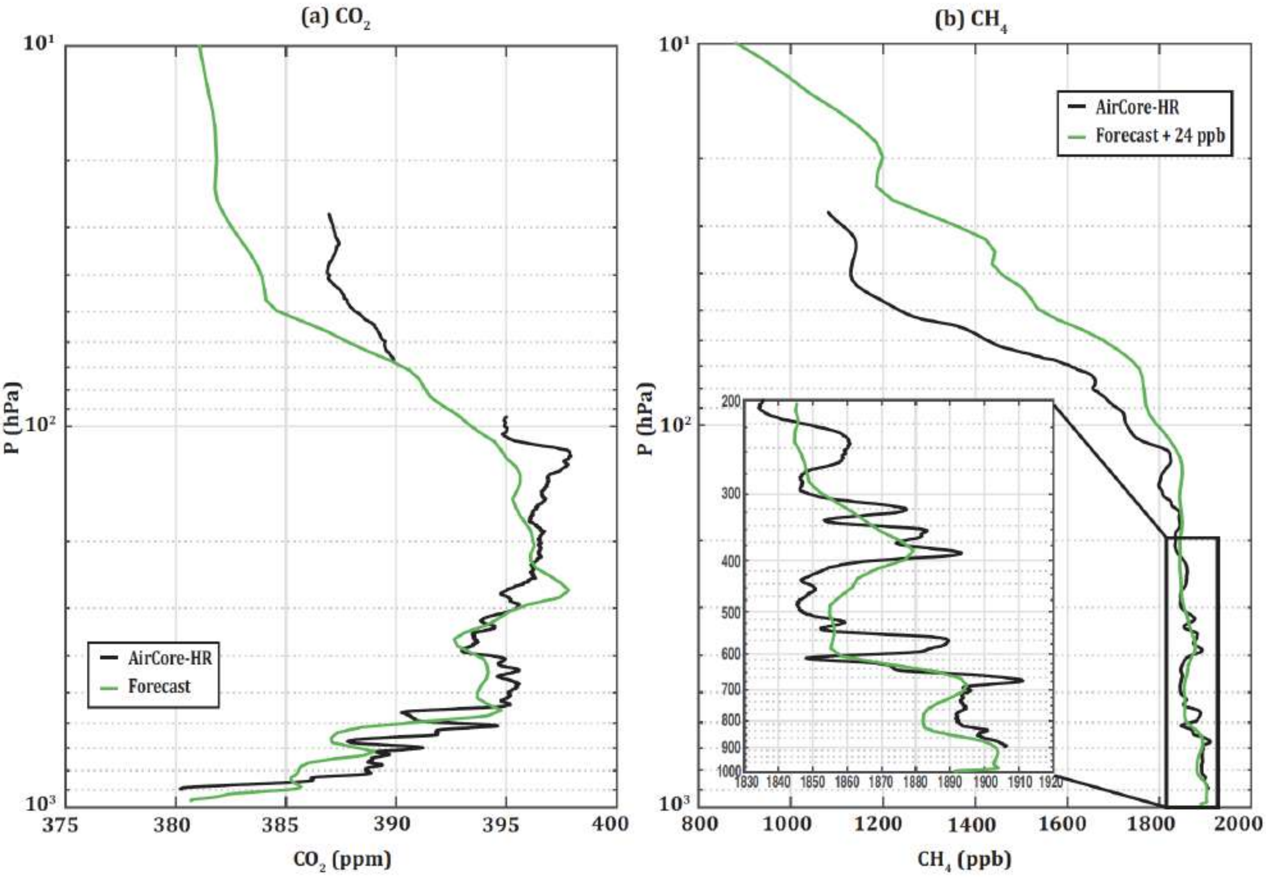


Figure 125: Vertical Profiles in Black for CO_2 and CH_4. The Green Lines are High Resolution Forecasts [17].

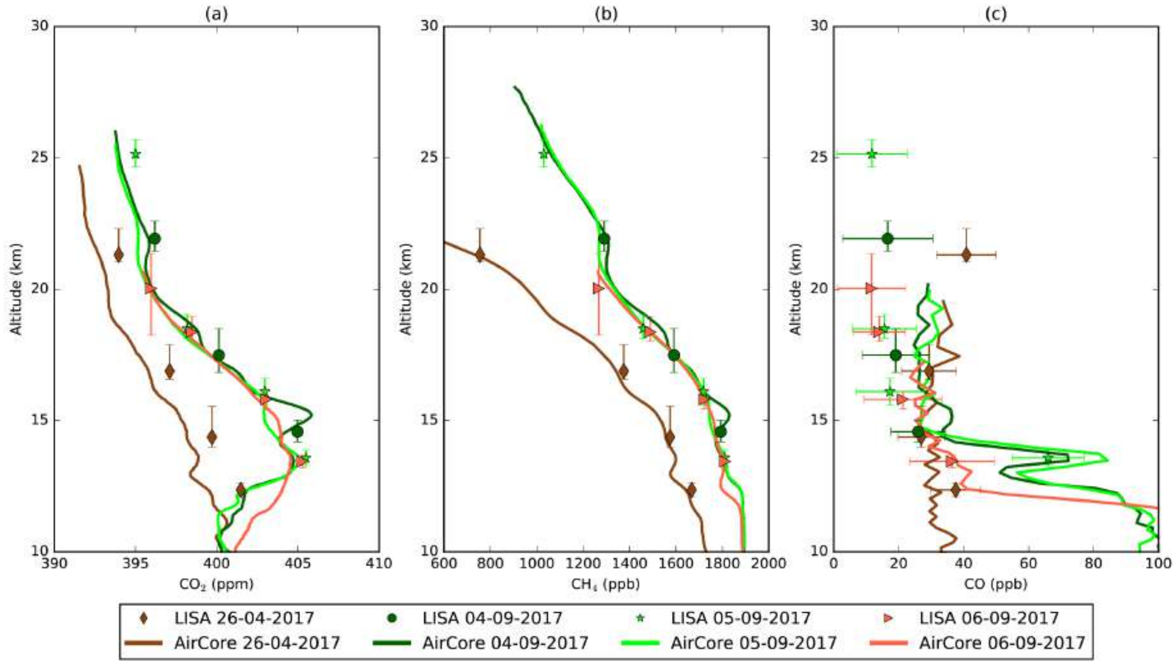


Figure 126: Vertical Profiles Comparison of AirCore and LISA Measurements of CO_2, CH_4 and CO Mole Fractions[5].

H.3 Sampling Flowrate

H.3.1 Pump Efficiency

For the air sampling process, the micro diaphragm gas pum *850 1.2 KNDC B* from KNF company will be used.

The TUBULAR Team has tested this pump in vacuum conditions in IRF facilities in Kiruna. Table 72 shows the obtained results. It has been proved that the pump is operative down to $20\ hPa$.

Altitude	Pressure	Datasheet Flowrate	Datasheet Efficiency	Empirical Flowrate	Empirical Efficiency
0 km	1013 hPa	8 L/min	100 %	4.35 L/min	54.4 %
0.5 km	925 hPa	7 L/min	87.5 %	4.26 L/min	63.25 %
1.5 km	850 hPa	6 L/min	75 %	4.16 L/min	52 %
2.3 km	760 hPa	5 L/min	62.5 %	3.88 L/min	48.5 %
3.1 km	680 hPa	4 L/min	50 %	3.61 L/min	45 %
4.6 km	560 hPa	3 L/min	37.5 %	3.11 L/min	38.9 %
6.4 km	450 hPa	2 L/min	25 %	2.61 L/min	32.6 %
8.3 km	320 hPa	1 L/min	12.5 %	2.12 L/min	26.5 %
10.7 km	230 hPa	0 L/min	0 %	1.50 L/min	18.8 %
12 km	194 hPa	0 L/min	0 %	1.22 L/min	15.3 %
17 km	88 hPa	0 L/min	0 %	0.47 L/min	5.9 %
20 km	55.29 hPa	0 L/min	0 %	0.27 L/min	3.4 %
24 km	30 hPa	0 L/min	0 %	0.13 L/min	1.6 %
30 km	11.97 hPa	0 L/min	0 %	0.07 L/min	0.9 %

Table 72: Pump Flowrate/Efficiency According to the Datasheet and Tests.

H.4 Discussion of the Results

H.4.1 Computational Methods vs. Flight Measurements

Atmospheric Model

In this section, the data from the past BEXUS flights is compared with the 1976 US Standard Atmosphere, for validation reasons. Figure 127 compares the changes in pressure over altitude for the BEXUS flights with the atmospheric model. It can be seen that the flights data-sets are in good agreement with the atmospheric model.

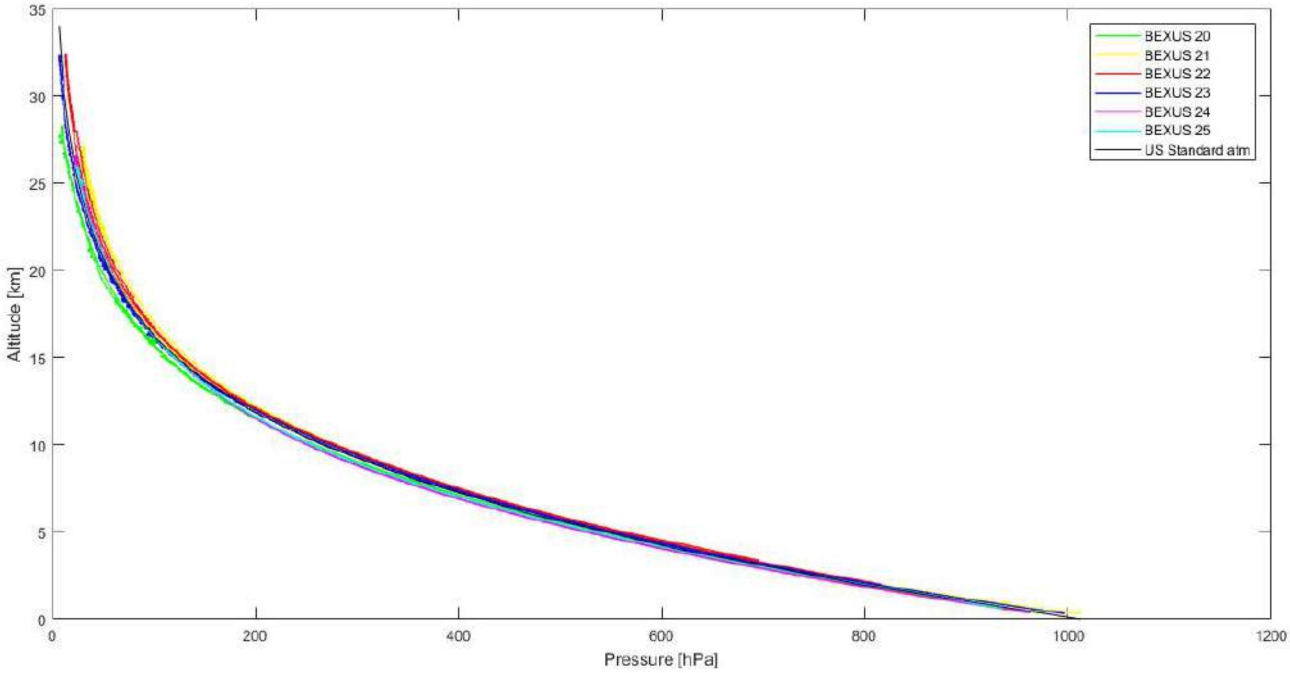


Figure 127: Comparative of Pressure Variation Over the Altitude During Different BEXUS Flights with the US Standard Atmosphere (1976).

Figure 128 below shows the changes in temperature over altitude, for all the BEXUS flights with the atmospheric model. It can be seen that there is a quite large deviation of the temperature above $20km$ of altitude between the BEXUS flights and the US Standard Atmosphere 1976 model. This is not arbitrary since it appears in all flights. But it is not surprising either, because most of the atmospheric models fail to precisely predict the temperatures at higher altitudes.

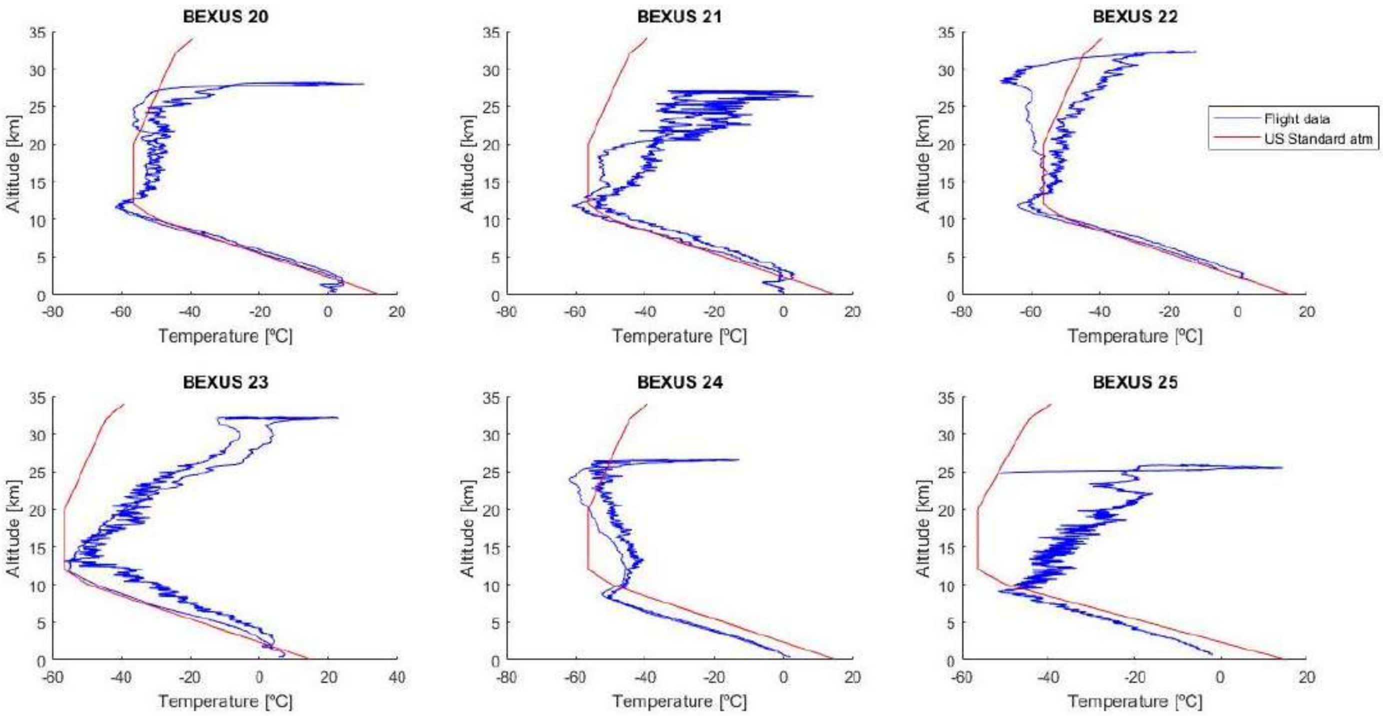


Figure 128: Comparative of Temperature Variation Over the Altitude During Different BEXUS Flights with the US Standard Atmosphere (1976).

Descent Curve

Again, in this section, the trajectories of past BEXUS flights, were compared with the mathematical model for validation reasons as shown in Figure 129. Overall, BEXUS flights 20, 23 and 24 are in good agreement with the mathematical model. Some deviations exist between the mathematical model and the BEXUS flights 21 and 22 mostly in the last $5km$ of the flight.

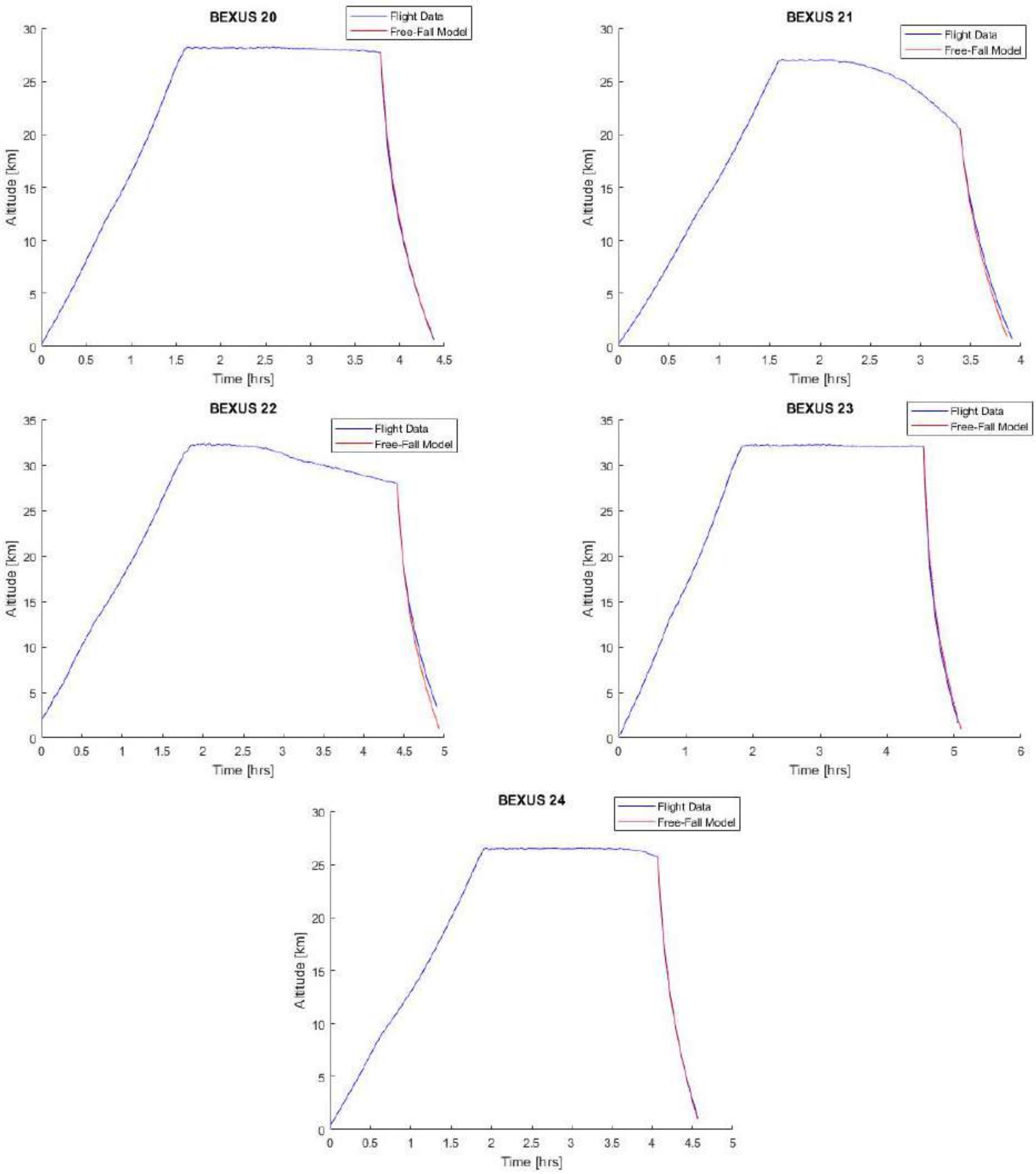


Figure 129: Comparative of the Altitude Over Time During the BEXUS Flights 20, 21, 22, 23, 24 with the Mathematical Model.

Velocity Profile

Here, the mathematical model was compared with the velocity profiles during the flights. It can be seen that the mathematical model in general follows the velocity profile with some minor deviations during Descent Phase, which means that the estimation is quite reliable.

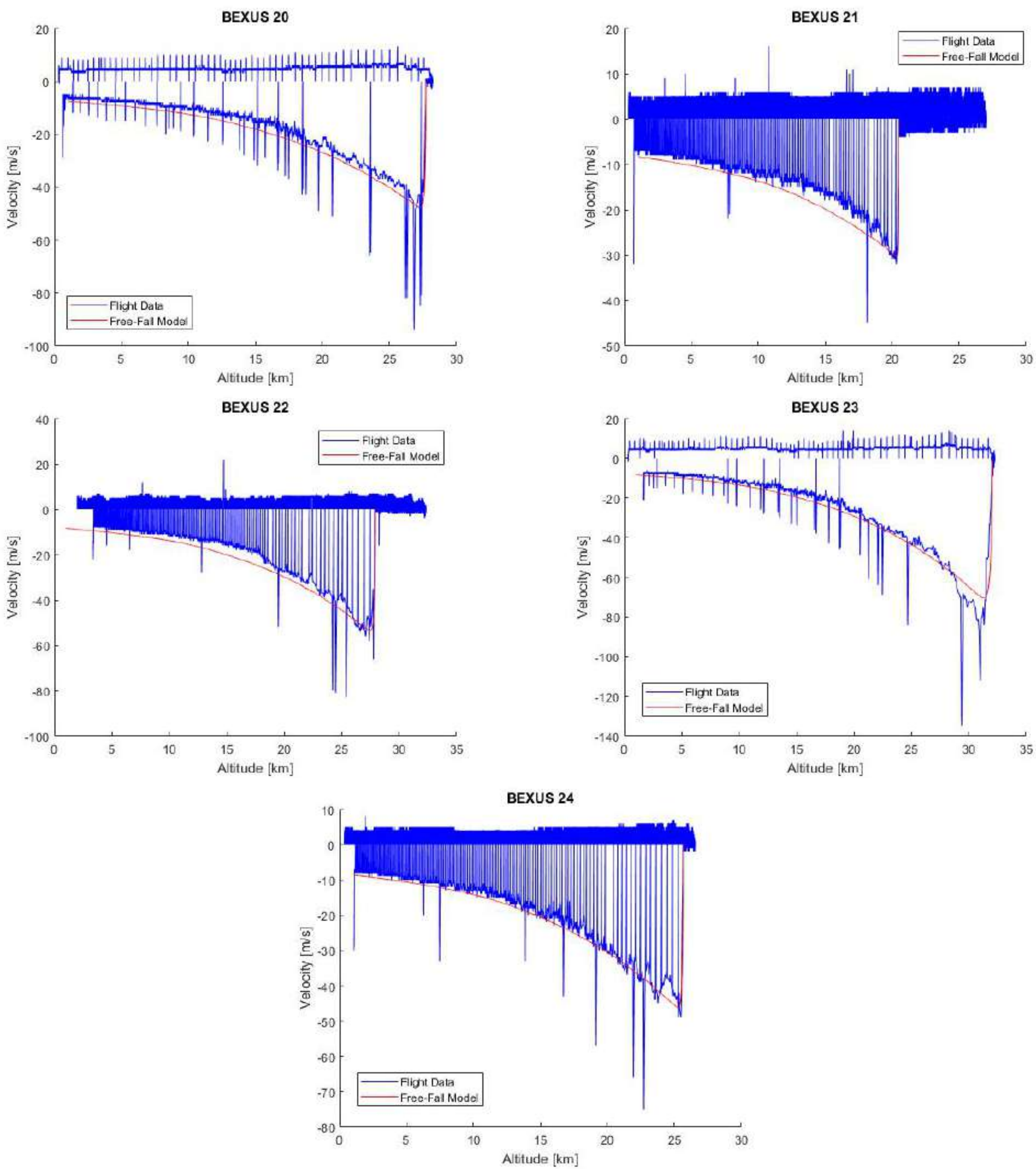


Figure 130: Comparative of the Velocity Over Altitude During the BEXUS Flights 20, 21, 22, 23, 24 with the Mathematical Model.

H.4.2 Mass Effects in the Descent Curve

Figure 131, shows how the descent time changes with different gondola mass values, after the cut-off phase. The heavier the payload, the sooner it will land. For example, if the gondola weights $250kg$, it will land in approximately 25 minutes after the cutoff, while it would take approximately 40 minutes to land if it weights $100kg$.

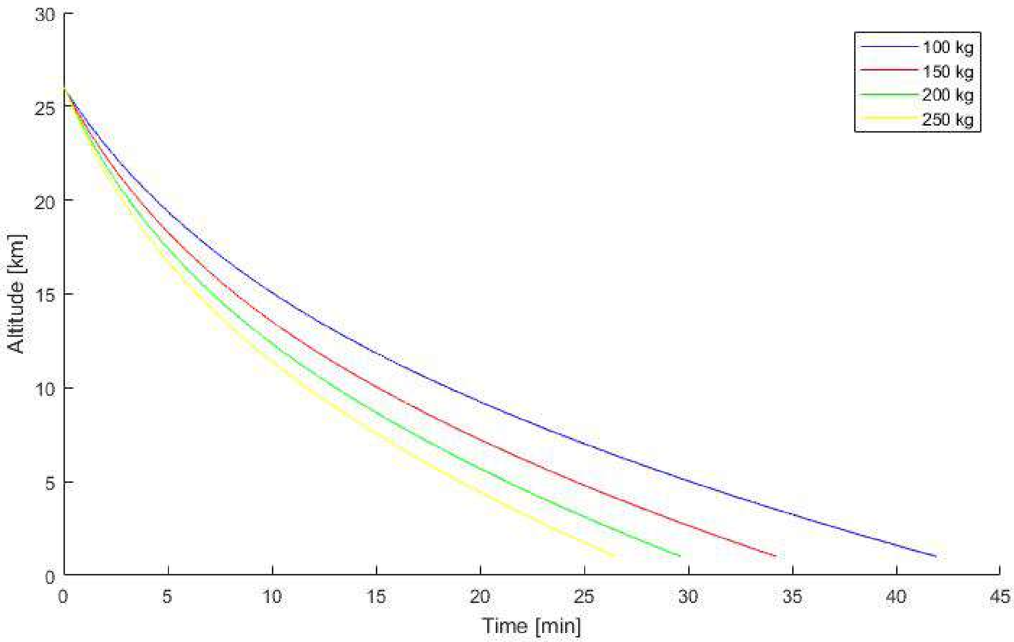


Figure 131: Mass Effects.

H.4.3 Discrete Sampling Volumes

Figure 132 supports the TUBULAR Team's decision to use a pump if sampling at high altitudes is meant, even though there is a single point failure risk. At $21km$ of altitude, the minimum amount of air that would be needed to be sampled, in order to ensure that there is enough left for analysis at ground, would be $2.4L$. Considering the low pressure at this high altitude, and the time it would be needed to fill the bag, it would be impossible to fulfill the experiment's objectives without using a pump. Moreover, without a pump, sampling at altitudes higher than $22km$, and also during Ascent Phase, would be impossible.

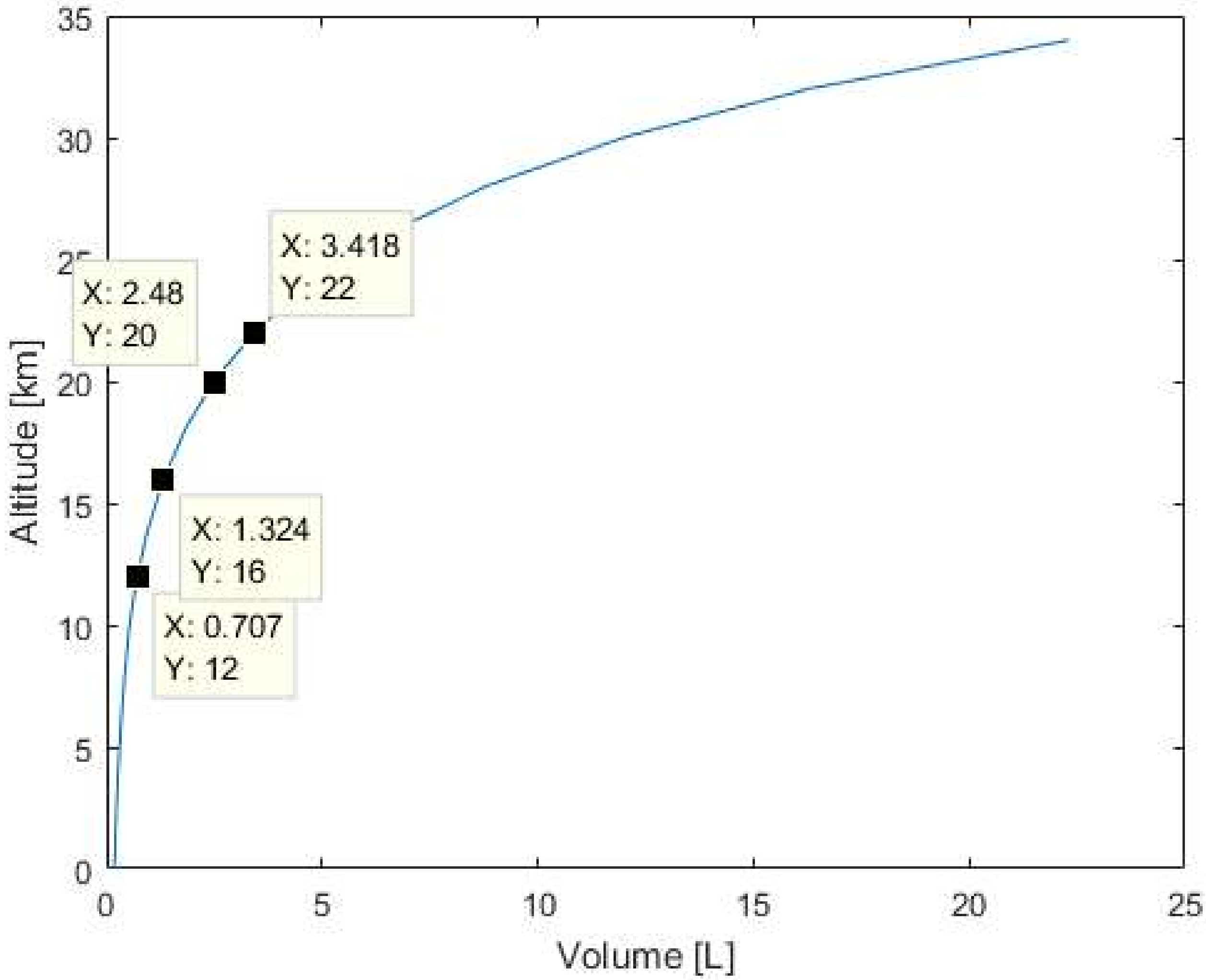
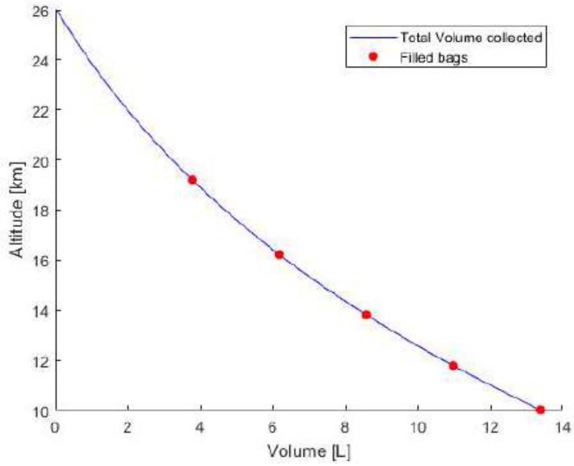


Figure 132: Minimum Sampling Volume at Each Altitude to Obtain Enough Air to Perform a Proper Analysis (180 mL at Sea Level).

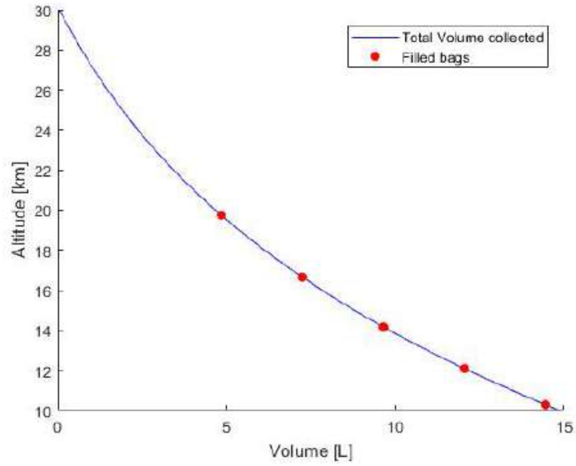
H.4.4 Limitations of the Bag Sampling Method

Roof Altitude Effect

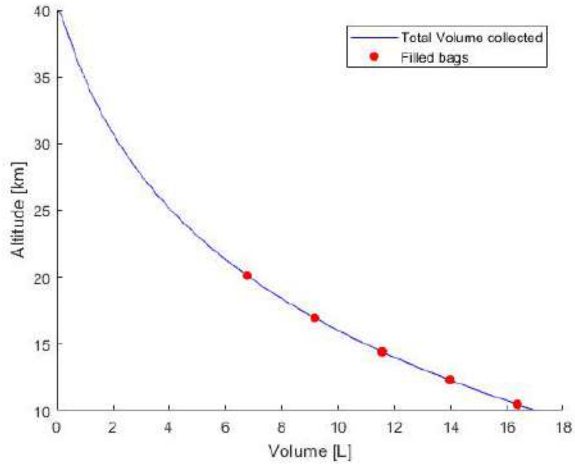
For a hypothetical study case, an ideal and continuous flow rate was used ($1L/min$). The obtained diagrams below, show that even if the sampling starts at $26km$, or at $30km$, or at $40km$, the number of filled bags would still be the same. This happens, due to the low pressure conditions at such altitudes which not allow a faster filling of a bag, and specially the low air density which forces to sample much more volume of air. Of course, the number of bags that can be filled, depends on the pump's efficiency at high altitudes. So, the altitude of the gondola's cut-off over about $26km$ would not affect the experiment's outcome.



(a) Starting of Sampling at 26 km.



(b) Starting of Sampling at 30 km.



(c) Starting of Sampling at 40 km.

Figure 133: Bag's Sampling System Limitations.

One Single Pump

Since the experiment uses a single pump, it is not possible to sample more than one bags at the same time. For the above hypothetical case, the maximum number of filled bags was five, considering continuous sampling. However, this is not the case when it comes to real life. Before sampling a bag, the system has to be flushed. Then, the sampling of a bag begins. After filling one bag, the system has to be flushed again before starting sampling a second bag. In that case, filling five bags, according to the hypothetical scenario, would be practically impossible.

H.5 Conclusions

H.5.1 Sampling Strategy

After testing the pump at low pressure environment, an overall idea about the performance of the pump at high altitudes is now known and an approximation of the sampling strategy is possible. The total weight of the BEXUS 26 gondola is approximated to be 266.55 kg, and the balloon is expected to reach 25.8 km altitude, following almost the trajectory of the BEXUS 24 flight as shown in figure 129. This serves the objectives of the TUBULAR experiment since, as indicated in Section H.2.2 the altitudes with higher differences in trace gases concentrations, are between 10 and 25 km. These are the altitudes where the sampling will be done. Sampling six bags in total, is enough to fulfil the objectives of the experiment and it is also feasible. Two bags will be sampled during Ascent Phase and four during Descent Phase. The ascent speed of the gondola, as shown in Figure 118, is estimated to be 5 m/s. A velocity of this rate, makes sampling of two bags possible while achieving a good resolution. It is important to mention here that the pressure inside the two bags that will be sampled during Ascent Phase shall not exceed 140 hPa since their volume will increase with decreasing pressure and they could burst. On the other hand, during Descent Phase the four remaining bags shall be filled with the full 3 L. This is because their volume will decrease with increasing pressure and it has to be made sure that there will be enough sample left for analysis.

The sampling of the first bag will start at 18 km of altitude. The minimum sampling time is estimated to be 29s with an achieved resolution of 143m. The second bag will be sampled at 21 km of altitude, and it will take 43 s to fill the minimum desired volume of air, with a resolution of 214 m. Before sampling, flushing of the AAC system for one minute is taken into account. During that, the gondola will cover a distance of 300 m.

During Descent Phase and considering a descent speed of 8 m/s, the sampling of the third bag will start from 17.5 km. The minimum sampling time is estimated to be 27 sec with a resolution of 216.5 m. The fourth bag will be sampled at 16 km for at least 20 s and resolution of 156 m. The fifth bag will be sampled at 14 km for 14.3 s minimum and resolution of 115 m. The sample of the last bag will start at 12 km for 9 s minimum sampling time and 71 m resolution. Again, one minute of flushing is taken into account, in between the sampling of each bag.

The flow rates of the pump, at each sampling altitude were taken from Table 56.

H.5.2 Discusion of the Results

Overall, the mathematical model is in good agreement with the data from the past BEXUS flights as well as, with the atmospheric model used for the Arctic region. Making this document, helped the TUBULAR Team to cross-check some theoretical values, important for the layout and the planning of the experiment. Tables 70 and 71 show that the estimated data before each flight are pretty close with the real data obtained by the flights which helped the TUBULAR Team to define the experiment's parameters with higher accuracy. In order to make a sampling plan, it is important to know the duration time of each phase. Figure 117, shows the trajectories of the different BEXUS flights, giving the TUBULAR Team a general idea of what the trajectory of the flight can look like and how the duration of each phase changes regarding the maximum altitude that the gondola reaches.

The velocity profile, Figure 119, is of high importance since the velocity during Ascent and Descent Phase, will determine the resolution of the samples. In general, the velocity values are in agreement with the BEXUS manual, with an ascent speed of 5 m/s and a descent speed, fluctuating after cutoff, before stabilizing at 8 m/s at the last kilometers of the flight. Another important thing that has to be mentioned here, is the TUBULAR Team's decision to sample during Ascent Phase too and not only during Descent Phase. As seen in figure 119 the gondola is turbulent after the cutoff with velocities up to 83 m/s, and needs more or less 6 km before stabilizing its velocity as figure 118 indicates. Hence, the altitudes that the gondola will be turbulent, will be covered by sampling during Ascent Phase. This will not affect the comparison with the CAC that will be sampled during Descent Phase only, since the horizontal displacement of the gondola is much smaller than the vertical.

Atmospheric conditions play a crucial role for the TUBULAR experiment. The TUBULAR Team should know, the different pressures at each altitude, since the pressure is the parameter that will trigger the sampling of the bags. What is more, the pressure will determine the performance of the pump and it is crucial to know under what pressures the pump needs to be tested depending on the sample altitude. The temperature is of high importance too and the trickier to predict especially at high altitudes. The TUBULAR Team should be able to keep the temperature of the pump within its working temperature range in order to assure that the pump will start working. To do so, the air temperature must be known at each altitude which will help the TUBULAR Team to come up with a good thermal plan.

The sampling altitude range will not be chosen randomly. The idea is to find the altitude range, where the trace gases show the bigger differences in concentration. In Section H.2.2, were presented some theoretical trace gases concentration values as well as, some results from past research papers. According to them, the more interesting area to sample is between 10 and 25 km of altitude. The TUBULAR Team, plans to sample between 17 and 22 km during Ascent Phase and 17 to 10 km during Descent Phase.

Additionally, the sampling software revealed some limitations of the sampling system and also which parameters should be taken into account for the experiment's layout and which not. The weight of the gondola, will affect the maximum altitude that the balloon will reach, and the time needed for the gondola to land, but it doesn't contribute to the decision of how many bags will be used.

The decision of the TUBULAR Team to use a pump was questioned at the beginning, as a single point failure risk. However, this decision is justified by the need of sampling during Ascent Phase, ohterwise the sampling would not be possible. Figure 132, supports the use of a pump because without a pump, sampling at 22 km of altitude, would be impossible considering the low pressure and the time it would take to fill a bag.

Note that even with the pump, some limitations still exist. The sampling of the bags cannot be continuous since the system has to be flushed before sampling a bag. Furthermore, the flow rate of the pump will be lower at high altitudes than it is on the ground, due to pressure differences. Figure 133 points out that even with an ideal flow rate of 1 L/min and sampling continuously, it is not possible to sample more than five bags, because it takes a lot of time to sample a bag at high altitude atmospheric conditions. Additionally, it makes clear why the maximum altitude that the gondola will reach, does not affect the experiment's outcome. As the gondola ascents, the pressure gets lower and takes more time to sample a bag. So, sampling more bags would not be possible even if the balloon reaches a higher altitude. The same applies for the Descent Phase and the cutoff altitude.

Concluding, whilst at the beginning, the idea was to sample a total of sixteen bags in order to have more samples to compare with the continuous vertical profile obtained by the CAC, this document justifies that this is not feasible. Taking into account all the different parameters, it made clear which of them are important and which are not. Parameters like the gondola's velocity, the pressure at different altitudes, and the pump's flow rate, will determine the outcome of the TUBULAR experiment, the number of the bags that will be used, as well as the sampling altitudes. Parameters like the gondola's weight or the maximum altitude that the balloon will reach, does not affect the experiment's outcome and have a secondary role.

Appendix I Experiment Thermal Analysis

I.1 Component Temperature Ranges

Table 73, below covers the thermal ranges of all components included in the experiment's flight stage as listed in Section 4.3:

ID	Components	Operating ($^\circ C$)		Survivable ($^\circ C$)		Expected ($^\circ C$)	
		Min.	Max.	Min.	Max.	Min.	Max.
E1	Arduino Due	-40	85	-60	150	-15.7	54.0
E2	Ethernet Shield	-40	85	-65	150	-15.7	54.0
E3	Miniature diaphragm air pump	5	40	-10	40	10	34.9
E4	Pressure Sensor	-40	85	-40	125	-15.7	54.0
E5	Sampling Valve (inlet and outlet 1/8"" female)	-20	68	-20[3]	68[3]	-15	20
E6	Airflow sensor AWM43300V	-20	70	-20[3]	70[3]	-8.8	34.9
E7	Heater $(12.7 \times 50.8mm)$	-200	200	-200[3]	200[3]	-20	36
E9	Temperature Sensor	-55	125	-65	150	-19.7	43
E10	DCDC 24 V	-40	85	-55	125	-15.7	54.0
E12	Micro SD	-25	85	-200[3]	200[3]	-15.7	54.0
E13	Logic CAT5E	-55	60	-55[3]	60[3]	-34	15
E16	MOSFET for current control	-55	175	-55	175	-15.7	54.0
E17	Diodes for DCDC converters	-65	175	-65[3]	175[3]	-15.7	54.0
E18	3.3V LED	-40	85	-40[3]	85[3]	-15.7	54.0
E19	15-pin D-SUB Female connector with pins	-55	120	-200[3]	200[3]	-15.7	54.0
E20	9-pin D-SUB Female connector with pins	-55	120	-200[3]	200[3]	-15.7	54.0
E21	9-pin D-SUB Female connector with soldering cups	-55	105	-55[3]	105[3]	-15.7	54.0
E22	9-pin D-SUB Male connector with soldering cups	-55	105	-55[3]	105[3]	-15.7	54.0
E23	15-pin D-SUB Male connector with soldering cups	-55	105	-55[3]	105[3]	-15.7	54.0
E24	9-pin D-SUB backing	-40	120	-40[3]	120	-15.7	54.0

E25	15-pin D-SUB backing	-40	120	-40[3]	120	-15.7	54.0
E28	3.3 Zener diode	-65	175	-65[3]	175[3]	-15.7	54.0
E29	Male connector on PCB	-40	85	-40[3]	85	-15.7	54.0
E30	Female connector from wall	-40	85	-40[3]	85	-50.7	15
E31	Grounding contact	-55	125	-55[3]	125[3]	-50.7	15
E32	Logic CAT5 E-link for inside box	-55	60	-55[3]	60[3]	-34	15
E33	Signal Wires	-60	200	-60[3]	200[3]	-34	15
E34	Flushing valve (inlet and outlet 1/8”’ female)	-20	68	-20[3]	68	-7.4	25.8
E35	Valves manifold (outlet 1/8”’ female)	-10	50	-10[3]	50[3]	3	18
E36	Power wire black	-60	200	-60[3]	200[3]	-34	15
E48	Power wire red	-60	200	-60[3]	200 [3]	-34	15
E50	6-pin male	-55	105	-55[3]	105[3]	-8.8	24.0
E51	8-pin male single row header	-40	105	-40[3]	105[3]	-8.8	24.0
E52	10-pin male single row header	-55	105	-55[3]	105[3]	-8.8	24.0
E53	36-pin male double row header	-40	105	-40	125	-8.8	24.0
E54	12 V DC/DC converter	-40	85	-55	125	-15.7	54.0
E55	50 kΩ Potentiometer	-55	125	-55[3]	125[3]	-15.7	54.0
E56	Static pressure sensor	-40	120	-40[3]	120[3]	-8.8	34.9
E57	Connector for static pressure sensor	-25	80	-25[3]	80[3]	-8.8	34.9
E58	PCB	-50	110	-50[3]	110[3]	-15.7	54.0
E59	Pressure Sensor PCB	-50	110	-50[3]	110[3]	-50	39

Table 73: Table of Component Temperature Ranges.

I.2 Thermal equations

I.2.1 Variables and Tables

Variable	Description	Unit	Value
α_{Al}	Absorption of aluminum	-	0.3
S	Solar constant	$\frac{W}{m^2}$	1362
A_{Sun}	Area affected by the sun	m^2	0.28
Albedo	Albedo coefficient	-	0.15
A_{Albedo}	Area affected by the albedo	m^2	0.65
ε_{Earth}	Emissivity of Earth	-	0.95
A_{IR}	Area affected by the IR flux	m^2	0.65
IR_{25km}	Earth IR flux at 25 km	$\frac{W}{m^2}$	220
P	Dissipated power from electronics	W	varies
h	Convection heat transfer constant	$\frac{W}{m^2 \cdot K}$	18
K	Scaling factor for convection	-	varies
$A_{Convection}$	Area affected by the convection	m^2	1.3
σ	Stefan-Boltzmann constant	$\frac{W}{m^2 \cdot K^4}$	$5.67051 \cdot 10^{-8}$
$A_{Radiation}$	Radiating area	m^2	1.3
ε_{Al}	Emissivity of aluminum	-	0.09
T_{Out}	Temperature wall outside	K	varies
T_{Inside}	average uniform temperature inside	K	varies
$T_{Ambient}$	Ambient temperature outside	K	varies
T_{Ground}	Temperature of the ground	K	273
k_{Al}	Thermal conductivity of aluminum	$\frac{W}{m \cdot K}$	205
k_{PS}	Thermal conductivity of polystyrene foam	$\frac{W}{m \cdot K}$	0.03
L_{Al}	Thickness of aluminum sheeting	m	0.0005
L_{PS}	Thickness of polystyrene foam	m	varies
P_{Ground}	Pressure at ground	Pa	$101.33 \cdot 10^3$
P_{25km}	Pressure at $25km$	Pa	$2.8 \cdot 10^3$

Table 74: Variables Used in Thermal Calculation.

Wall part	Thickness (m)
Aluminum sheet	0.0005
AAC (Styrofoam)	
Vertical	0.02
Horizontal	0.02
Top/Bottom	0.03
CAC (Styrofoam)	
Horizontal towards AAC	0.02
All other walls	0.05

Table 75: The Different Wall Thicknesses Used for AAC and CAC.

I.3 Thermal calculations in MATLAB

For the MATLAB calculations, a few assumptions were made. They were as follows:

- Taking the average of MATLAB calculations for calculations with or without sunlight.
- Calculating the average temperature on the outside wall of the experiment.
- Assuming the inner temperature at the bags section is uniform.
- Ignoring the pipes letting cold air into the experiment.
- Assuming no interference between the two experiment boxes.
- All conduction was uniform from the inside.
- Assume steady flow through the walls from conduction.
- Assume radiation and convection from/on 6 walls not 5.

I.3.1 Solar flux and Albedo

The albedo is the reflected solar flux from earth so it was put into the same equation as the solar flux. It was assumed that the sun hit two sides of the experiment at a $45°$ angle at all times while over 10 km altitude. In the middle of October at the time of launch the sun was expected to hit the experiment with a maximum inclination of $15°$ from the horizon.

$$Q_{Sun+Albedo} = \alpha_{Al} \cdot S \cdot cos(15) \cdot (A_{Sun} \cdot cos(45) + Albedo \cdot A_{Albedo})$$

I.3.2 Conduction

For calculating the outer walls temperature, the assumption of steady flow through walls was used.

$$Q_{Conduction} = [\text{Steady flow through wall}] = \text{Dissipated power} = P$$

I.3.3 Earth IR flux

The earth IR flux is the flux that comes from earth as a black body radiating. It was calculated from the determined IR flux at ground level then scaled to the altitude the experiment would reach. The following equations were found from [9]:

$$IR_{Ground} = \varepsilon_{earth} \cdot \sigma \cdot T^4_{ground}$$

$$\tau_{atmIR} = 1.716 - 0.5 \cdot \left[e^{-0.65 \frac{P_{25km}}{P_{ground}}} + e^{-0.95 \frac{P_{25km}}{P_{ground}}} \right]$$

$$IR_{25km} = \tau_{atmIR} \cdot IR_{Ground}$$

After the IR was calculated for the floating altitude it was put into the following equation.

$$Q_{IR} = \varepsilon_{earth} \cdot A_{IR} \cdot IR_{25km}$$

I.3.4 Radiation

It was assumed that the experiment would experience radiation from all 6 sides. In reality it would experience radiation from 5 sides because the CAC box will be in contact with one of the AAC box's sides. It was decided to leave the simulation with input from the 6 sides for the calculations in order to compensate for having no holes to let cold air in to the pump.

$$Q_{Radiation} = \sigma \cdot \varepsilon_{Al} \cdot A_{Radiation} \cdot (T_{Out}^4 - T_{Ambient}^4)$$

I.3.5 Convection

At an altitude of 25 km there is far lower air density than at sea level. This therefore gave a scaling factor K that had to be taken into account when calculating the convection and K can be seen in Table 76 for different altitudes.

$$Q_{Convection} = h \cdot K \cdot A_{Convection} \cdot (T_{Out} - T_{Ambient})$$

The equation for approximating the heat transfer coefficient for air was outlined as:

$$h = 10.45 - v + 10 \cdot \sqrt{v}$$

Where v is the velocity of the fluid medium.

As the balloon was expected to rise at approximately $5m/s$ for the duration of the Ascent Phase, the starting value for the convective heat transfer coefficient h was expected to be 27.811, assuming negligible wind currents perpendicular to the direction of ascent.

The equations used to obtain the value of K are listed below:

$$F(T_{sea}, T_{alt}) = \left(\frac{k_{alt}}{k_{sea}}\right)^{1-n} \times \left[\left(\frac{\beta_{alt}}{\beta_{sea}}\right) \times \left(\frac{\mu_{sea}}{\mu_{alt}}\right) \times \left(\frac{c_{p-alt}}{c_{p-sea}}\right) \times \left(\frac{\rho(T_{alt})}{\rho(T_{sea})}\right)^2\right]^n$$

Where:

- n is an exponent value dependent on the turbulence of the fluid medium ($\frac{1}{4}$ for laminar flow and $\frac{1}{3}$ for turbulent flow)
- k is the thermal conductivity of the air
- β is the thermal expansion coefficient for air
- μ is the dynamic viscosity of the air
- c_p is the specific heat capacity of the air at constant pressure
- $\rho(T)$ is the density of the air as a function of only temperature difference (i.e. for constant pressure)
- "sea" denotes the current variable is represented by its value found at sea level
- "alt" denotes the current variable is represented by its value found at a specified altitude

The values for F from this equation were then applied to its respective position in the following equation to determine the ratio between the convective heat transfer coefficient h at sea level (assumed to have negligible differences for Esrange ground level) and the same coefficient at a specified altitude:

$$K = \left(\frac{\rho(P_{alt})}{\rho(P_{sea})}\right)^{2n} \times \left(\frac{\Delta T_{air}}{\Delta T_{sea}}\right)^{n} \times F(T_{sea}, T_{alt})$$

Where:

- $\rho(T)$ is the density of the air as a function of only temperature difference (i.e. for constant pressure)
- δT is the difference between the temperature of the ambient air and the surface in question

Table 76 combines the previously listed convection and radiation formulae integrated into the MATLAB scripts to determine the convective and radiative heat loss in the worst case for (highest) power dissipation during each stage of the experiment. Additional information on the thermodynamics of the atmosphere was obtained from *Engineering Toolbox* [23]

Altitude	**Case**	T_{amb}	K	h_{alt}	T_{out}	Q_{conv}	Q_{rad}
Hangar (Preparations)	Cold	283	1	10.45	20.3	139.409	6.516
	Expected	288	1	10.45	25.2	139.081	6.844
	Warm	293	1	10.45	30.2	138.743	7.182
Ground (Stationary)	Cold	263	1	18	-0.8	215.705	4.690
	Expected	273	1	18	9.2	215.171	5.222
	Warm	283	1	18	19.2	214.600	5.790
Ground (Launched)	Cold	263	1	28.945	-4.2	217.528	2.884
	Expected	273	1	28.945	5.8	217.195	3.217
	Warm	283	1	28.945	15.8	216.837	3.573
5 km	Cold	228	0.7868	22.774	-37.6	217.979	2.430
	Expected	263	0.8468	24.511	-3.2	216.990	3.417
	Warm	273	0.8507	24.624	6.3	216.615	3.792
10 km	Cold	193	0.4882	14.131	-68.1	217.916	2.480
	Expected	223	0.5286	15.300	-39.1	216.940	3.453
	Warm	238	0.5421	15.691	-24.4	216.336	4.055
15 km	Cold	193	0.3300	9.552	-61.9	224.325	3.961
	Expected	233	0.3680	10.652	-23.9	222.309	5.972
	Warm	253	0.3825	11.071	-4.6	221.050	7.226
20 km	Cold	213	0.2401	6.950	-35.6	220.777	7.430
	Expected	243	0.2563	7.419	-7.4	218.297	9.899
	Warm	268	0.2687	7.778	16.4	215.906	12.282
25 km	Cold	223	0.1683	4.871	-16.0	215.482	12.549
	Expected	253	0.1792	5.187	11.4	211.791	16.226
	Warm	273	0.1847	5.346	30.1	208.893	19.112
Float Phase	Cold	223	0.1683	3.029	-1.7	190.087	19.521
	Expected	253	0.1792	3.226	24.1	185.077	24.530

	Warm	273	0.1847	3.325	41.9	181.196	28.402
25 km	Cold	223	0.1683	5.173	-20.3	199.514	10.633
	Expected	253	0.1792	5.508	7.4	196.295	13.838
	Warm	273	0.1847	5.677	26.3	193.765	16.356
20 km	Cold	213	0.2401	7.379	-36.9	221.276	6.948
	Expected	243	0.2563	7.877	-8.6	218.934	9.280
	Warm	268	0.2687	8.258	15.2	216.672	11.534
15 km	Cold	193	0.3300	10.142	-63.6	216.808	3.561
	Expected	233	0.3680	11.310	-25.4	214.974	5.389
	Warm	253	0.3825	11.756	-6.0	213.829	6.530
10 km	Cold	193	0.4882	15.004	-68.8	218.074	2.326
	Expected	223	0.5286	16.246	-39.7	217.155	3.242
	Warm	238	0.5421	16.661	-25.0	216.586	3.809
5 km	Cold	228	0.7868	24.182	-38.1	218.127	2.284
	Expected	263	0.8468	26.026	-3.6	217.195	3.214
	Warm	273	0.8507	26.145	6.4	216.841	3.567
Ground (Landed)	Cold	263	1	30.734	-4.6	217.700	2.713
	Expected	273	1	30.734	5.4	217.386	3.027
	Warm	283	1	30.734	15.4	217.049	3.363
Ground (Stationary)	Cold	263	1	18	-4.8	207.753	2.586
	Expected	273	1	18	5.2	207.453	2.885
	Warm	283	1	18	15.2	207.132	3.205

Table 76: Table of Predicted Heat Loss.

I.3.6 Thermal equations

If there is no incident sunlight on the experiment.

$$Q_{IR} + Q_{Conduction} = Q_{Radiation} + Q_{Convection}$$
$$\updownarrow$$
$$\varepsilon_{earth} \cdot A_{IR} \cdot IR_{25km} + P$$
$$= \sigma \cdot \varepsilon_{Al} \cdot A_{Radiation} \cdot (T_{Out}^4 - T_{Ambient}^4) + h \cdot K \cdot A_{Convection} \cdot (T_{Out} - T_{Ambient})$$

If there is incident sunlight on the experiment, existing parameters stay included, and the parameter $Q_{Sun+Albedo}$ is also included.

$$Q_{IR} + Q_{Conduction} + Q_{Sun+Albedo} = Q_{Radiation} + Q_{Convection}$$
$$\updownarrow$$
$$\varepsilon_{earth} \cdot A_{IR} \cdot IR_{25km} + P + \alpha_{Al} \cdot S \cdot cos(15) \cdot (A_{Sun} \cdot cos(45) + Albedo \cdot A_{Albedo})$$
$$= \sigma \cdot \varepsilon_{Al} \cdot A_{Radiation} \cdot (T_{Out}^4 - T_{Ambient}^4) + h \cdot K \cdot A_{Convection} \cdot (T_{Out} - T_{Ambient})$$

From these equations T_{Out} could be calculated and it was found to be the average temperature on the aluminum sheets facing the outside air. After T_{Out} was found, the inner temperature could be calculated by determining the heat transfer through the wall.

$$P = \frac{T_{Inside} - T_{Outside}}{A \cdot (\frac{L_{Al}}{k_{Al}} + \frac{L_{PS}}{k_{PS}})}$$
$$\updownarrow$$
$$T_{Inside} = P \cdot A \cdot (\frac{L_{Al}}{k_{Al}} + \frac{L_{PS}}{k_{PS}}) + T_{Outside}$$

T_{Inside} was then assumed to be the uniform air temperature in the experiment.

I.3.7 Trial run with BEXUS 25 air temperature data for altitudes

The air temperature data varying over altitude from previous BEXUS flights could be found on the REXUS/BEXUS website. To do a simulated test flight for the calculations done in MATLAB (with the intention of seeing how the temperature profile would appear for a real flight), it was calculated and plotted in with data from BEXUS 25 flight. Because of it originally having approximately 42000 data points, the profile had to be scaled down. Only every 25^{th} data point was used to reduce processing time and this resulted in little detail loss. In Figure 134, the TUBULAR test flight is the uniform temperature on the inside with a insulation consisting as specified in Table 75.

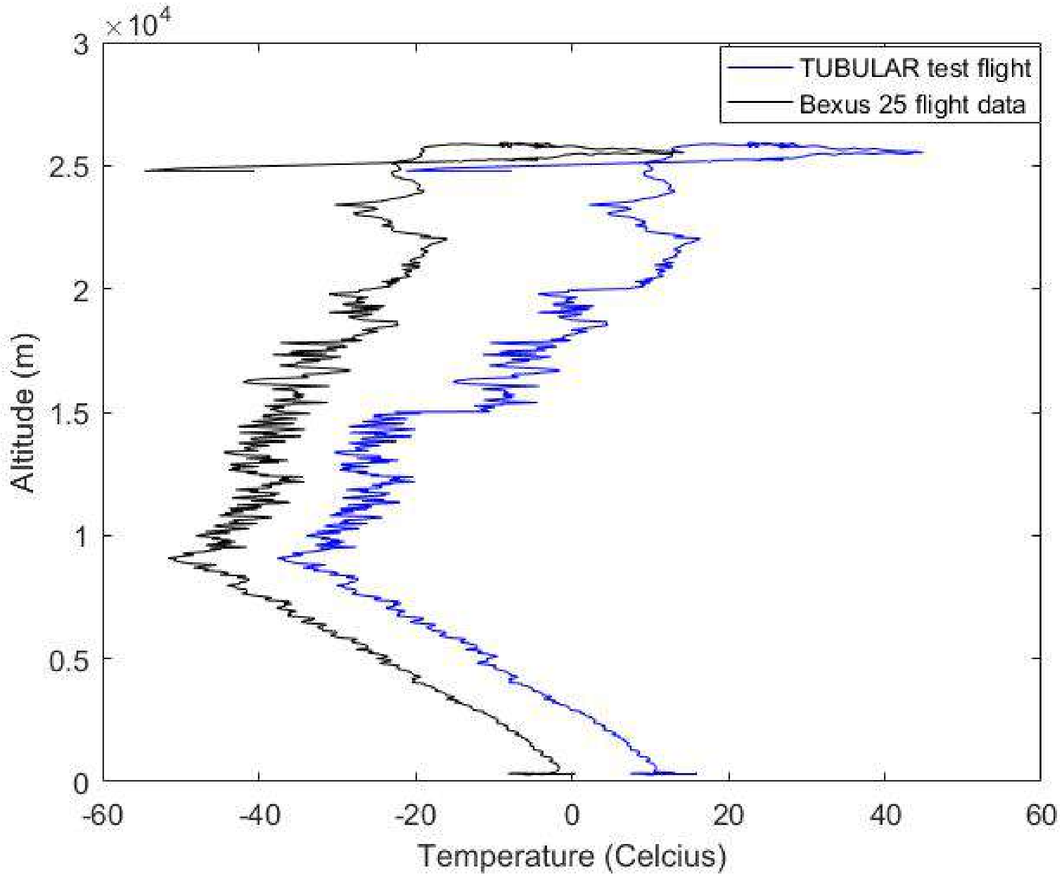


Figure 134: Simulated Test Flight of TUBULAR AAC Box with Data From BEXUS 25.

When the data was found it was checked in ANSYS to determine and add heaters to control the most critical parts of the model.

I.3.8 Trial flight for the CAC

The CAC box did not require as much thermal design as the AAC box. The only part to be considered was the valve, which had a lower limit of the operating temperature of $-10°C$. It would not be a problem because the valve would open just prior launch and have current running through it throughout the whole flight — heating it self up. If the thermal analysis was proven wrong by a test, showing that it was not sufficient to use only self-heating, a heater could be applied at a later date. The passive thermal design for the CAC box would consist of aluminum sheets and Styrofoam as specified in 75.

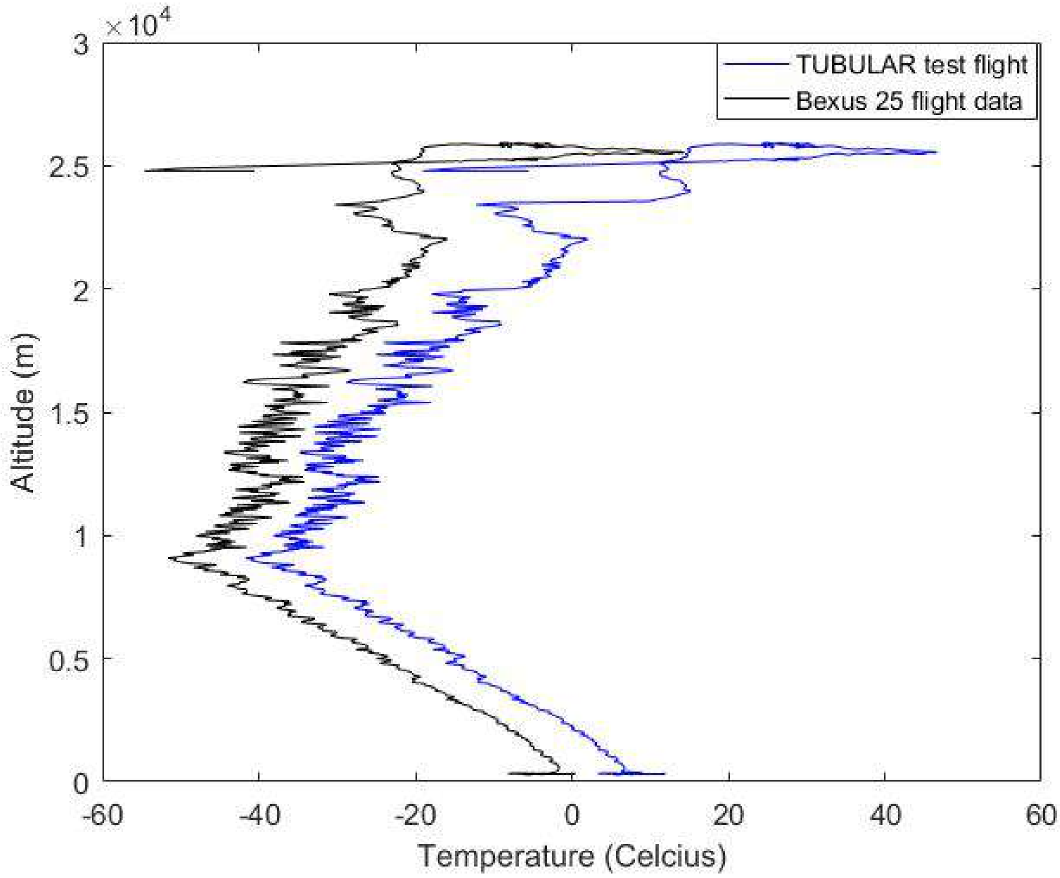


Figure 135: Simulated Test Flight of TUBULAR CAC Box with Data From BEXUS 25.

I.3.9 MATLAB Conclusion

By running the MATLAB script, the hottest and coldest case for $0.02m$ on the wall and $0.03m$ on the top and bottom of the Styrofoam could be found for ascent and descent sampling. The thermal conductivity of Styrofoam is $k = 0.03$. In Table 77 it is shown the hottest and coldest case of temperature on the inside when samples should be taken. The hottest and coldest cases are taken from Figure 134.

	Ascent		**Descent**	
	Coldest	Hottest	Coldest	Hottest
AAC	-11.39	16.41	-30.28	-4.393
Outer air	-38.22	-15.9	-44.41	-38.18

Table 77: The Sampling Temperature Ranges for Ascent and Descent for the AAC Box.

I.4 Thermal Simulations in ANSYS

The CAD model used is seen in the figure 136. The side exterior walls were $0.02m$ in height, the interior walls of the Brain to the bags were $0.03m$ in length and the top and bottom wall consisted of $0.03m$ long Styrofoam as well. The outer parts of the pipes were set to stainless steel with a constant temperature (the same as the ambient outside). The tubes closest to the pump and the one leading from the pump to the manifold were set to include air to be able to vary during the simulation depending on the temperature outside of the experiment and the pump heating up from the heater.

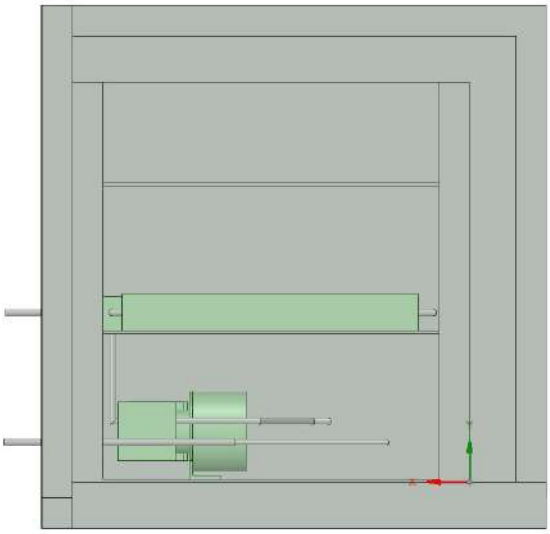


Figure 136: The CAD Model Used for ANSYS Simulations

In ANSYS, FEA simulations were done using both Steady-State Thermal and Transient Thermal analysis. Because of the limitations in ANSYS student license, a simplified model was used, which can be seen in Figure 137. It was focused on the corner region of the experiment housing the Brain and had three walls to the sampling bags and assumed the air was uniformly heated on the inside. The uniform inside air could be taken from the data from the test flight in Figure (134). These simulations were done to find what temperature the pump and manifolds would reach, as they were the most critical components in the experiment.

A transient thermal analysis was also performed by simulating a test flight with data from BEXUS 25 using results from MATLAB. It was performed so the thickness of the wall could be verified to see if it was good enough and whether adding heaters was required. Through the addition of, correct placement, adequate assigned power, and activation time for the heaters, it was possible to enable the pump and the manifold to operate in their required temperature ranges.

I.5 ANSYS Result

I.5.1 Including Air With Same Density as Sea Level in the Brain

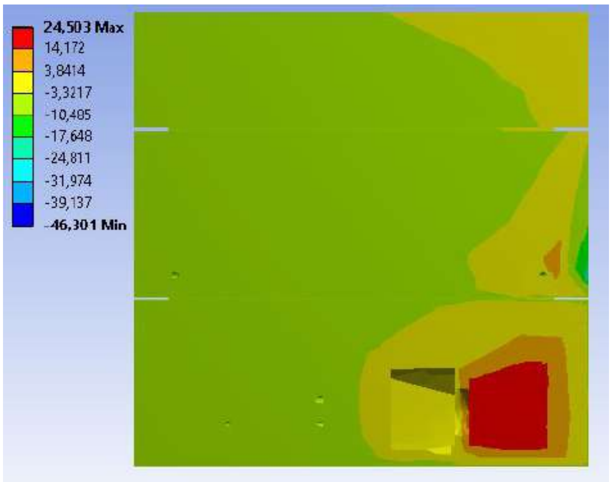


Figure 137: Cross Section of the Air in the Brain at the Time to Sample During Ascent.

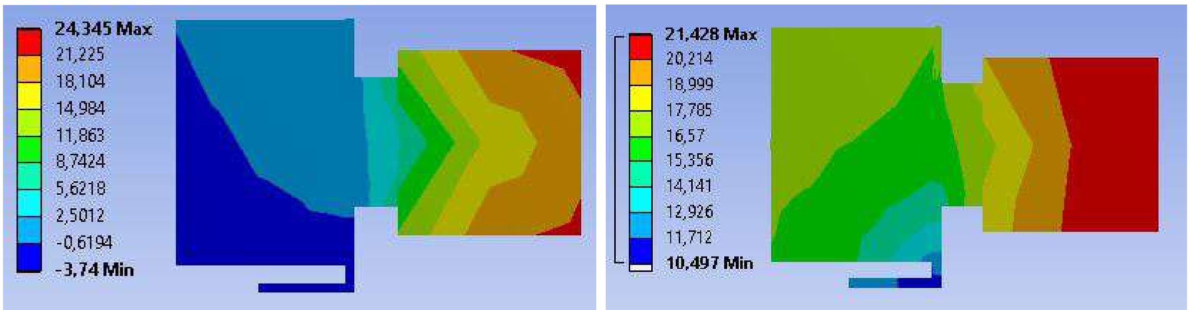


Figure 138: The Pump at the Time to Sample During Ascent (left) and Descent (right).

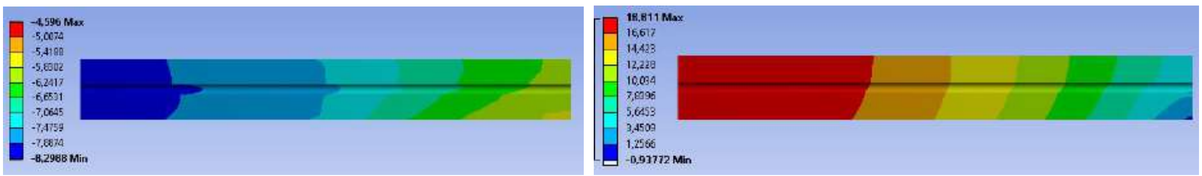


Figure 139: The manifold at the Time to Sample During Ascent (left) and Descent (right).

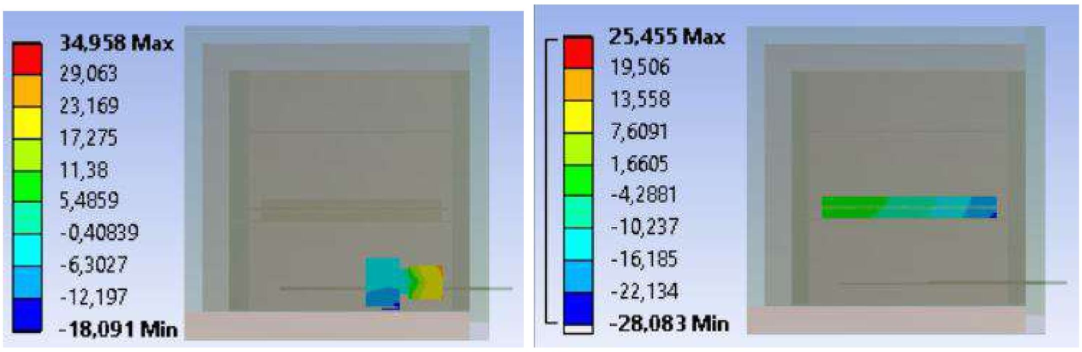


Figure 140: Pump and Manifold at the Coldest Part of Ascent.

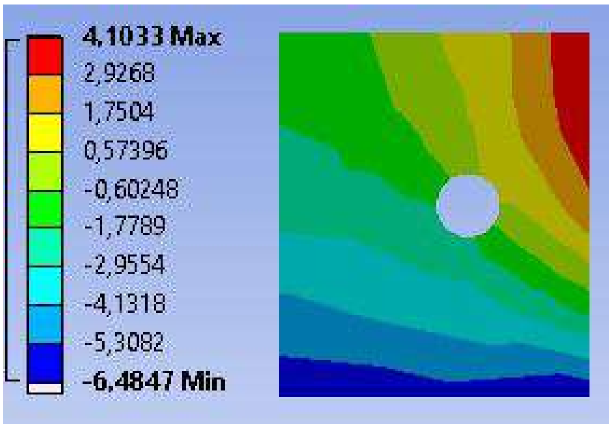


Figure 141: Flushing Valve a Little Before Sampling Shall Start.

I.5.2 No Air in the Brain

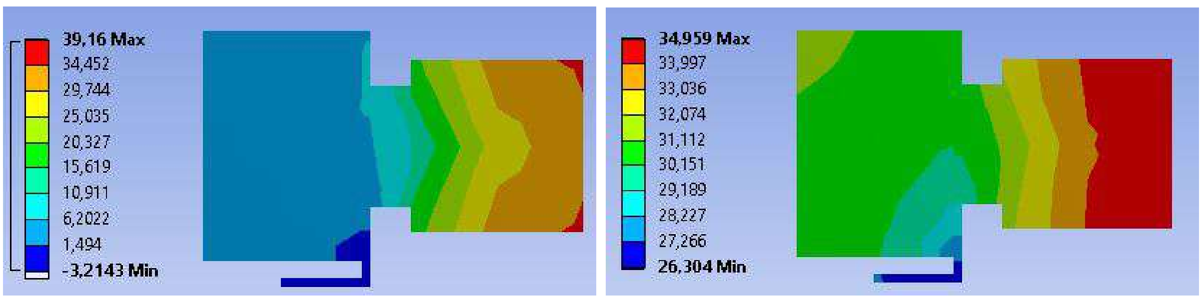


Figure 142: The Pump at the Time to Sample During Ascent (left) and Descent (right).

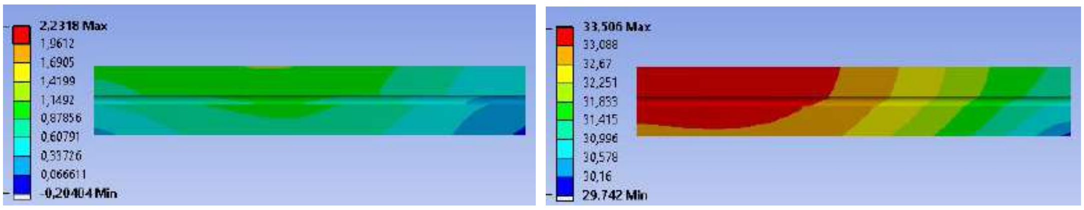


Figure 143: The manifold at the Time to Sample During Ascent (left) and Descent (right).

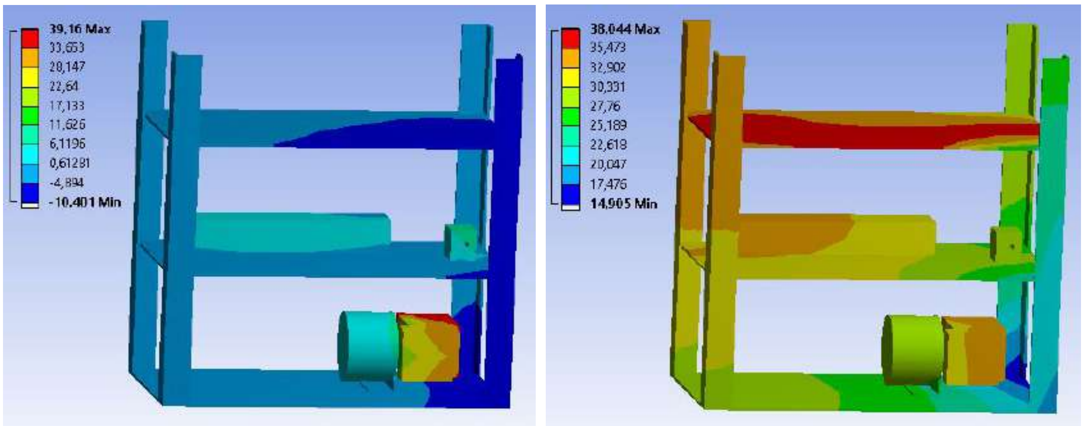


Figure 144: The Structure of the Brain at the Time to Sample During Ascent (left) and Descent (right).

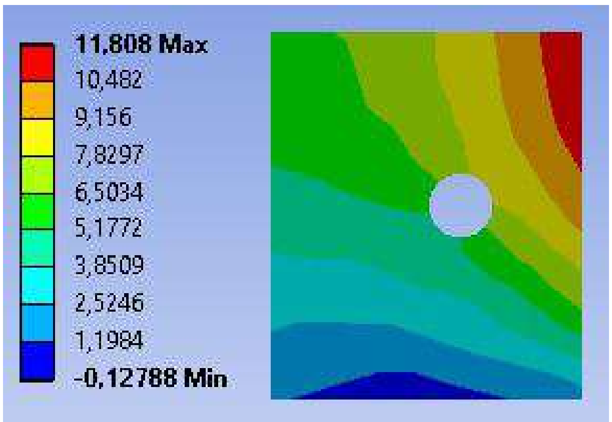


Figure 145: Flushing Valve a Little Before Sampling Shall Start.

I.6 Result

The main objective from first performing the MATLAB calculations and then the ANSYS simulations was to find the wall thickness of Styrofoam between the Brain and the inside of the AAC box and make updated iterations of the result. The next objective was to iterate the design by adding heaters to find the required amount and find approximately how long they need to run. By running a transient thermal analysis for the test flight it was possible to simulate heaters that will be on and off to determine how strong they need to be.

The results from the ANSYS simulations assumed a worst case scenario. It was to be expected that the results were not fully accurate, and instead were slightly warmer in reality. The worst case was with air inside the experiment at normal density. In reality when it was time to sample (at 17km), the air density would be less then 15% of the air density at sea level [22]. This meant that there would be less heat loss from components to the air inside the brain than predicted. Figures 138 and 139 show that the temperature of the pump was above $5°C$ and the manifold was above $-10°C$. It was only during a portion of the Ascent Phase, just prior to the start of sampling that the heater would need to be on in order for the pump to be above $5°C$, and it would only need to be on during this Phase. By having a heater on the flushing valve and the manifold it was possible to get all the valves to the operating temperature. The flushing tube that led out to the open air outside would cool down the flushing valve, so a heater there to compensate for the heat loss would be required. It would then be time to flush right before sample can be seen in Figure 145. The manifold would still need a heater because it will be affected by the cold outer air and help heat up all the components.

The insulation for the AAC used is specified in Table 75. For the three inner walls between the Brain and the bags there was a $0.03m$ long wall of Styrofoam. Two $5\,W$ heaters for the pump (one on top and one on bottom side), a 5 W heater for the flushing valve and one for the manifold were used. The thermal simulations predicted that they would be within the operating limits with a satisfactory margin. For the heater controller, it would be set such that if the pump fell below $15°C$, it would turn on. As for the flushing valve, the heater would be set to turn on if the flushing valve and manifold fell below $-5°C$.

Appendix J Thermal Analysis MATLAB Code

J.1 Convection MATLAB Code

```
%% Reynolds Number for Forced Convection

Re_v = 6;
Re_D = 0.4;
Re_rho = 1.225;
Re_mu = 1.764e5;

Re = (Re_v * Re_D * Re_rho)/Re_mu;

if Re < 2300
    n = 0.25
else
    n = 0.333333
end


%% Forced Convection

n = 0.25;
rho_sea = 1.225;
rho_alt = 0.0400; %At 25 km
k_alt = 0.02281;
k_sea = 0.02436;
beta_sea = 0.00369;
mu_sea = 1.710e-05;
mu_alt = 1.610e-05;
cp_alt = 1006.0;
cp_sea = 1003.7;
T_sea_cold = 263;
T_sea_exp = 273;
T_sea_hot = 283;
T_5_cold = 228;
T_5_exp = 263;
T_5_hot = 273;
T_10_cold = 193;
T_10_exp = 223;
T_10_hot = 238;
T_15_cold = 193;
T_15_exp = 233;
T_15_hot = 253;
T_20_cold = 213;
T_20_exp = 243;
T_20_hot = 268;
T_alt_cold = 223; % 25 km
T_alt_exp = 253;
T_alt_hot = 273;

F = ((k_alt/k_sea)^(1-n)) * ((beta_alt/beta_sea)*(mu_sea/mu_alt)*(cp_alt/
    cp_sea)*(((T_alt_exp)/(T_sea_exp))^2))^n

P_sea = 101300;
deltaT_sea = 10;
```

```
P_alt = 2549; %at 25 km
P_5 = 54050;
P_10 = 26500;
P_15 = 12110;
P_20 = 5529;
deltaT_alt = 20; % Assumed from surface temperature at 25000 km from previous main Thermal script.

h_ratio = (((P_alt)/(P_sea))^(2*n)) * ((deltaT_alt/deltaT_sea)^n) * F
```

The resulting $h - ratio$ is then applied to the value of K in the main script written below:

J.2 Main Thermal MATLAB Code

```
%Erik test earlier version
clear all

%Trial v1.2 ,Erik
%Variables:
Area_outside=2*0.5*0.4 + 2*0.5*0.5 + 2*0.5*0.4;
Area_inside=2*(0.5-0.04)*(0.4-0.04) + 2*(0.5-0.06)*(0.5-0.06) + 2*(0.5-0.04)*(0.4-0.04);
alpha_al = 0.3;                         %Absorbity of aluminium
S = 1362*cosd(15);                      %Solar constant
A_sun = (0.5*0.4+0.4*0.49)*cosd(45);    %Area affectd by the sun
Albedo = 0.15;                          %The albedo coefficient of earth
A_albedo = Area_outside/2;              %Area affected by the alebedo reflection
e_earth = 0.95;                         %Emissivity of earth
IR = 220;                               %Earth IR
A_IR = Area_outside/2;                  %Area affected by the IR
P = 11.499;                             %Worst Disapated power
P2 = 8.993;                             %Average Disapated power
h = 27.811*0.3392;                      %Convection heat transfere constant
                                        %h=18 ground h=27.811 ascent h=30.33 descent
A_convect = Area_outside;               %Area affected by convection
K = 1;                                  %Factor which decrease convection at high altitude
%TO = ;                                 %Temperature wall outside
%TI = ;                                 %Temperature wall inside
Ta = 223;                               %Ambient temperature outside
sigma = 5.67051*10^-8;                  %Stefan-Boltzmann constant
A_tot = Area_outside;                   %Whole outer area
e_Al = 0.09;                            %Emissivity of aluminium

%Scaling factors IR flux Tground=10C
Qir=e_earth*sigma*273^4;
tau=1.716-0.5*(exp(-0.65*(2.8/101.33))+exp(-0.95*(2.8/101.33)));
Qir_25k=tau*Qir;

%Equations that are used:
%{
Q_sun_Albedo = alpha_al*S*(A_sun+Albedo*A_albedo);
Q_conduction = P; %Assumed steady heat flow through wall
Q_IR = e_earth*A_IR*IR;
```

```
Q_radiation = sigma*e_AL*A_tot*(TO^4 - Ta^4);
Q_convection = (h*A_convect*(TO-Ta))/K;
%}

%%%%
%For the Worst dissipated power
%%%%
%Sides with no sun
syms x positive
outside_temperature = P + e_earth*IR*A_IR == e_Al*sigma*A_tot*((x^4)-(Ta^4)
    ) + (h*A_convect*(x-Ta))/K;
solx = solve(outside_temperature, x);
T_no_sun = vpa(solx);

%Solving TO
syms x positive
outside_temperature = P + e_earth*IR*A_IR + alpha_al*S*(A_sun+Albedo*
    A_albedo) == e_Al*sigma*A_tot*((x^4)-(Ta^4)) + (h*A_convect*(x-Ta))/K;
solx = solve(outside_temperature, x);
TO = vpa(solx);

%Solving TI
%Assume TI is a uniform temperature inside
Lal = 0.002;    %thicknes aluminium
Lps = 0.02;     %thicknes polystyrene foam
Lpe = 0.00;     %thicknes polyethylene foam

kal = 205;      %thermal conductivity aluminium
kps = 0.03;     %thermal conductivity polystyrene foam
kpe = 0.47;     %thermal conductivity polyethylene foam

TI = P*((Lal/(kal*Area_inside))+(Lps/(kps*Area_inside))+(Lpe/(kpe*
    Area_inside))) + TO;
TI_no_sun = P*((Lal/(kal*Area_inside))+(Lps/(kps*Area_inside))+(Lpe/(kpe*
    Area_inside))) + T_no_sun;

%%%%
%For the Average dissipated power
%%%%
%Sides with no sun
syms x positive
outside_temperature = P2 + e_earth*IR*A_IR == e_Al*sigma*A_tot*((x^4)-(Ta
    ^4)) + (h*A_convect*(x-Ta))/K;
solx = solve(outside_temperature, x);
T_no_sun2 = vpa(solx);

%Solving TO
syms x positive
outside_temperature = P2 + e_earth*IR*A_IR + alpha_al*S*(A_sun+Albedo*
    A_albedo) == e_Al*sigma*A_tot*((x^4)-(Ta^4)) + (h*A_convect*(x-Ta))/K;
solx = solve(outside_temperature, x);
TO2 = vpa(solx);

TI2 = P2*((Lal/(kal*Area_inside))+(Lps/(kps*Area_inside))+(Lpe/(kpe*
    Area_inside))) + TO2;
TI_no_sun2 = P2*((Lal/(kal*Area_inside))+(Lps/(kps*Area_inside))+(Lpe/(kpe*
    Area_inside))) + T_no_sun2;
```

```
%Results
TO=TO-273;
TI=TI-273;
Ta=Ta-273;
T_no_sun=T_no_sun-273;
TI_no_sun=TI_no_sun-273;

TO2=TO2-273;
TI2=TI2-273;
T_no_sun2=T_no_sun2-273;
TI_no_sun2=TI_no_sun2-273;
%only use if it is Launch pad, Early ascent, shutdown descent, landed
T_wall_average2=(T_no_sun2+TO2)/2;
T_in_average2=(TI_no_sun2+TI2)/2;
T_wall_average=(T_no_sun+TO)/2;
T_in_average=(TI_no_sun+TI)/2;

Results = [Ta T_wall_average T_in_average ; Ta T_wall_average2
    T_in_average2] %TO TI T_no_sun TI_no_sun

%%%%
%The part to run if a test run with BEXUS 25 data wants to be used.
%%%%
%Testing bexus 25 flight data, Erik
Area_inside=2*(0.5-0.04)*(0.4-0.04) + 2*(0.5-0.06)*(0.5-0.06) +
    2*(0.5-0.04)*(0.4-0.04);

% test CAC
%{
Area_outside=4*0.5*0.25+2*0.5*0.5;
Area_inside=4*(0.5-0.1)*(0.25-0.1)+2*(0.5-0.04)*(0.5-0.1);
A_convect = Area_outside;
A_sun = (0.5*0.5+0.5*0.25)*cosd(45);
A_IR = Area_outside/2;
A_albedo=A_IR;
%}
Allti='Alltitude.txt';
Alltitude=csvread(Allti);
for i=2:1:length(Alltitude)
    if Alltitude(i) < 20
        Alltitude(i)=Alltitude(i-1);
    elseif Alltitude(i) > 30000
        Alltitude(i)=Alltitude(i-1);
    end
end
Alltitude(41948)=Alltitude(41947);
Alltitude(41949)=Alltitude(41947);
Alltitude(41950)=Alltitude(41947);

M='test.txt';
T1=csvread(M);

T1(41948)=T1(41947);
T1(41949)=T1(41947);
T1(41950)=T1(41947);
```

```
j=length(T1)/25
ty=1;
for r=25:25:length(T1)
    T12(ty)=T1(r);
    Alltitude2(ty)=Alltitude(r);
    ty=ty+1;
end

for i=1:1:length(T12)
    h=18;
    if Alltitude2(i) < 400
        h=18*1;
        P=0.075+10;
    elseif Alltitude2(i) > 400 && Alltitude2(i) < 5000
        h=27.811*1;
        P=0.075+10;
    elseif Alltitude2(i) > 5000 && Alltitude2(i) < 10000
        h=27.811*0.7962;
        P=0.075+10;
    elseif Alltitude2(i) > 10000 && Alltitude2(i) < 15000
        h=27.811*0.5134;
        P=0.075+10;
    elseif Alltitude2(i) > 15000 && Alltitude2(i) < 20000
        h=27.811*0.3392;
        P=7.5+10+5;
    elseif Alltitude2(i) > 20000 && Alltitude2(i) < 23500
        h=27.811*0.2292;
        P=7.5+10+5;
    elseif Alltitude2(i) > 23500
        h=18*0.1592;
        P=0.075;
    end


%Solving TO
syms x positive
outside_temperature = P + e_earth*IR*A_IR + alpha_al*S*(A_sun+Albedo*
    A_albedo) == e_Al*sigma*A_tot*((x^4)-(T12(i)^4)) + (h*A_convect*(x-T12(i
    )))/K;
solx = solve(outside_temperature, x);
TO(i) = vpa(solx);

%Solving TI
%Assume TI is a uniform temperature inside
Lal = 0.002; %thicknes aluminium
Lps = 0.02; %thicknes polystyrene foam
Lpe = 0.00; %thicknes polyethylene foam

kal = 205; %thermal conductivity aluminium
kps = 0.03; %thermal conductivity polystyrene foam
kpe = 0.47; %%thermal conductivity polyethylene foam

TI(i) = P*((Lal/(kal*Area_inside))+(Lps/(kps*Area_inside))+(Lpe/(kpe*
    Area_inside))) + TO(i);

syms x positive
outside_temperature = P + e_earth*IR*A_IR == e_Al*sigma*A_tot*((x^4)-(T12(i
```

```
    )^4)) + (h*A_convect*(x-T12(i)))/K;
sol = solve(outside_temperature, x);
TO2(i) = vpa(sol);

TI2(i) = P*((Lal/(kal*Area_inside))+(Lps/(kps*Area_inside))+(Lpe/(kpe*
    Area_inside))) + TO2(i);

TI(i)=TI(i)-273;
T12(i)=T12(i)-273;
TI2(i)=TI2(i)-273;
if Alltitude2(i) < 10000
     Tmid(i)=(TI(i)+TI2(i))/2;
else
     Tmid(i)=TI2(i);
end
i
end
%{
figure(1)
plot(TI,Alltitude2,'b',T12,Alltitude2,'k',TI2,Alltitude2,'g')
xlabel('Temperature (Kelvin)');
ylabel('Altitude (m)')
legend('Sun all the way','Bexus 25 flight data','No sun all the way')
figure(2)
plot(TI,Alltitude2,'b',T12,Alltitude2,'k',TI2,Alltitude2,'g')
xlabel('Temperature (Celcius)');
ylabel('Altitude (m)')
legend('Sun all the way','Bexus 25 flight data','No sun all the way')
%}
figure(3)
plot(Tmid,Alltitude2,'b',T12,Alltitude2,'k')
xlabel('Temperature (Celcius)');
ylabel('Altitude (m)')
legend('TUBULAR test flight','Bexus 25 flight data')
%}
```

Appendix K Budget Allocation and LaTeX Component Table Generator Google Script Code

K.1 Budget Allocation Code

```
// Define constants for range and cell locations.
var COLUMN_RANGE_SPONSOR = 'K5:K221';
var COLUMN_RANGE_COST = 'J5:J221';

var CELL_SHIPPING_COST = 'J224';
var CELL_ERROR_MARGIN_COST = 'J225';

var CELL_SPONSOR_SHIPPING = 'K224';
var CELL_SPONSOR_ERROR_MARGIN = 'K225';

var CELL_SHIPPING_COST_PERCENTAGE = 'F233';
var CELL_ERROR_MARGIN_PERCENTAGE = 'F234';


// Mapping between sponsors and the total allocated funds cell
var SPONSORS_TOTAL_ALLOCATION_CELL_DICT = {
  'LTU': 'G239',
  'SNSA': 'G240',
  'FMI': 'G241',
  'RESTEK': 'G242',
  'TEKNOLAB': 'G243',
  'SMC': 'G244',
  'PARKER': 'G245',
  'SWAGELOK': 'G246',
  'KNF': 'G247',
  'SILCOTEK': 'G248',
  'EUROCIRCUITS': 'G249'
  };

// Sheet and ranges.
var sheet = SpreadsheetApp.getActiveSpreadsheet();
var rangeSponsor = sheet.getRange(COLUMN_RANGE_SPONSOR);
var rangeCost = sheet.getRange(COLUMN_RANGE_COST);

/**
 * Iterator through all the item/coponent rows in the budget table
 * and sum to total cost sponsored by a given sponser.
 */
function calculateSponsorBudgetAllocation_(sponsor) {

  var numRows = rangeSponsor.getNumRows();
  var totalAmountSponsored = 0;

  for (var i = 1; i <= numRows; i++) {
    var componentSponsor = rangeSponsor.getCell(i,1).getValue();
    if(componentSponsor == sponsor){
      var amountSponsored = rangeCost.getCell(i,1).getValue();
      totalAmountSponsored = totalAmountSponsored + amountSponsored;
    }
  }
```

```

  var cell = sheet.getRange(SPONSORS_TOTAL_ALLOCATION_CELL_DICT[sponsor]);
  cell.setValue(totalAmountSponsored);

  return totalAmountSponsored;
}


/**
 * Allocate shipping cost to a given sponsor.
 */
function allocateShippingCostToSponsor_(shippingCost, sponsor){
  var cell = sheet.getRange(CELL_SPONSOR_SHIPPING);
  cell.setValue(sponsor);

  allocateExtraCostToSponsor_(shippingCost, sponsor)
}

/**
 * Allocate error margin cost to a given sponsor.
 */
function allocateErrorMarginCostToSponsor_(errorMarginCost, sponsor){
  var cell = sheet.getRange(CELL_SPONSOR_ERROR_MARGIN);
  cell.setValue(sponsor);

  allocateExtraCostToSponsor_(errorMarginCost, sponsor)
}

/**
 * Allocate extra cost to a given sponsor.
 */
function allocateExtraCostToSponsor_(extraCost, sponsor){
  var costAllocatedToSponsorCell = sheet.getRange(
      SPONSORS_TOTAL_ALLOCATION_CELL_DICT[sponsor]);
  costAllocatedToSponsorCell.setValue(costAllocatedToSponsorCell.getValue()
       + extraCost);
}


/**
 * Calculate sponsorship allocation of funds for all sponsors.
 */
function calculateAllSponsorBudgetAllocations(){
  var amountLTU = calculateSponsorBudgetAllocation_('LTU');
  var amountSNSA = calculateSponsorBudgetAllocation_('SNSA');
  var amountFMI = calculateSponsorBudgetAllocation_('FMI');
  var amountRESTEK = calculateSponsorBudgetAllocation_('RESTEK');
  var amountTEKNOLAB = calculateSponsorBudgetAllocation_('TEKNOLAB');
  var amountSMC = calculateSponsorBudgetAllocation_('SMC');
  var amountPARKER = calculateSponsorBudgetAllocation_('PARKER');
  var amountSWAGELOK = calculateSponsorBudgetAllocation_('SWAGELOK');
  var amountKNF = calculateSponsorBudgetAllocation_('KNF');
  var amountSILCOTEK = calculateSponsorBudgetAllocation_('SILCOTEK');
  var amountEUROCIRCUITS = calculateSponsorBudgetAllocation_('EUROCIRCUITS'
      );

  // Calculate error margin.
```

```
  // Error margin only applies to components purchased with LTU and SNSA funds.
  // This is because other sponsorships are not based on funds but on components donated.
  var errorMarginPercentage = sheet.getRange(CELL_ERROR_MARGIN_PERCENTAGE).getValue();
  var errorMarginCost = errorMarginPercentage * (amountLTU + amountSNSA);
  var cell = sheet.getRange(CELL_ERROR_MARGIN_COST);
  cell.setValue(errorMarginCost);

  // Calculate shipping cost.
  // Treat the shipping cost the same way as error margin.
  // only applies to components purchased with LTU and SNSA funds.
  var shippingCostPercentage = sheet.getRange(CELL_SHIPPING_COST_PERCENTAGE).getValue();
  var shippingCost = shippingCostPercentage * (amountLTU + amountSNSA);
  var cell = sheet.getRange(CELL_SHIPPING_COST);
  cell.setValue(shippingCost);

  // Allocate shipping and error costs to specific sponsor.
  allocateShippingCostToSponsor_(shippingCost, 'SNSA');
  allocateErrorMarginCostToSponsor_(errorMarginCost, 'SNSA');
}
```

K.2 Latex Component Table Generator

```
RANGE_TABLE = 'B5:P226';

var sheet = SpreadsheetApp.getActiveSpreadsheet();
var tableRange = sheet.getRange(RANGE_TABLE);

/**
 * Generate all component tables.
 */
function generateAllComponentTables(){
  generateTable_('M', 'Mechanical Components Table', 'tab:components-table-mechanical', 'E300');
  generateTable_('E', 'Electrical Components Table', 'tab:components-table-electrical', 'E302');
  generateTable_('O', 'Other Components Table', 'tab:component-table-other', 'E304');
}

/**
 * Generate speficic component table based on provided arguments.
 */
function generateTable_(divisionCode, caption, label, outputCell) {

  var header = '\\ begin{longtable} ' +
  '{|m{0.05\\ textwidth}|m{0.25\\ textwidth}|m{0.15\\ textwidth}|m{0.2\\ textwidth}|m{0.05\\ textwidth}|m{0.07\\ textwidth}|m{0.07\\ textwidth}|m{0.25\\ textwidth}|m{0.11\\ textwidth}||} ' +
  '\\ hline ' +
  '\\ textbf{ID} & \\ textbf{Component Name} & \\ textbf{Manufacturer} & \\ textbf{Manufacturer Code} & \\ textbf{Qty} & \\ textbf{Total Mass [g]} & \\ textbf{Total Cost [Eur]}  & \\ textbf{Note}  & \\ textbf{Status} \\\\  \\ hline ';

  var footer = '\\ caption{' + caption + '} ' +
    '\\ label{' + label + '} ' +
    '\\ end{longtable} ' +
    '\\ raggedbottom';

  var rowArray = new Array();

  var numRows = tableRange.getNumRows();
  var numCols = tableRange.getNumColumns();

  for (var i = 1; i <= numRows; i++) {
    var id = tableRange.getCell(i, 13).getValue();

    if(id.toString().indexOf(divisionCode) == 0){

      var itemNumber = tableRange.getCell(i, 1).getValue();
      var itemSubNumber = '';
      var component = tableRange.getCell(i, 2).getValue();

      if(itemNumber == ''){
        itemSubNumber = tableRange.getCell(i, 2).getValue();
        component = tableRange.getCell(i, 3).getValue();
      }
```

```
      var manufacturerCode = tableRange.getCell(i, 4).getValue();
      var quantity = tableRange.getCell(i, 5).getValue();

      var unitMass = tableRange.getCell(i, 6).getValue();
      if (unitMass != 'n/a' && totalMass != '' && totalMass != '-'){
        unitMass = significantFigure_(unitMass, 2);
      }

      var unitCost = tableRange.getCell(i, 7).getValue();
      if (unitCost != 'n/a' && unitCost != '' && unitCost != '-'){
        unitCost = significantFigure_(unitCost, 2);
      }

      var totalMass = tableRange.getCell(i, 8).getValue();
      if (totalMass != 'n/a' && totalMass != '' && totalMass != '-'){
        totalMass = significantFigure_(totalMass, 2);
      }

      var totalCost = tableRange.getCell(i, 9).getValue();
      if (totalCost != 'n/a' && totalCost != '' && totalCost != '-'){
        totalCost = significantFigure_(totalCost, 2);
      }

      var sponsor = tableRange.getCell(i, 10).getValue();
      var manufacturer = tableRange.getCell(i, 12).getValue();
      var status = tableRange.getCell(i, 14).getValue();
      var note = tableRange.getCell(i, 15).getValue();

      var key = padStart_(id.substr(1), 2, "0")
      rowArray[key] = '' + id + ' & ' + component + ' & ' + manufacturer + ' & ' + manufacturerCode + ' & '  + quantity + ' & ' + totalMass + ' & ' + totalCost + ' & ' + note + ' & ' + status + ' \\\\  \\hline ';

    }

  }

  // Make sure that rows are sorted by their Component IDs.
  var rowBuffer = '';
  var sortedComponentIds = keys_(rowArray, true);
  for (var i = 0; i < sortedComponentIds.length; i++) {
    rowBuffer = rowBuffer + rowArray[sortedComponentIds[i]];
  }

  // Building LaTeX string for the entire component table.
  var completeTable = header + rowBuffer + footer;
  completeTable = completeTable.replace(/\\ /g, '\\');

  // Output to spreadsheet so it can be copy and pasted into SED.
  var cell = sheet.getRange(outputCell);
  cell.setValue(completeTable);

  return completeTable
}
```

```
/**
 * Get keys of an array
 */
function keys_(obj, sorted){
    var keys = [];
    for(var key in obj){
        if(obj.hasOwnProperty(key)){
            keys.push(key);
        }
    }

    if(sorted){
      return keys.sort();

    }else{
      return keys;
    }
}

/**
 * Format numbers
 */
function significantFigure_(n, sig) {
  var mult = Math.pow(10, sig - Math.floor(Math.log(n) / Math.LN10) - 1);
  return Math.round(n * mult) / mult;
}

/**
 * The padStart() method pads the current string with another string (repeated, if needed)
 * so that the resulting string reaches the given length. The padding is applied from
 * the start (left) of the current string.
 *
 * Source code taken from here:
 * https://developer.mozilla.org/en-US/docs/Web/JavaScript/Reference/Global_Objects/String/padStart
 */
function padStart_(str, targetLength, padString) {
  targetLength = targetLength >> 0; // truncate if number or convert non-number to 0;
  padString = String((typeof padString !== 'undefined' ? padString : ' '));

  if (str.length > targetLength){
    return String(str);

  }else {

    targetLength = targetLength - str.length;
    if (targetLength > padString.length) {
      //append to original to ensure we are longer than needed
      padString += padString.repeat(targetLength/padString.length);
    }

    return padString.slice(0, targetLength) + String(str);
  }
}
```

Appendix L Center of Gravity Computation

The Center of Gravity of the experiment has been calculated considering all the components' mass listed in Section 4.3.

L.1 Code

```
%%-------------------------------------------------------------------------
%   TUBULAR COG (Center Of Gravity)
%%-------------------------------------------------------------------------
%   Date: May 2018
%%-------------------------------------------------------------------------

clear all
close all
clc

%% Data
m_CAC_valves = 850; %[g]
m_cub = 10; %[g]
m_aircoil = 5049; %[g]
m_profile = 4; %[g/cm]
m_Tunion = 71; %[g]
d_styro = 0.028; %[g/cm3]
d_al = 2.67; %[g/cm3]
m_brain1 = 687; %[g]
m_brain2 = 1522; %[g]
m_brain3 = 285; %[g]

%% CAC
% X-axis
m1_CAC = 2*m_cub+m_profile*19;
m2_CAC = m1_CAC;
m3_CAC = m1_CAC;
m4_CAC = m1_CAC;
m5_CAC = m_profile*46;
m6_CAC = m5_CAC;
m7_CAC = m5_CAC;
m8_CAC = m5_CAC;
m9_CAC = m_aircoil;
m10_CAC = (22*pi*25^2-15*pi*20^2)*d_styro;
m11_CAC = m_CAC_valves;
mT_CAC = m1_CAC+m2_CAC+m3_CAC+m4_CAC+m5_CAC+m6_CAC+m7_CAC+m8_CAC+m9_CAC+
    m10_CAC+m11_CAC;

X1_CAC = 1;
X2_CAC = 49;
X3_CAC = 1;
X4_CAC = 49;
X5_CAC = 25;
X6_CAC = 1;
X7_CAC = 49;
X8_CAC = 25;
X9_CAC = 25;
```

```
X10_CAC = 25;
X11_CAC = 11.5;

XG_CAC = (m1_CAC*X1_CAC+m2_CAC*X2_CAC+m3_CAC*X3_CAC+m4_CAC*X4_CAC+m5_CAC*
    X5_CAC+m6_CAC*X6_CAC+m7_CAC*X7_CAC+m8_CAC*X8_CAC+m9_CAC*X9_CAC+m10_CAC*
    X10_CAC+m11_CAC*X11_CAC)/mT_CAC;

% Y-axis
m1_CAC = 2*m_cub+m_profile*46;
m2_CAC = m1_CAC;
m3_CAC = m1_CAC;
m4_CAC = m1_CAC;
m5_CAC = m_profile*19;
m6_CAC = m5_CAC;
m7_CAC = m5_CAC;
m8_CAC = m5_CAC;
m9_CAC = m_aircoil;
m10_CAC = (22*pi*25^2-15*pi*20^2)*d_styro;
m11_CAC = m_CAC_valves;
mT_CAC = m1_CAC+m2_CAC+m3_CAC+m4_CAC+m5_CAC+m6_CAC+m7_CAC+m8_CAC+m9_CAC+
    m10_CAC+m11_CAC;

Y1_CAC = 22;
Y2_CAC = 1;
Y3_CAC = 22;
Y4_CAC = 1;
Y5_CAC = 11.5;
Y6_CAC = 22;
Y7_CAC = 1;
Y8_CAC = 11.5;
Y9_CAC = 9.5;
Y10_CAC = 20;
Y11_CAC = 3;

YG_CAC = (m1_CAC*Y1_CAC+m2_CAC*Y2_CAC+m3_CAC*Y3_CAC+m4_CAC*Y4_CAC+m5_CAC*
    Y5_CAC+m6_CAC*Y6_CAC+m7_CAC*Y7_CAC+m8_CAC*Y8_CAC+m9_CAC*Y9_CAC+m10_CAC*
    Y10_CAC+m11_CAC*Y11_CAC)/mT_CAC;

% % Z-axis
m1_CAC = 2*m_cub+m_profile*19;
m2_CAC = m1_CAC;
m3_CAC = m1_CAC;
m4_CAC = m1_CAC;
m5_CAC = m_profile*46;
m6_CAC = m5_CAC;
m7_CAC = m5_CAC;
m8_CAC = m5_CAC;
m9_CAC = m_aircoil;
m10_CAC = (22*pi*25^2-15*pi*20^2)*d_styro;
m11_CAC = m_CAC_valves;
mT_CAC = m1_CAC+m2_CAC+m3_CAC+m4_CAC+m5_CAC+m6_CAC+m7_CAC+m8_CAC+m9_CAC+
    m10_CAC+m11_CAC;

Z1_CAC = 49;
Z2_CAC = 49;
Z3_CAC = 1;
Z4_CAC = 1;
```

```
Z5_CAC = 49;
Z6_CAC = 25;
Z7_CAC = 25;
Z8_CAC = 1;
Z9_CAC = 25;
Z10_CAC = 25;
Z11_CAC = 3;

ZG_CAC = (m1_CAC*Z1_CAC+m2_CAC*Z2_CAC+m3_CAC*Z3_CAC+m4_CAC*Z4_CAC+m5_CAC*
    Z5_CAC+m6_CAC*Z6_CAC+m7_CAC*Z7_CAC+m8_CAC*Z8_CAC+m9_CAC*Z9_CAC+m10_CAC*
    Z10_CAC+m11_CAC*Z11_CAC)/mT_CAC;


%% AAC
% X-axis
m1_AAC = 2*m_cub+m_profile*46;
m2_AAC = m1_AAC;
m3_AAC = m1_AAC;
m4_AAC = m1_AAC;
m5_AAC = m_profile*46 +3*46*46*d_styro;
m6_AAC = m_profile*36 +3*36*46*d_styro;
m7_AAC = m6_AAC;
m8_AAC = m5_AAC;
m9_AAC = m_brain3;
m10_AAC = m_brain2;
m11_AAC = m_brain1;
m12_AAC = m_Tunion;
m13_AAC = m12_AAC;
m14_AAC = m12_AAC;
m15_AAC = m12_AAC;
m16_AAC = m12_AAC;
m17_AAC = m12_AAC;

mT_AAC = m1_AAC+m2_AAC+m3_AAC+m4_AAC+m5_AAC+m6_AAC+m7_AAC+m8_AAC+m9_AAC+
    m10_AAC+m11_AAC+m12_AAC+m13_AAC+m14_AAC+m15_AAC+m16_AAC+m17_AAC;

X1_AAC = 1;
X2_AAC = 49;
X3_AAC = 1;
X4_AAC = 49;
X5_AAC = 25;
X6_AAC = 1;
X7_AAC = 49;
X8_AAC = 25;
X9_AAC = 33.5;
X10_AAC = 33.5;
X11_AAC = 33.5;
X12_AAC = 41.67;
X13_AAC = 12.5;
X14_AAC = 33.33;
X15_AAC = 25;
X16_AAC = 16.67;
X17_AAC = 8.33;

XG_AAC = (m1_AAC*X1_AAC+m2_AAC*X2_AAC+m3_AAC*X3_AAC+m4_AAC*X4_AAC+m5_AAC*
    X5_AAC+m6_AAC*X6_AAC+m7_AAC*X7_AAC+m8_AAC*X8_AAC+m9_AAC*X9_AAC+m10_AAC*
    X10_AAC+m11_AAC*X11_AAC+m12_AAC*X12_AAC+m13_AAC*X13_AAC+m14_AAC*X14_AAC+
```

```
    m15_AAC*X15_AAC+m16_AAC*X16_AAC+m17_AAC*X17_AAC)/mT_AAC;

% Y-axis
m1_AAC = 2*m_cub+m_profile*46;
m2_AAC = m1_AAC;
m3_AAC = m1_AAC;
m4_AAC = m1_AAC;
m5_AAC = m_profile*46 +3*46*46*d_styro;
m6_AAC = m_profile*36 +3*36*46*d_styro;
m7_AAC = m6_AAC;
m8_AAC = m5_AAC;
m9_AAC = m_brain3;
m10_AAC = m_brain2;
m11_AAC = m_brain1;
m12_AAC = 5*m_Tunion;
m13_AAC = m_Tunion;

mT_AAC = m1_AAC+m2_AAC+m3_AAC+m4_AAC+m5_AAC+m6_AAC+m7_AAC+m8_AAC+m9_AAC+
    m10_AAC+m11_AAC+m12_AAC+m13_AAC;

Y1_AAC = 1;
Y2_AAC = 49;
Y3_AAC = 1;
Y4_AAC = 49;
Y5_AAC = 25;
Y6_AAC = 1;
Y7_AAC = 49;
Y8_AAC = 25;
Y9_AAC = 7.5;
Y10_AAC = 7.5;
Y11_AAC = 7.5;
Y12_AAC = 31;
Y13_AAC = 17;

YG_AAC = (m1_AAC*Y1_AAC+m2_AAC*Y2_AAC+m3_AAC*Y3_AAC+m4_AAC*Y4_AAC+m5_AAC*
    Y5_AAC+m6_AAC*Y6_AAC+m7_AAC*Y7_AAC+m8_AAC*Y8_AAC+m9_AAC*Y9_AAC+m10_AAC*
    Y10_AAC+m11_AAC*Y11_AAC+m12_AAC*Y12_AAC+m13_AAC*Y13_AAC)/mT_AAC;

% Z-axis
m1_AAC = 2*m_cub+m_profile*46;
m2_AAC = m1_AAC;
m3_AAC = m1_AAC;
m4_AAC = m1_AAC;
m5_AAC = m_profile*46 +3*46*46*d_styro;
m6_AAC = m_profile*36 +3*36*46*d_styro;
m7_AAC = m6_AAC;
m8_AAC = m5_AAC;
m9_AAC = m_brain3;
m10_AAC = m_brain2;
m11_AAC = m_brain1;
m12_AAC = 5*m_Tunion;
m13_AAC = m_Tunion;

mT_AAC = m1_AAC+m2_AAC+m3_AAC+m4_AAC+m5_AAC+m6_AAC+m7_AAC+m8_AAC+m9_AAC+
    m10_AAC+m11_AAC+m12_AAC+m13_AAC;

Z1_AAC = 39;
```

```
Z2_AAC = 39;
Z3_AAC = 1;
Z4_AAC = 1;
Z5_AAC = 39;
Z6_AAC = 20;
Z7_AAC = 20;
Z8_AAC = 1;
Z9_AAC = 24.5;
Z10_AAC = 15.5;
Z11_AAC = 6.5;
Z12_AAC = 10;
Z13_AAC = Z12_AAC;

ZG_AAC = (m1_AAC*Z1_AAC+m2_AAC*Z2_AAC+m3_AAC*Z3_AAC+m4_AAC*Z4_AAC+m5_AAC*
    Z5_AAC+m6_AAC*Z6_AAC+m7_AAC*Z7_AAC+m8_AAC*Z8_AAC+m9_AAC*Z9_AAC+m10_AAC*
    Z10_AAC+m11_AAC*Z11_AAC+m12_AAC*Z12_AAC+m13_AAC*Z13_AAC)/mT_AAC;

%% TOTAL
m_AAC= 12370;
m_CAC= 12080;
mT_TOTAL= m_AAC+m_CAC;

% X-axis
XG_TOTAL = (m_AAC*XG_AAC+m_CAC*XG_CAC)/mT_TOTAL;
% Y-axis
YG_TOTAL = (m_AAC*(YG_AAC+23)+m_CAC*YG_CAC)/mT_TOTAL;
% Z-axis
ZG_TOTAL = (m_AAC*ZG_AAC+m_CAC*ZG_CAC)/mT_TOTAL;
```

Appendix M Budget Spreadsheets

M.1 Structure

	Manufacturer Code	Quantity	Mass/Unit [g]	Cost/Unit [€]	Total Mass [g]	Total Cost [€]	Sponsor
1 STRUCTURE					**11,900.64**	**€851.57**	
1.1 Strut profile 20x20 M6/M6, length: 460 mm	3842993231	16	184.00	€5.81	2,944.00	€93.02	SNSA
1.2 Strut profile 20x20 M6/M6, length: 360 mm	3842993231	4	144.00	€5.45	576.00	€21.82	SNSA
1.3 Strut profile 20x20 M6/M6, length: 190 mm	3842993231	4	76.00	€5.14	304.00	€20.54	SNSA
1.4 T-nut N6 M4	3842536599	100	3.00	€0.74	300.00	€74.40	SNSA
1.5 Sliding block N6 M4	3842523140	100	3.00	€0.90	300.00	€90.00	LTU
1.5.1 Spares	3842523140	100	-	€0.90	-	€90.00	LTU
1.6 Bracket standard 20x20 N6/6	3842523508	100	5.00	€0.52	500.00	€51.56	SNSA
1.7 Variofix block S N6 20x20	3842548836	100	5.00	€0.62	500.00	€61.80	SNSA
1.8 Cubic connector 20/3 N6	3842523872	16	10.00	€1.97	160.00	€39.36	SNSA
1.9 Strap-shaped handle	3842518738	4	20.00	€1.88	80.00	€18.78	SNSA
1.10 Retainer ring M4	3842542328	100	0.50	€0.05	50.00	€5.40	SNSA
1.11 DIN 7984 M4x8 bolts	n/a	150	1.00	€0.00	150.00	€0.00	LTU LAB
1.12 M6x16 bolts	79850616	48	5.00	€0.13	240.00	€6.24	SNSA
1.13 ISO 4762 bolts	n/a	8	2.00	€0.00	16.00	€0.00	LTU LAB
1.14 Washers	n/a	20	0.20	€0.00	4.00	€0.00	LTU LAB
1.15 Aluminum sheets	204599	1	2,500.00	€24.50	2,500.00	€24.50	SNSA
1.16 Styrofoam 250 SL-A-N	3542005000	1	1,800.00	€96.99	1,800.00	€96.99	SNSA
1.17 Fixing bar for the bags	n/a	2	13.00	€3.00	26.00	€6.00	SNSA
1.18 Flat plate interface for fixing bar	n/a	4	32.00	€0.00	128.00	€0.00	SNSA
1.19 CAC-AAC interface 6-hole plate	n/a	4	16.40	€0.00	65.60	€0.00	SNSA
1.20 The Brain							
1.20.1 Aluminum sheets	204599	1	101.84	€1.02	101.84	€1.02	SNSA
1.20.2 DIN 7984 M4x8 bolts	n/a	26	1.00	€0.00	26.00	€0.00	LTU LAB
1.20.3 DIN 7984 M4x30 bolts	n/a	16	2.00	€0.00	32.00	€0.00	LTU LAB
1.20.4 Nut M4	n/a	42	1.00	€0.00	42.00	€0.00	LTU LAB
1.20.5 Styrofoam (bulk - 1 piece from 1.16)	3542005000	1	112.00	-	112.00	€0.00	LTU LAB
1.20.6 15mm M3 Standoff/Spacer for PCB	24339	10	2.00	€0.78	20.00	€7.80	SNSA
1.20.7 Lock nut M3 (DIN985) for PCB	n/a	5	1.00	€0.00	5.00	€0.00	LTU LAB
1.20.8 M3 Cheese Head Screws 6mm	n/a	5	0.80	€0.00	4.00	€0.00	LTU LAB
1.20.9 Strut profile 20x20 M6/M6, length: 360 mm	3842992888	2	144.00	€3.00	288.00	€6.00	SNSA
1.20.10 Strut profile 20x20 M6/M6, length: 170 mm	3842992888	2	68.00	€2.27	136.00	€4.53	SNSA
1.20.11 Strut profile 20x20 M6/M6, length: 263 mm	3842993230	1	105.20	€4.20	105.20	€4.20	SNSA
1.21 Sliding block N8 M6	3842547815	10	3.00	€1.10	30.00	€11.00	SNSA
1.21.1 Spares	3842547815	90	-	€1.10	-	€99.00	SNSA
1.22 Steel sheet 500x250x0.75mm	n/a	3	0.00	€5.87	0.00	€17.60	SNSA
1.23 Rubber bumper	n/a	10	35.50	€0.00	355.00	€0.00	LTU LAB

Figure 146: Budget Table for Structure Components.

M.2 Electronics Box

	Manufacturer Code	Quantity	Mass/Unit [g]	Cost/Unit [€]	Total Mass [g]	Total Cost [€]	Sponsor
2 ELECTRONIC BOX					**521.50**	**€1,618.12**	
2.1 Arduino Due with headers							
2.1.1 Arduino Due with headers	A000062	1	36.00	€35.00	36.00	€35.00	SNSA
2.1.2 Testing / Spare	A000062	2	-	€33.58	-	€67.17	SNSA
2.2 Ethernet Shield	SKU 103030021	1	36.00	€28.00	36.00	€28.00	SNSA
2.2.1 Spare	SKU 103030021	2	-	€28.00	-	€56.00	SNSA
2.3 Heater							
2.3.1 *Heater*	HK5160R157L12	4	4.00	€95.00	16.00	€380.00	SNSA
2.3.2 Testing / Spare	HK5160R157L12	1	-	€95.00	-	€95.00	SNSA
2.4 DC/DC converter 24 V							
2.4.1 *DC/DC converter 24 V*	S24SP24003PDFA	2	46.00	€49.00	92.00	€98.00	SNSA
2.4.2 Testing / Spare		3	-	€49.00	-	€147.00	SNSA
2.5 MicroSD	SDCIT/16GB	1	0.50	€20.00	0.50	€20.00	SNSA
2.5.1 Spare	SDCIT/16GB	1	-	€20.00	-	€20.00	SNSA
2.6 Logic CAT5E Network	VLCT85000Y30	1	90.00	€7.00	90.00	€7.00	SNSA
2.7 DC/DC converter 12 V							
2.7.1 DC/DC converter 12 V	R-7812-0.5	2	20.00	€34.00	40.00	€68.00	LTU
2.7.2 Testing / Spare	R-7812-0.5	3	-	€34.00	-	€102.00	LTU
2.8 PCB board	n/a	1	100.00	€178.20	100.00	€178.20	EUROCIRCUITS
2.8.1 Spare	n/a	1	-	€178.20	-	€178.20	EUROCIRCUITS
2.9 Pressure sensor PCB	n/a	3	25.00	€14.11	75.00	€42.33	EUROCIRCUITS
2.9.1 Spares	n/a	2	-	€14.11	-	€28.22	EUROCIRCUITS
2.10 Arduino Due without headers	2	1	36.00	€34.00	36.00	€34.00	LTU
2.10.1 Testing / Spare	A000056	1	-	€34.00	-	€34.00	LTU

Figure 147: Budget Table for Electronics Box Components.

M.3 Cables and Sensors

	Manufacturer Code	Quantity	Mass/Unit [g]	Cost/Unit [€]	Total Mass [g]	Total Cost [€]	Sponsor
3 CABLES AND SENSORS					**1,176.62**	**€696.08**	
3.1 Temperature sensor							
3.1.1 Temperature sensor	DS1631+-ND	8	2.00	€3.00	16.00	€24.00	LTU
3.1.2 Testing / Spare		13	-	€3.00	-	€39.00	SNSA
3.2 Pressure sensor							
3.2.1 Pressure sensor	MS560702BA03-50	4	5.00	€2.30	20.00	€9.20	SNSA
3.2.2 Testing / Spare		8	-	€2.30	-	€18.40	SNSA
3.3 Airflow sensor	AWM5102VN	1	60.00	€132.00	60.00	€132.00	LTU
3.4 Humidity sensor(NBU)	HDC2010	3	0.00	€3.00	0.00	€9.00	SNSA
3.7 Resistors	n/a	25	1.00	€0.00	25.00	€0.00	LTU Lab
3.8 Capacitors (0.1 uF, 5uF, 10 uF, 100uF)	n/a	7	1.00	€0.00	7.00	€0.00	LTU Lab
3.10 Mosfets for curent control							
3.10.1 Mosfet for current control	IRLB8748PBF	11	2.00	€0.70	22.00	€7.70	SNSA
3.10.2 Testing / Spare		15	-	€0.70	-	€10.50	SNSA
3.11 Diodes for DCDC converters							
3.11.1 Diodes for DCDC converters	1N5059	4	0.40	€0.10	1.60	€0.40	SNSA
3.11.2 Spare / Testing	1N5059	12	-	€0.10	-	€1.20	SNSA
3.12 LED 3.3 V							
3.12.1 LED 3.3 V	151034GS03000	16	0.40	€0.52	6.40	€8.32	SNSA
3.12.2 Spare/Testing	151034GS03000	22	-	€0.52	-	€11.44	SNSA
3.13 D-SUB connectors							
3.13.1 15-pin D-SUB Female connector with pins	RND 205-00779	2	11.00	€0.75	22.00	€1.50	SNSA
3.13.1 15-pin D-SUB Female connector with pins (Spare)	RND 205-00779	2		€0.75		€1.50	SNSA
3.13.2 9-pin D-SUB Female connector with pins	RND 205-00777	3	8.50	€0.68	25.50	€2.04	SNSA
3.13.2 9-pin D-SUB Female connector with pins (Spare)	RND 205-00777	3		€0.68		€2.04	SNSA
3.12.3 9 pin D-SUB Female connector with soldering cups	RND 205-00704	3	9.00	€0.56	27.00	€1.68	SNSA
3.12.4 9 pin D-SUB Male connector with soldering cups	RND 205-00700	6	9.00	€0.48	54.00	€2.88	SNSA
3.12.5 15-pin D-SUB Male connector with soldering cups	RND 205-00701	2	11.00	€0.60	22.00	€1.20	SNSA
3.12.6 9-pin D-SUB backing	MHDTZK-9-BK-K	6	40.00	€2.86	240.00	€17.16	SNSA
3.12.7 15-pin D-SUB backing	MHDTZK-15-BK-K	2	66.00	€3.06	132.00	€6.12	SNSA
3.12.8 Wall mounting bolts	RND 205-00786	3	2.50	€1.04	7.50	€3.12	SNSA
3.12.9 D-SUB cable CAC to AAC	n/a	1	0.00	€3.78	0.00	€3.78	SNSA
3.14 3.3 V Zener diode							
3.3 V Zener diode	RND 1N746A	15	0.50	0.07	7.50	€1.05	SNSA
Spare / Testing		24		0.07	-	€1.68	SNSA
3.15 Power to PCB							
3.15.1 Male connector on PCB	Serie 768	1	5.00	€8.46	5.00	€8.46	SNSA
3.15.2 Female connector from wall	Serie 768	1	11.00	€11.58	11.00	€11.58	SNSA
3.15.3 Grounding contact	DIN 46234	4	0.58	€8.60	2.32	€8.60	SNSA
3.15.4 Spare - female connector from wall	Serie 768	1	-	€11.58	-	€11.58	SNSA
3.15.5 Spare - male connector on PCB	Serie 768	5	-	€8.46	-	€42.30	SNSA
3.16 Logic CAT5 E-link for inside box 0.5m	VLCP85121E05	1	20.00	€1.32	20.00	€1.32	SNSA
3.16.2 Spare - Logic CAT5 E-link for inside box 0.15m	VLCP85121E015	1	-	€1.05	-	€1.05	SNSA
3.16.3 Spare - Logic CAT5 E-link for inside box 1m	VLCP85121E10	1	-	€1.41	-	€1.41	SNSA
3.17 Cables for wiring							
3.17.1 Signal wire	5854/7 YL005	1	230.00	€33.88	115.00	€33.88	SNSA
3.17.2 Power wire - Back	5856 BK005	1	365.00	€46.38	73.00	€46.38	SNSA
3.17.3 Power wire - Red	5856 RD005	1	365.00	€46.38	73.00	€46.38	SNSA
3.18 Electrical Tape for marking wires.							
3.18.1 Electrical Tape for marking wires - White	HTAPE-FLEX15WH-15X10	1	34.00	€0.82	13.60	€0.82	SNSA
3.18.2 Electrical Tape for marking wires - Black	HTAPE-FLEX15BK-15X10	1	33.00	€0.82	13.20	€0.82	SNSA
3.18.3 Electrical Tape for marking wires - Green	HTAPE-FLEX15GN-15X10	1	34.00	€0.82	13.60	€0.82	SNSA
3.18.4 Electrical Tape for marking wires - Violet	HTAPE-FLEX15VT-15X10	1	34.00	€0.82	13.60	€0.82	SNSA
3.18.5 Electrical Tape for marking wires - Gray	HTAPE-FLEX15GY-15X10	1	34.00	€0.82	13.60	€0.82	SNSA
3.18.6 Electrical Tape for marking wires - Brown	HTAPE-FLEX15BN-15X10	1	34.00	€0.82	13.60	€0.82	SNSA
3.18.7 Electrical Tape for marking wires - Blue	HTAPE-FLEX15BU-15X10	1	34.00	€1.85	13.60	€1.85	SNSA
3.19 Potentiometer							
3.19.1 Potentiometer 1 kOhm	M64Y102KB40	4	0.00	€1.83	0.00	€7.32	SNSA
3.19.2 Potentiometer 50 kOhm	3296Y-1-503LF	10	1.00	€1.80	10.00	€18.00	SNSA
3.20 Header pins to solder arduino on PCB							
3.20.1 6-pin male double row header	RND 205-00634	2	1.00	€0.22	2.00	€0.44	SNSA
3.20.2 8-pin male single row header	RND 205-00629	5	1.00	€0.28	5.00	€1.40	SNSA
3.20.3 10-pin male single row header	SD-2X5-T1-7/3MM	1	1.00	€0.26	1.00	€0.26	SNSA
3.20.4 36-pin male double row header	61303621121	1	2.00	€1.65	2.00	€1.65	SNSA
3.21 Static Pressure Sensor	3500S0001A05E000	1	53.00	€116.39	53.00	€116.39	LTU
3.22 Connector for the Static Pressure Sensor	XZCPV1141L2	1	14.00	€14.00	14.00	€14.00	LTU

Figure 148: Budget Table for Cables and Sensors Components.

M.4 CAC

	Manufacturer Code	Quantity	Mass/Unit [g]	Cost/Unit [€]	Total Mass [g]	Total Cost [€]	Sponsor
4 CAC					**6,957.00**	**€22,948.01**	
4.1 Coiled tube	n/a	1	6,200.00	€22,000.00	6,200.00	€22,000.00	FMI
4.2 Sampling Valve (inlet and outlet 1/8" female)							
4.2.1 *Sampling Valve (inlet and outlet 1/8" female)*	VDW22UANXB	1	100.00	€45.00	100.00	€45.00	SMC
4.2.2 Spare		1	-	€45.00	-	€45.00	SMC
4.3 Straight tube union (OD 1/4" - ID 5/32")	SS-400-6	1	30.00	€13.37	30.00	€13.37	SWAGELOK
4.4 Interface tube-screw male (OD 1/4" - ID 5/32" to male 1/8")	SS-400-1-2	2	50.00	€10.00	100.00	€20.00	SWAGELOK
4.5 Straight reducing tube union (OD 1/4" to OD 1/8")	SS-400-6-2	1	25.00	€16.55	25.00	€16.55	FMI
4.6 Interface attached to the coiled tube outlet, quick connector	SS-QC4-B-200	1	91.00	€65.00	91.00	€65.00	SWAGELOK
4.7 Interface attached to the coiled tube inlet, quick connector	SS-QC4-B-400	1	68.00	€50.00	68.00	€50.00	SWAGELOK
4.8 Interface quick connector stem with valve	SS-QC4-D-400	1	58.00	€40.00	58.00	€40.00	SWAGELOK
4.9 90 degree elbow 1/4"	SS-400-9	3	55.00	€19.40	165.00	€58.20	SWAGELOK
4.10 Port Connector, 1/4 in. Tube OD	SS-401-PC	5	5.00	€6.30	25.00	€31.52	FMI
4.11 Magnesium filter with interface	n/a	1	65.00	€150.00	65.00	€150.00	FMI
4.12 Testing Valve	Lucifer 121K, 122K	1	-	€100.00	-	€100.00	LTU
4.13 Testing / Backup seal valve	4M4F-V6LN-SS	2	-	€150.00	-	€300.00	PARKER
4.14 Straight tube union (OD 1/8" - ID 5/32")	SS-200-6	1	30.00	€13.37	30.00	€13.37	FMI

Figure 149: Budget Table for CAC Components.

M.5 AAC

	Manufacturer Code	Quantity	Mass/Unit [g]	Cost/Unit [€]	Total Mass [g]	Total Cost [€]	Sponsor
5 AAC					**3,718.00**	**€4,264.32**	
5.1 Miniature diaphragm air pump							
5.1.1 *Miniature diagphram air pump*	NMP 850.1.2 KNDC-B	1	430.00	€350.00	430.00	€350.00	LTU
5.1.2 Spare	NMP 850.1.2 KNDC-B	1	-	€350.00	-	€350.00	KNF
5.2 Gas Sampling Bags							
5.2.1 *Gas Sampling Bag, Multi-Layer Foil, 3L, 10"x10", 5pk*	22951	6	5.00	€20.00	30.00	€120.00	RESTEK
5.2.2 Testing / Spare	22951	19	-	€20.00	-	€380.00	TEKNOLAB
5.3 Flushing valve (inlet and outlet 1/8" female)							
5.3.1 *Flushing valve (inlet and outlet 1/8" female)*	VDW22UANXB	1	100.00	€45.00	100.00	€45.00	SMC
5.3.2 Spare	VDW22UANXB	1	-	€45.00	-	€45.00	SMC
5.4 Manifold (inlet and outlet 1/8" female)							
5.4.1 *Manifold (inlet and outlet 1/8" female)*	VV2DW2-H0601N-F-Q	1	440.00	€140.00	440.00	€140.00	SMC
5.4.2 Spare	VV2DW2-H0601N-F-Q	1	-	€140.00	-	€140.00	SMC
5.5 Valves manifold (outlet 1/8" female)							
5.5.1 *Valves manifold (outlet 1/8" female)*	VDW23-5G-1-H-Q	6	100.00	€40.00	600.00	€240.00	SMC
5.5.2 Spare	VDW23-5G-1-H-Q	4	-	€40.00	-	€160.00	SMC
5.6 Interface tube-screw male (OD 1/4" - ID 5/32" to male 1/8")	SS-400-1-2	8	13.00	€14.00	104.00	€112.00	SWAGELOK
5.7 Interface tube-screw male 90 degree(OD 1/4" - ID 5/32" to male 1/8")	SS-400-2-2	3	13.00	€16.00	39.00	€48.00	SWAGELOK
5.8 Male 90-degree connector (OD 1/4" - ID 5/32" to male 1/4")	SS-400-2-4	1	16.00	€14.00	16.00	€14.00	SWAGELOK
5.10 T-Union							
5.10.1 *Interface T-Union (male 1/4")*	SS-400-3	1	71.00	€33.00	71.00	€33.00	SWAGELOK
5.10.2 Spare	SS-400-3	6	-	€33.00	-	€198.00	SWAGELOK
5.11 Nut Ferrule set Spares	SS-400-NFSET	15	-	€2.25	-	€33.75	SWAGELOK
5.12 Tubing, Sulfinert 304SS Welded/Drawn 50ft (OD 1/4" - ID 0.21")	29255	1	600.00	€840.00	600.00	€840.00	SILCOTEK
5.13 Quick Coupling female 1/4"	SS-QC4-B-4PF	6	45.00	€50.00	270.00	€300.00	SWAGELOK
5.14 Interface 90 degree elbow 1/4"							
5.14.1 *90 degree elbow 1/4"*	SS-400-9	1	55.00	€19.40	55.00	€19.40	SWAGELOK
5.14.2 Spare	SS-400-9	1	-	€19.40	-	€19.40	SWAGELOK
5.15 Interface female 90-degree connector (OD 1/4" - ID 5/32" to female 1/4")	SS-400-8-4	2	62.00	€23.28	124.00	€46.56	SWAGELOK
5.16 Female tube adapter (Tube OD 1/4" - ID 5/32" to female 1/4" ISO Parallel Thread	SS-4-TA-7-4RG	1	46.00	€20.37	46.00	€20.37	SWAGELOK
5.17 Tube Fitting Reducer (OD 3/16 in. to 1/4 in. Tube OD)	SS-300-R-4	6	20.00	€11.93	120.00	€71.58	SWAGELOK
5.17.1 Spares Tube Fitting Reducer (OD 3/16 in. to 1/4 in. Tube OD)	SS-300-R-4	2	-	€11.93	-	€23.86	SWAGELOK
5.18 Tube plug 1/4 in.	SS-400-C	4	-	€6.79	0.00	€27.16	SWAGELOK
5.19 Magnesium filter tube with interface	n/a	1	65.00	€150.00	65.00	€150.00	FMI
5.20 Ferrule Set 1/4 in. Spares	SS-400-SET	20	-	€2.33	-	€46.56	SWAGELOK
5.21 T-Union 6 mm Tube OD	SS-6M0-3	2	50.00	€27.16	100.00	€54.32	SWAGELOK
5.22 Tube Fitting Reducer (1/4 in. to 6 mm Tube OD)	SS-400-R-6M	2	30.00	€12.32	60.00	€24.64	SWAGELOK
5.23 Tubing Insert, 6 mm OD x 4 mm ID	SS-6M5-4M	4	10.00	€2.72	40.00	€10.86	SWAGELOK
5.24 Ferrule Set 3/16 in. Spares	SS-300-SET	10	-	€2.81	-	€28.13	SWAGELOK
5.25 Male Branch Tee (OD 1/4" - 1/4" Male NPT)	SS-400-3-4TTM	5	63.00	€18.50	315.00	€92.48	SWAGELOK
5.26 Male Branch Tee (OD 1/4" - 1/4" Male NPT)	SS-400-3-4TMT	1	63.00	€18.50	63.00	€63.00	SWAGELOK
5.27 Male connector (OD 1/4" - 1/4" Male NPT)	SS-400-1-4	1	30.00	€8.63	30.00	€8.63	SWAGELOK
5.27.1 Spare Male connector (OD 1/4" - 1/4" Male NPT)	SS-400-1-4	1	-	€8.63	-	€8.63	SWAGELOK

Figure 150: Budget Table for AAC Components.

M.6 Tools, Travel, and Other

	Quantity	Mass/Unit [g]	Cost/Unit [€]	Total Mass [g]	Total Cost [€]	Sponsor
6 TOOLS					**€1,745.00**	
6.1 Hand Tube Bender 1/4 in	1	n/a	€250.00	-	€250.00	SWAGELOK
6.2 Tube Cutter (4 mm to 25 mm)	1	n/a	€35.00	-	€35.00	SWAGELOK
6.3 Tubing Reamer	1	n/a	€26.00	-	€26.00	SWAGELOK
6.4 PTFE Tape Thread Sealant, 1/4"	1	n/a	€1.94	-	€1.94	SWAGELOK
6.5 Double-Sided Adhesive Tape	8	n/a	€9.80	-	€78.37	LTU
6.6 PTFE Tape, 32.9 m	1	n/a	€67.90	-	€67.90	LTU
6.7 Microfibre cloth	1	n/a	€9.41	-	€9.41	LTU
6.8 IPA Cleaner Spray, 400 ml	3	n/a	€3.88	-	€11.64	LTU
6.9 IPA Cleaner fluid, 1000 ml	2	n/a	€17.46	-	€34.92	LTU
6.10 Disposable gloves L	1	n/a	€11.83	-	€11.83	SNSA
6.11 Electronic Leak Detector	1	n/a	€1,000.00	-	€1,000.00	RESTEK
6.12 Thermal Adhesive	1	n/a	€18.00	-	€18.00	LTU
6.13 Flushing process (nitrogen or dry calibrated gas)	2	-	€100.00	-	€200.00	FMI
7 TRAVEL				**-**	**€500.00**	
7.1 Travel to FMI for sample bag testing	1	n/a	€250.00	-	€250.00	LTU
7.2 Travel to FMI for integration testing	1	n/a	€250.00	-	€250.00	LTU
8 OTHER				**2,427.38**	**€588.13**	
8.1 Shipping costs	n/a	n/a	n/a	-	€392.09	SNSA
8.2 Error margin	n/a	n/a	n/a	2,427.38	€196.04	SNSA

Figure 151: Budget Table for Tools, Travel, and Other Components.

Appendix N Full List of Requirements

N.1 Functional Requirements

F.1 ~~The experiment *shall* collect air samples.~~[12]

F.2 The experiment *shall* collect air samples by the CAC.

F.3 The experiment *shall* collect air samples by the AAC.

F.4 ~~The experiment's AAC System *shall* be able to collect air samples during the Ascent Phase.~~[12]

F.5 ~~The experiment's AAC System *shall* be able to collect air samples during the Descent Phase.~~[12]

F.6 ~~The altitude from which a sampling bag will start sampling *shall* be programmable.~~ [13]

F.7 ~~The altitude from which a sampling bag will stop sampling *shall* be programmable.~~[13]

F.8 ~~The experiment *shall* pump air into the AAC Sampling Bags.~~[12]

F.9 The experiment *should* measure the air intake flow to the AAC.

F.10 The experiment *shall* measure the air pressure.

F.11 The experiment *shall* measure the temperature.

F.12 ~~The experiment *shall* collect data on the humidity.~~ [12]

F.13 ~~The experiment *shall* measure the temperature inside the AAC Valve Box.~~[12]

F.14 ~~The experiment *should* measure the humidity inside the AAC Valve Box.~~[12]

F.15 ~~The experiment *shall* collect data on the time.~~[14]

F.16 ~~The experiment *shall* accept telecommand instructions to program AAC sampling altitudes for each sampling bag.~~[12]

F.17 ~~The experiment *shall* accept telecommand instructions to open designated valves.~~[12]

F.18 ~~The experiment *shall* accept telecommand instructions to close designated valves.~~[12]

F.19 ~~The experiment *may* accept telecommand instructions to change the sampling rate of the ambient pressure sensor.~~[12]

F.20 ~~The experiment *may* accept telecommand instructions to change the sampling rate of the ambient temperature sensor.~~[12]

F.21 ~~The experiment *may* accept telecommand instructions to change the sampling rate of the AAC Valve Box temperature sensor.~~[12]

F.22 ~~The experiment *may* accept telecommand instructions to turn on the air pump.~~[12]

[12] Unnecessary requirement that has been removed.
[13] Moved to design requirements.
[14] Unverifiable requirement that has been removed.

F.23 ~~The experiment *may* accept telecommand instructions to turn off the air pump.~~[12]

F.24 ~~The experiment *may* accept telecommand instructions to turn on the Valve Heater.~~[12]

F.25 ~~The experiment *may* accept telecommand instructions to turn off the Valve Heater.~~[12]

F.26 ~~The experiment *may* accept telecommand instructions to turn on the Electronics Box Heater.~~[12]

F.27 ~~The experiment *may* accept telecommand instructions to turn off the Electronics Box Heater.~~[12]

N.2 Performance Requirements

P.1 ~~The telecommand data rate *shall* be 10 Kb/s.~~[13]

P.2 ~~The default sampling rate of the ambient pressure sensor during Standby mode *shall* be 0.1 Hz.~~[15]

P.3 ~~The default sampling rate of the ambient pressure sensor during Normal operation ascent mode *shall* be 0.2 Hz.~~[15]

P.4 ~~The default sampling rate of the ambient pressure sensor during Normal operation descent mode *shall* be 10 Hz.~~[15]

P.5 ~~The default sampling rate of the AAC Valve Box temperature sensor *shall* be 1 Hz.~~[15]

P.6 ~~The programmable sampling rate of the ambient pressure sensor *shall* not be lesser than 0.1 Hz.~~[15]

P.7 ~~The programmable sampling rate of the ambient pressure sensor *shall* not be greater than 100 Hz.~~[15]

P.8 ~~The programmable sampling rate of the Electronics Box temperature sensor *shall* not be lesser than 1 Hz.~~[15]

P.9 ~~The programmable sampling rate of the Electronics Box temperature sensor *shall* not be greater than 7 Hz.~~[15]

P.10 ~~The programmable sampling rate of the AAC Valve Box temperature sensor *shall* not be lesser than 1 Hz.~~[15]

P.11 ~~The programmable sampling rate of the AAC Valve Box temperature sensor *shall* not be greater than 7 Hz.~~[15]

P.12 The accuracy of the ambient pressure measurements *shall* be -1.5/+1.5 hPa for 25°C.

P.13 The accuracy of temperature measurements *shall* be +3.5/-3°C (max) for condition of -55°C to 150°C.

P.14 ~~The accuracy of the ambient humidity measurements *shall* be $\pm3\%$.~~ [13][12]

P.15 ~~The accuracy of the AAC Valve Box temperature measurements *shall* be +3.5/-2°C(max).~~[16]

[15]Replaced by P.23

[16]Combined with P13

P.16 ~~The air intake rate of the air pump *shall* be minimum 3 L/min.~~[13]

P.17 ~~The temperature of the Electronics Box *shall* be between 0°C and 25°C.~~ [13]

P.18 ~~The temperature of the Electronics Box *shall* not exceed 25°C.~~[17]

P.19 ~~The temperature of the AAC Valve Box *shall* be between 0°C and 25°C.~~[13]

P.20 ~~The temperature of the AAC Valve Box *shall* not exceed 25°C.~~[18]

P.21 ~~The air sampling systems *shall* filter out all water molecules before filling the sampling containers.~~ [13]

P.22 ~~The CAC air sampling *shall* filter out all water molecules before filling the tube.~~[19]

P.23 The sensors sampling rate *shall* be 1 Hz.

P.24 The temperature of the Pump *shall* be between 5°C and 40°C.

P.25 The minimum volume of air in the bags for analysis *shall* be 0.18 L at ground level.

P.26 The equivalent flow rate of the pump *shall* be between 8 to 3 L/min from ground level up to 24 km altitude.

P.27 The accuracy range of the sampling time, or the resolution, *shall* be less than 52.94 s, or 423.53 m.

P.28 The sampling rate of the pressure sensor *shall* be 1 Hz.

P.29 The sampling rate of the airflow sensor *shall* be 1 Hz.

P.30 The accuracy of the pressure measurements inside the tubing and sampling bags *shall* be -0.005/+0.005 bar for 25°C.

N.3 Design Requirements

D.1 The experiment *shall* operate in the temperature profile of the BEXUS flight[8].

D.2 The experiment *shall* operate in the vibration profile of the BEXUS flight[8].

D.3 The experiment *shall* not have sharp edges that can harm the launch vehicle, other experiments, and people.

D.4 The experiment's communication system *shall* be compatible with the gondola's E-link system.

D.5 The experiment's power supply *shall* be compatible with the gondola's provided power.

D.6 ~~The experiment *shall* not disturb other experiments on the gondola.~~[12]

D.7 The total DC current draw *should* be below 1.8 A.

D.8 The total power consumption *should* be below 374 Wh.

[17] Combined with P17 and moved to design requirements.
[18] Combined with P19 and moved to design requirements.
[19] Combined with P21 and moved to design requirements.

D.9 ~~The experiment *shall* be able to operate in low pressure conditions (10-15 hPa) up to 30 km altitude.~~[20]

D.10 ~~The components of the experiment *shall* operate within their temperature ranges.~~[12]

D.11 ~~The OBC *shall* be able to autonomously control the heaters.~~[12]

D.12 ~~The ground station GC *shall* be able to display some of the received data.~~[12]

D.13 ~~The experiment *shall* be able to survive and operate between -30°C and 60°C.~~[12]

D.14 ~~The external components that are directly exposed to the outside environment *shall* be able to operate at -70°C.~~[12]

D.15 ~~The watchdog *should* be able to reset the system.~~[12]

D.16 The experiment *shall* be able to autonomously turn itself off just before landing.

D.17 The experiment box *shall* be placed with at least one face exposed to the outside.

D.18 The experiment *shall* operate in the pressure profile of the BEXUS flight[8].

D.19 The experiment *shall* operate in the vertical and horizontal accelerations profile of the BEXUS flight[8].

D.20 ~~The experiment *shall* operate in the horizontal accelerations profile of the BEXUS flight.~~ [8] [21]

D.21 The experiment *shall* be attached to the gondola's rails.

D.22 The telecommand data rate *shall* not be over 10 kb/s.

D.23 The air intake rate of the air pump *shall* be equivalent to a minimum of 3 L/min at 24 km altitude.

D.24 The temperature of the Brain *shall* be between -10°C and 25°C.

D.25 ~~The temperature of the Brain level 2 *shall* be between 0°C and 25°C.~~ [22]

D.26 The air sampling systems *shall* filter out all water molecules before filling the sampling bags.

D.27 The total weight of the experiment *shall* be less than 28 kg.

D.28 The AAC box *shall* be able to fit at least 6 air sampling bags.

D.29 The CAC box *shall* take less than 3 minutes to be removed from the gondola without removing the whole experiment.

D.30 The AAC *shall* be re-usable for future balloon flights.

D.31 The altitude from which a sampling bag will start sampling *shall* be programmable.

D.32 The altitude from which a sampling bag will stop sampling *shall* be programmable.

[20] Repeated in D18
[21] Combined with D19
[22] Combined with D24

N.4 Operational Requirements

O.1 ~~The TUBULAR Team *shall* send telecommands from the ground station to the experiment before and during the flight.~~[12]

O.2 ~~The TUBULAR Team *shall* receive telemetry from the experiment during the flight.~~[12]

O.3 ~~The experiment *shall* change modes autonomously.~~[12]

O.4 ~~The heating mechanism *shall* work autonomously.~~[12]

O.5 ~~The experiment *shall* store data autonomously.~~[12]

O.6 ~~The Air sampling control system *shall* work autonomously.~~[12]

O.7 ~~The valves in air sampling control system *should* be controllable from the ground station.~~[12]

O.8 ~~The experiment *should* be able to handle a timeout or drop in the network connection.~~[12]

O.9 ~~The heaters *should* be controllable from the ground station.~~[12]

O.10 ~~The watchdog[23] *should* be able to reset the system.~~[12]

O.11 ~~The system *should* be able to be reset with a command from the ground station.~~[12]

O.12 ~~The experiment *should* enter different modes with a telecommand from the ground station.~~[12]

O.13 The experiment *should* function automatically.

O.14 The experiment's air sampling mechanisms *shall* have a manual override.

N.5 Constraints

C.1 Constraints specified in the BEXUS User Manual.

C.2 ~~The person-hours allocated to project implementation is limited by university related factors such as exams, assignments, and lectures.~~[12]

C.3 ~~Budget limited to TBD.~~[12]

C.4 ~~The dimensions show a minimum print area of 50 x 50 cm and 65 cm height experiment box.~~[12]

[23]Explained in subsection 4.8. Software Design

Appendix O Test Results

O.1 Test 28: Pump Operations

The pump was connected via crocodile connections to a power supply set to 24 V. The power supply was then switched on and the current was read off. This set-up can be seen in Figure 152.

It was found that when the power supply was switched on the current went up to 600 mA for less than one second. It then settled to 250 mA. By covering the air intake, simulating air intake from a lower pressure, the current drops to 200 mA. By covering the air output, simulating pushing air into a higher pressure, the current rises to 400 mA.

Therefore the power for each of these conditions is 14.4 W at turn on, 6 W in normal use, 4.8 W when sucking from low pressure, 9.6 W when pushing to high pressure.

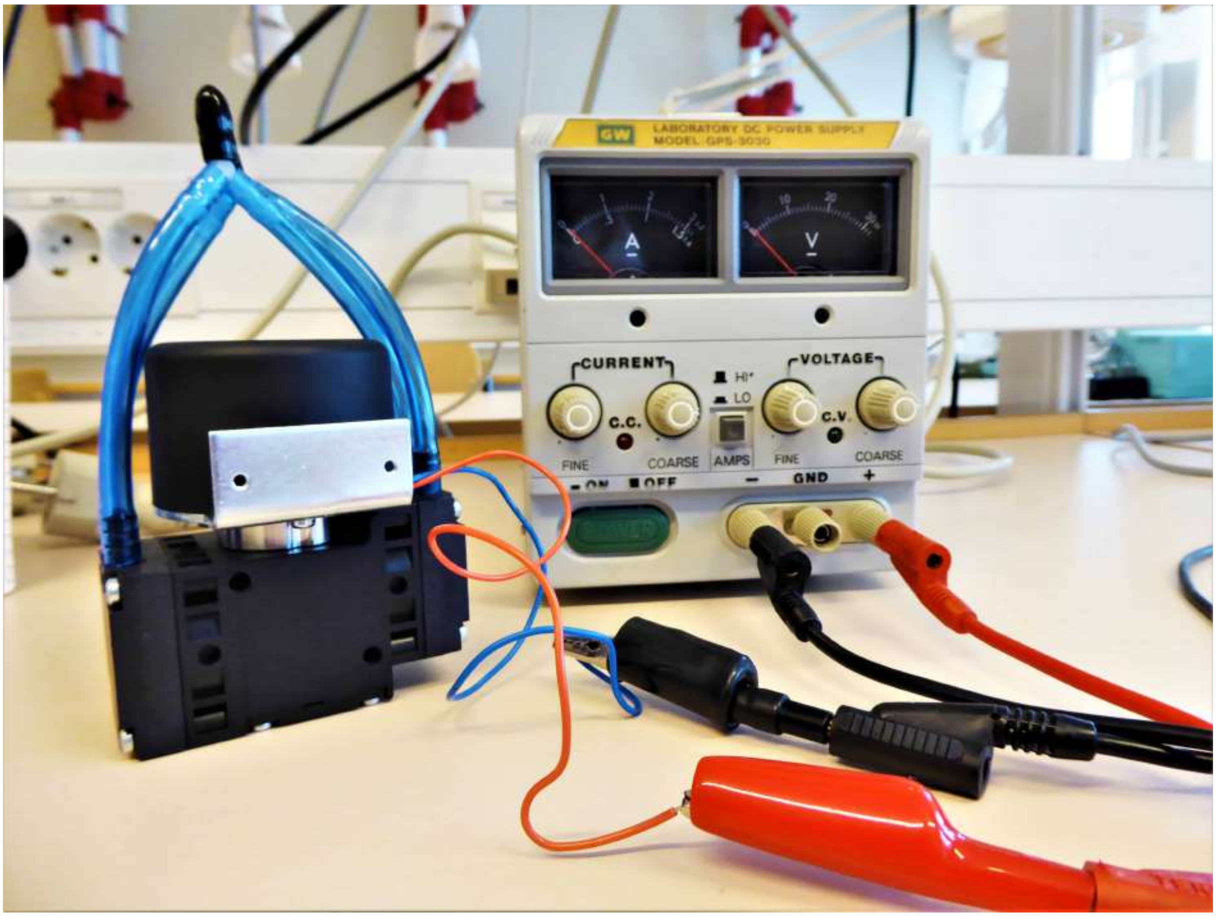


Figure 152: Photo Showing the Set-up for the Pump Testing in the Laboratory.

O.2 Test 18: Pump Low Pressure

The pump was tested at low pressure using a small vacuum chamber that is capable of going down to 1 hPa. For this test the chamber was only taken down to 30 hPa as this is the expected pressure at 24 km, the highest altitude that will be sampled. The experiment set-up can be seen in Figure 153. The pump was connected to the power supply via two cables. It was also screwed into the base plate to prevent it from moving due to its own vibration during the test. A vacuum pump was connected to the chamber wall with a pressure sensor attached to monitor the pressure inside the chamber.

Figure 153: Photo Showing the Set-up of the Vacuum Chamber, Power Supply and Vacuum Pump.

The glass top and cage were then placed on top of the sampling bag and pump and the air slowly removed. Figure 154 shows the test as it was in progress.

As the air was removed from the chamber a new problem became immediately obvious. Air that was inside the bag before the test was expanding as the pressure decreased until the bag reached around 75% of its total volume. The air had been pushed out of the sampling bag before the test but this had not been completed thoroughly enough. Therefore care must be taken to ensure that there is no, or very very small amounts, of air inside the bag before it enters a low pressure environment. For subsequent tests the pump was used in reverse to suck any remaining air out of the bags.

Figure 154: Photo Showing the Pump and Sampling Bag in the Vacuum Chamber During the Test.

Repeating the test and using the pump to suck out excess air from the bags the chamber was taken to around 30 hPa. Once the chamber was at this pressure the pump was switched on and a stopwatch began. Once the bag stopped inflating the stopwatch was stopped. During this test there was also a drop in pressure to 28 hPa and during a repeat there was a drop to 25 hPa. This also occurred in later tests. This is not seen as a significant problem as during the flight this is exactly what will happen when testing during ascent. In addition the flow rate increases with increasing outside pressure therefore this is showing our worst case flow rate. It was found that the pump was able to successfully switch on and fill the bag at this altitude with a flow rate of approximately 3 L/min.

The test was repeated again at 88 hPa, representing 17 km altitude and 220 hPa, representing 11 km altitude. Here the flow rates were found to be 3.4 L/min and 4.9 L/min respectively. The results can also be seen in Table 78 and Figure 155.

As this test could only provide and approximation due to the lack of equipment such as flowmeters that would have made this test more precise it was later repeated. In the repeat of this test the flow rates were found to be within the same magnitude. The full results can be seen in Section 7.3.5 in Table 56.

Altitude (km)	Pressure Start (hPa)	Pressure End (hPa)	Time (sec)	Flow Rate (L/min)
24	30	23	60	3
17	87	80	53	3.4
11	220	190	37	4.9

Table 78: Table Showing the Time Taken Until the 3 L Bag Stopped Expanding at Various Different Pressures.

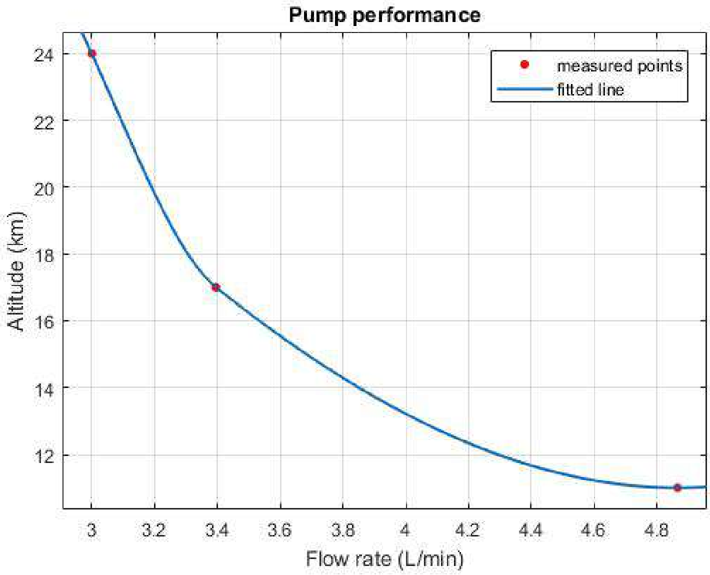


Figure 155: Obtained Pump Performance at Low Pressure.

O.2.1 Test 30: Sampling Bag Bursting

A sampling bag was placed in a small vacuum chamber connected to the pump with the same set up as in Test 18, see Figures 153 and 154. The pump was run for 3 minutes with a full bag to see how the bag reacted. No changes were observed in the bag and no leaks appeared whilst it was in the testing chamber. Upon returning it to atmospheric levels it also appeared to be able to withstand the over pressure. The bag was then left, with the valve closed, on a table where it was handled a little during this time. Approximately 30 minutes after the test the bag made an audible popping noise and air leaked out. The damage that occurred to the bag during the burst can be seen in Figure 156 for the front of the bag and Figure 157 for the back of the bag.

Figure 156: Photo Showing the Extent of Damage on the Front of the Bag Due to Bursting.

Figure 157: Photo Showing the Extent of Damage on the Back of the Bag Due to Bursting.

This kind of bag failure could occur if bags are overfilled, particularly during ascent.

Next the system was set-up in the same way with a new bag. This time the pump was continuously run until failure occurred. This took around 6 minutes. The bag failed along the lower seam close to the valve and also at the valve connection. At the valve connection the bag ripped just above the valve. This time the burst was more energetic with the bottom of the bag moving outwards. Upon inspection the bottom of the bag was completely open and the part of the bag connected to the valve partially ripped open. In addition at the top of the bag small failures similar to those seen in Figure 156 were seen again. It is therefore thought that the bag was starting to fail at both the top and the bottom of the bag and but the bottom failed first.

The damage can be seen in Figures 158 and 159. It should be noted that the white bag valve was pulled off after the test and before photos were taken.

Figure 158: Photo Showing the Damage Sustained to the Bottom of the Bag After Bursting Due to Continuous Pumping.

Figure 159: Photo Showing Where the Bag Ripped Around the Valve.

This kind of bag failure could occur if there is a software error that results in the pump not switching off or a valve not closing, or if there is a malfunction in one of the valves which means it fails to close.

From the damage seen on the bags and from witnessing the burst it can be concluded that, as long as the bags are well secured to the valves at the bottom and through the metal ring at the top, bag bursting during flight would not cause damage to any other components on board. Even during the more energetic burst that occurs from continuous pumping the bag remained fixed to the valve connection and experienced no fragmentation. The consequences of a single bag burst would be limited to loss of data and a disturbance to audio frequencies.

O.3 Test 29: Pump Current under Low Pressure

This test was set up in the same way as above in Test 18, see Figure 153 and 154. The addition to this test was a multimeter to read the current that the pump was drawing. The pump was tested once with the outlet attached to a bag and once with the outlet sealed. This provides the current when the pump is pumping into an ambient pressure and into a higher pressure.

In general it was found for both cases that decreasing the pressure, or increasing the altitude, lead to a decrease in pump current draw. It was noted that there was an increase in current draw in between sea level conditions and 11 km altitude conditions. However as the lowest sampling point it intended to be at 11 km this should not be a problem for the experiment. The full results can be seen in Table 79.

Altitude (km)	**Pressure (hPa)**	**Into Bag Current (mA)**	**Into Seal Current (mA)**
20	57	140	138
18	68	150	141
16	100	161	146
12	190	185	175
9	300	-	200
6	500	-	242
0	1013	-	218

Table 79: Table Showing How the Current Draw of the Pump Changed With Outside Air Pressure for Two Different Conditions. The First Pumping Into a Sampling Bag and the Second Pumping Into a Sealed Tube.

A graphical representation of these results are shown in Figures 160 and 161. From the table and figures it can be seen that the current draw is higher during the bag filling than during the sealed case. As the experiment will sample between 11 km and 24 km it can be concluded that the highest current draw will occur during the 11 km altitude sample and can be expected to be around 200 mA.

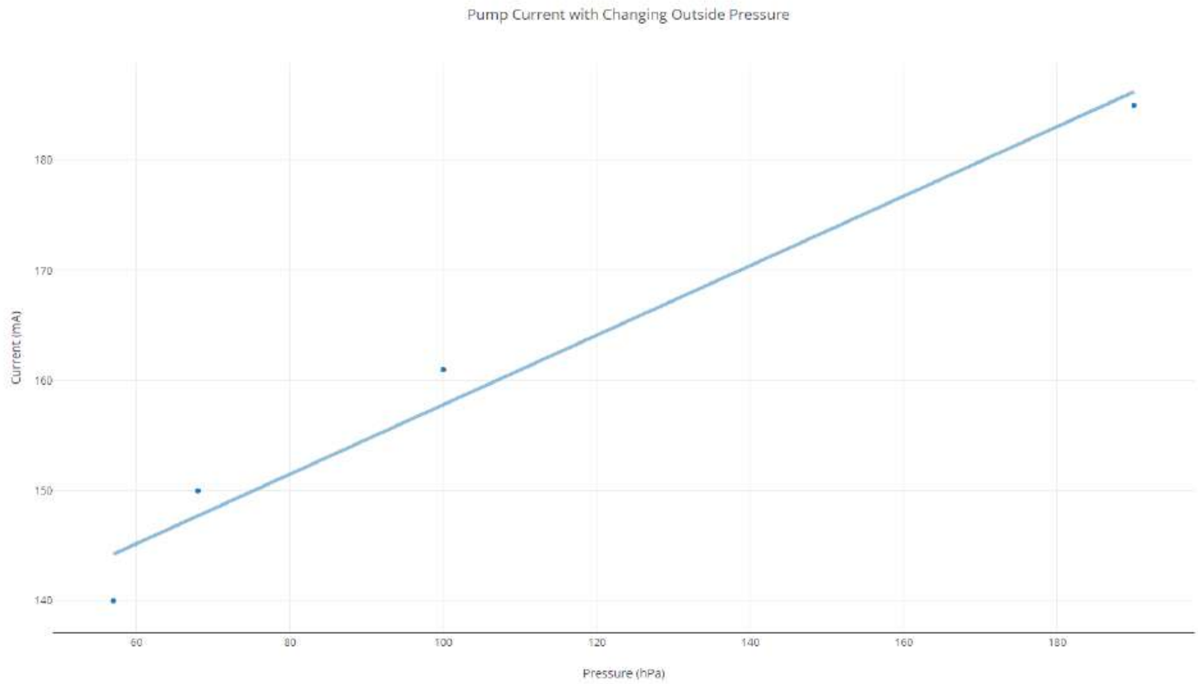


Figure 160: Graph Showing the Expected Current Values When the Pump is Pumping Air Into a Bag Based Upon the Results Obtained.

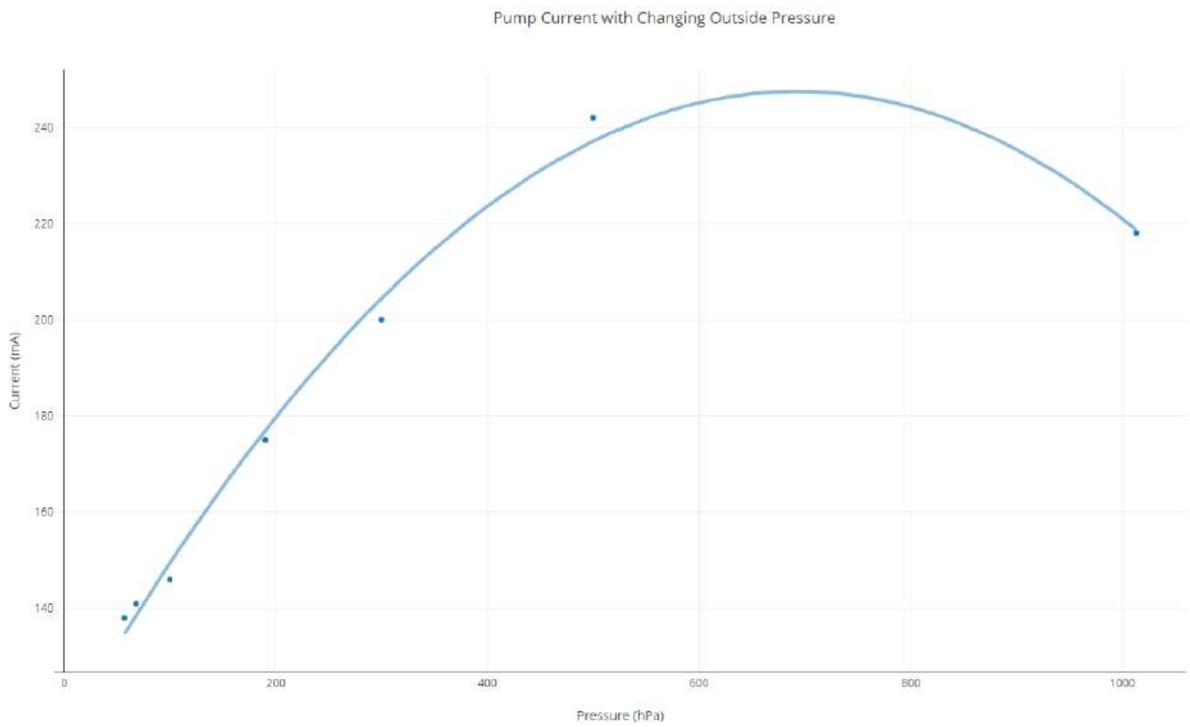


Figure 161: Graph Showing the Expected Current Values When the Pump is Pumping Air Into a Sealed Outlet Based Upon the Results Obtained and the Data Shown In Figure 31.

By looking at the data from both Test 18 and Test 29 a relationship can be seen between the outside air pressure, the flow rate of the pump and the current draw of the pump.

O.4 Test 17: Sampling bags' holding times and samples' condensation verification

The main objective of this test was to flush eight 1 L sampling bags with nitrogen, the same way it will be done for the flight. After the flushing is done, fill them with a dry gas and leave them outside for 6, 14, 24 and 48 hours. Then analyze two sampling bags after each time duration and see if the concentration of gases inside has changed.

A dry gas is a gas of high concentration of CO and low H_2O and its exact concentration can be known by comparison to the calibrating gas in the Picarro analyzer. Therefore, the concentration when sampling the bags is known and it can be compared with the concentration after analysis. If the sampling bags can hold the samples for 48 hours then when analyzing, the concentration of gases should not change. If condensation occurs that will be seen as an increase in water vapour concentration.

Note that the size of the sampling bags was not the same as the size that will be used during the experiment. The reasons were availability of 1 L sampling bags at FMI and a first assumption that the size would not affect the results. The sampling bags were exactly the same model/material.

This test was realized at FMI in Sodankylä. Eight Multi-Layer Foil bags of 1 L volume were connected to SMC valves as shown in Figure 162 and all together connected in series with stainless steel tubes as can be seen in Figure 163.

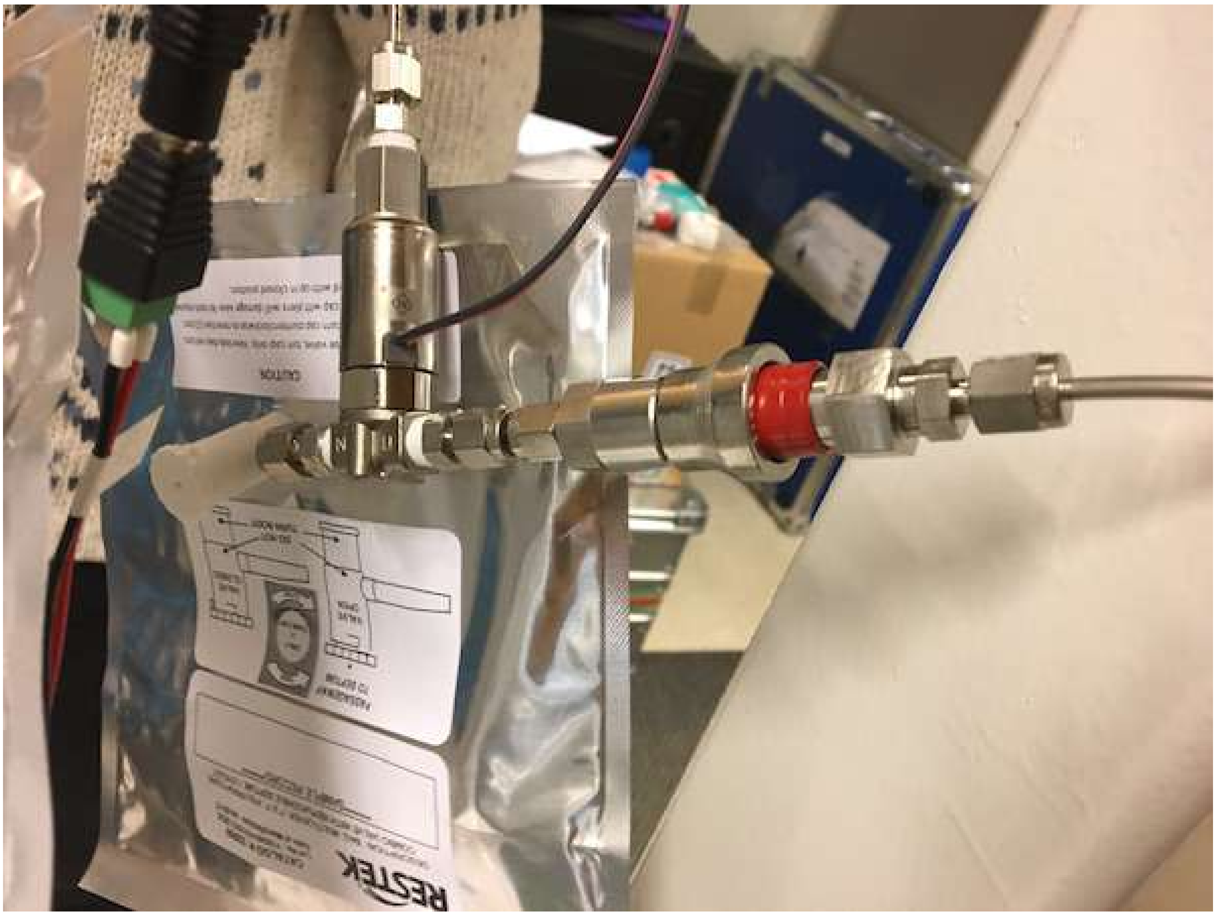


Figure 162: 1 L Sampling Bag With SMC Valve Attached to It. The Valve is at One of the Ends of the System so a Quick Connector is Connecting it to the Tube That Goes to the Nitrogen Bottle/Vacuum Pump.

Figure 163: Sampling Bags System Connected in Series.

Figure 164 shows a general overview of the experiment set up before the sampling bags were attached to the SMC valves. The picture shows the eight SMC valves hanging on a bar and red and black cables connecting them to the switches. It can also be seen a nitrogen bottle standing at the right side of the table and a vacuum pump under the table. Figure 165 shows the pressure sensor on the table, a flow-metre, a needle valve that adjusts the flow rate and a valve. This valve was used to control the filling and flushing of the sampling bags realized with nitrogen. The position shown in Figure 165 is for vacuuming, the pump is sucking the air from the sampling bags and the nitrogen tube is closed. The valve position for filling is the opposite, opening the nitrogen tube and closing the vacuum. There is also an intermediate position that closes both, nitrogen and vacuum.

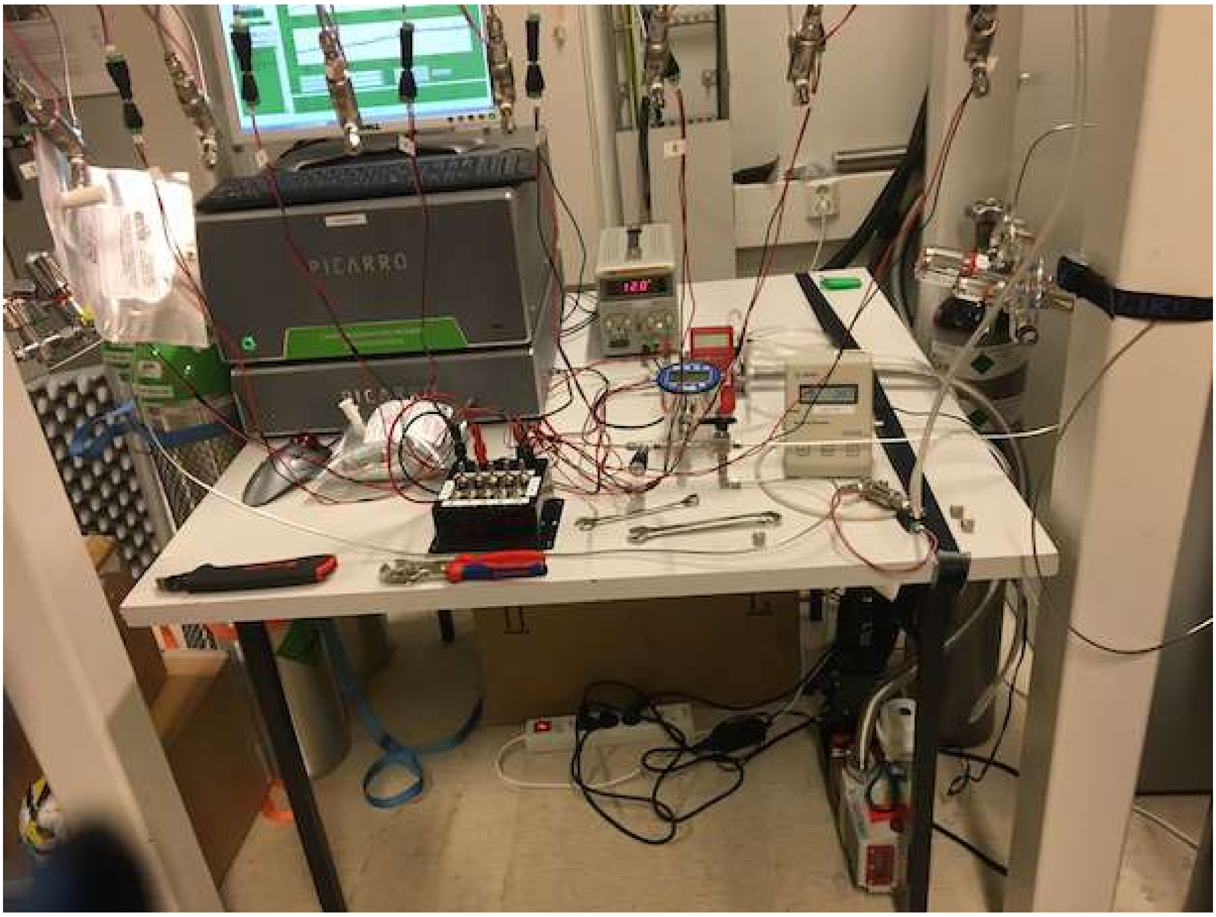


Figure 164: General Overview of the test Set up Before the Sampling Bags Were Attached to the Valves

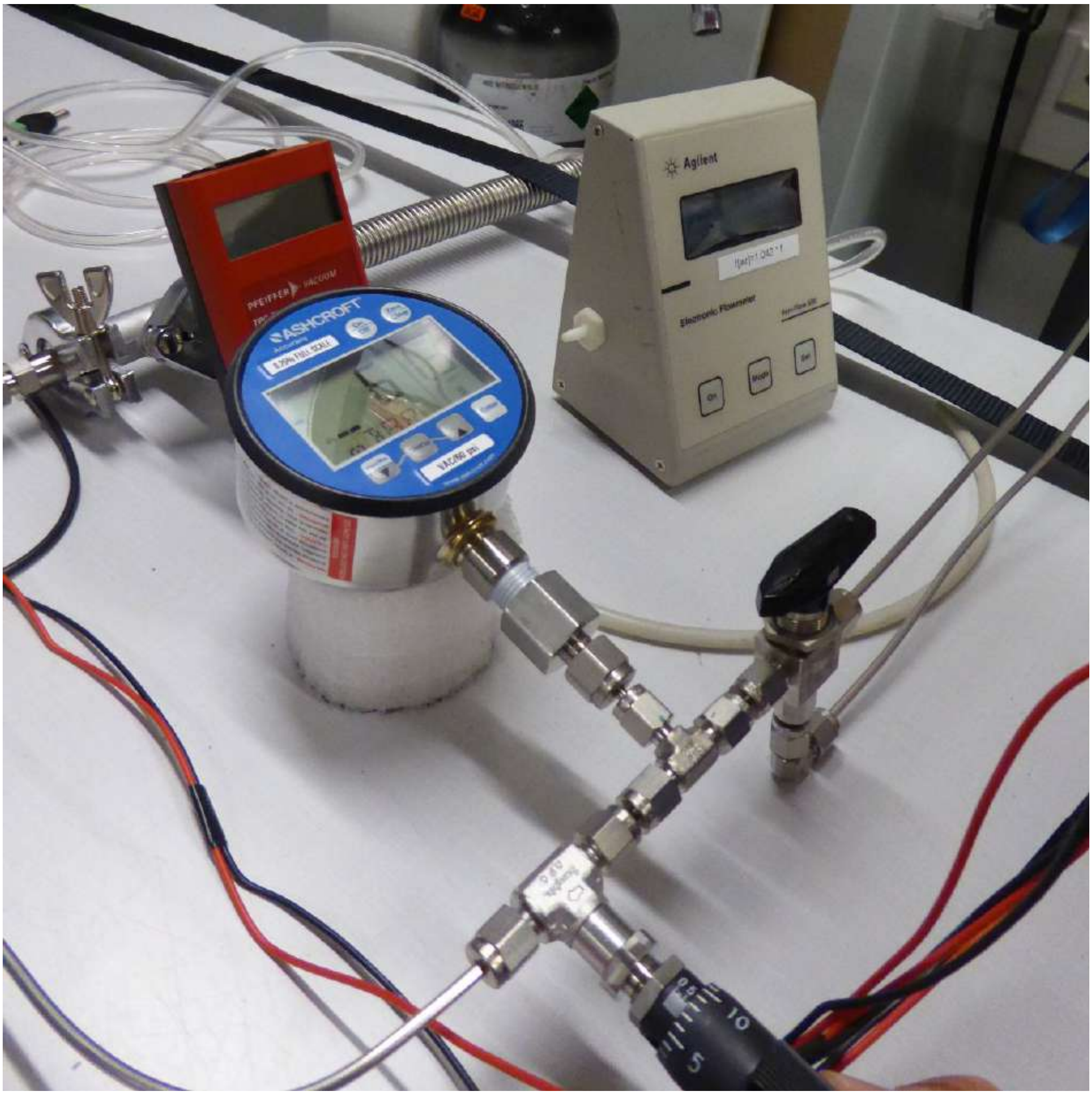


Figure 165: Valve that Controls Filling/Vacuum in of the Sampling Bags. Pressure Sensor, Flow-metre and Needle Valve.

The procedure during the test was as follows:

- Set up all the connections between pump, nitrogen bottle, valves system in series.
- Attach the sampling bags to the SMC valves.
- Start flushing the tubes with nitrogen. For this all the sampling bags' valves are closed.
- Adjust the flow rate of nitrogen at 500 ml/min.
- Open sampling bags' manual valves (not to be confused with the SMC valves which are still all closed).

- Turn on valve 1. Fill sampling bag number 1 for 2 minutes. Turn off valve 1. Repeat it for the seven sampling bags left.
- Change the valve seen in Figure 165 to vacuum position and empty the bags.
- Flush the tubes after all the sampling bags have been emptied. This is to remove as much air as possible that could be left inside the sampling bags.
- Repeat the flushing for two more times.
- Change the nitrogen bottle for the dry gas bottle.
- Flush the tubes with nitrogen.
- Fill the eight sampling bags one by one.
- Take the sampling bags outside as shown in Figure 166 to simulate the conditions at which they will be exposed after landing.

Figure 166: Sampling Bags Left Outside Waiting to be Analyzed.

After each of the mentioned times, 6, 14, 24 and 48 hours, two sampling bags were taken inside the laboratory to be analyzed. The procedure to analyze was:

- Have the dry gas flowing through the Picarro analyzer for at least one hour before the analysis. This is to avoid having moisture inside the tubes and have stable measurements of concentrations.
- Flush the tubes in between the two sampling bags with dry gas. For that the dry gas has to be disconnected from the analyzer and moisture would get into the Picarro. To avoid this, calibrating gas is flowing through the analyzer while the tubes are being flushed.
- Connect the system formed by two sampling bags with one end to the dry gas bottle and the other to the Picarro inlet.

- Wait for one hour until the readings of dry gas concentrations are stable.
- Open the valve of the first sampling bag.
- Right after the first sampling bag is empty, close its valve and open the valve for the next one.
- Keep the dry gas flowing for one more hour after analysis.

After analyzing the sampling bags the obtained results are presented in Figure 167.

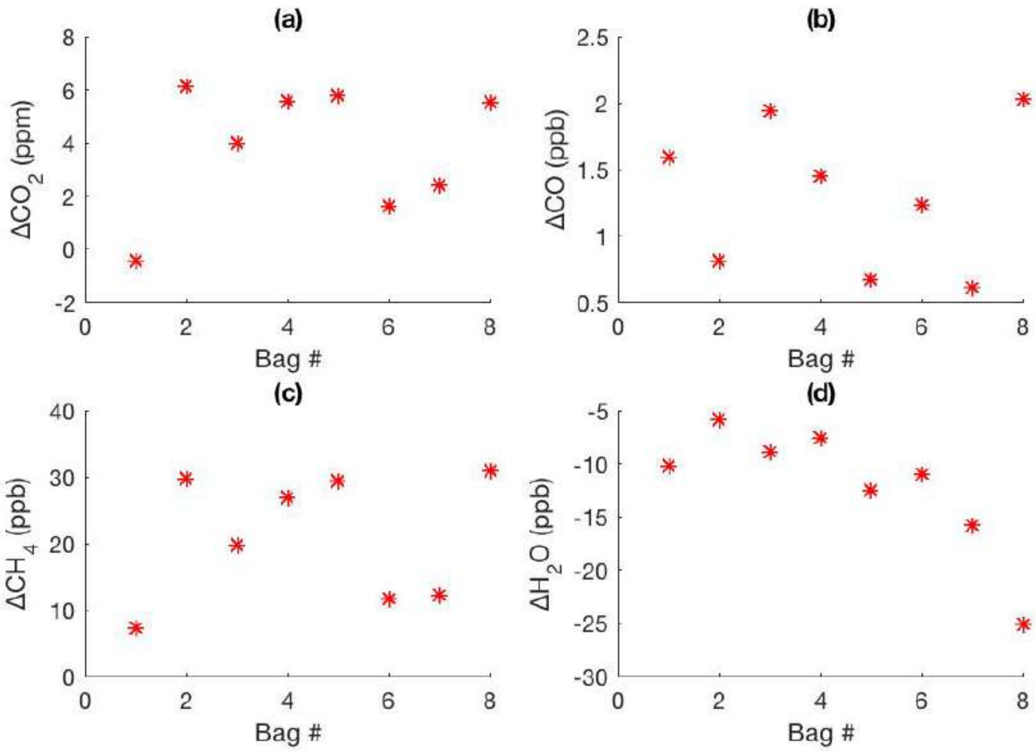


Figure 167: Obtained Variation in Concentration for (a) CO_2 in ppm, (b) CO in ppb, (c) CH_4 in ppb and (d) H_2O in ppb.

It should be mentioned that the results were not at all what was expected. If the sampling bags held the gases for 48 hours, the analyzed concentration should have been the same as the dry gas used to fill them or the variation should have been smaller.

A possible explanation for this results could be that the emptying of the sampling bags was not done rigorously enough and that some air/nitrogen was left inside which diluted in the dry gas and changed the concentrations. This effect is even increased due to the smaller size of the used sampling bags (1 L instead of 3 L). This would also explain why the results don't follow any pattern.

The general outcome of this test was that the team realized that the flushing of the sampling bags is a very delicate process. This test was also useful to decide that the flushing of the sampling bags should be done with dry gas instead of nitrogen in order to minimize the effects of the nitrogen diluting in the samples.

This test had to and was repeated, using the set-up described in Section 4, with some differences. This time 3L bags were flushed with dry gas and left outside for 15, 24, 48 hours. After the flushing was done, two bags for each time were filled with 0.5 L and 1L of dry gas and left outside. Then they were analyzed and checked if the sample concentrations were the same or close enough with the reference values of the filled dry gas.

The obtained results are shown in Figure 168. The blue points represent the sampling bags with the 0.5L sample, while the red points show the sampling bags with the 1L sample. Sampling Bag No1 with the sampling bag No4 were analyzed after 15 hours. The pair of sampling bags No2 and No5 were analyzed after 24 hours and the last pair of sampling bags, No4 and No6 after 48 hours.

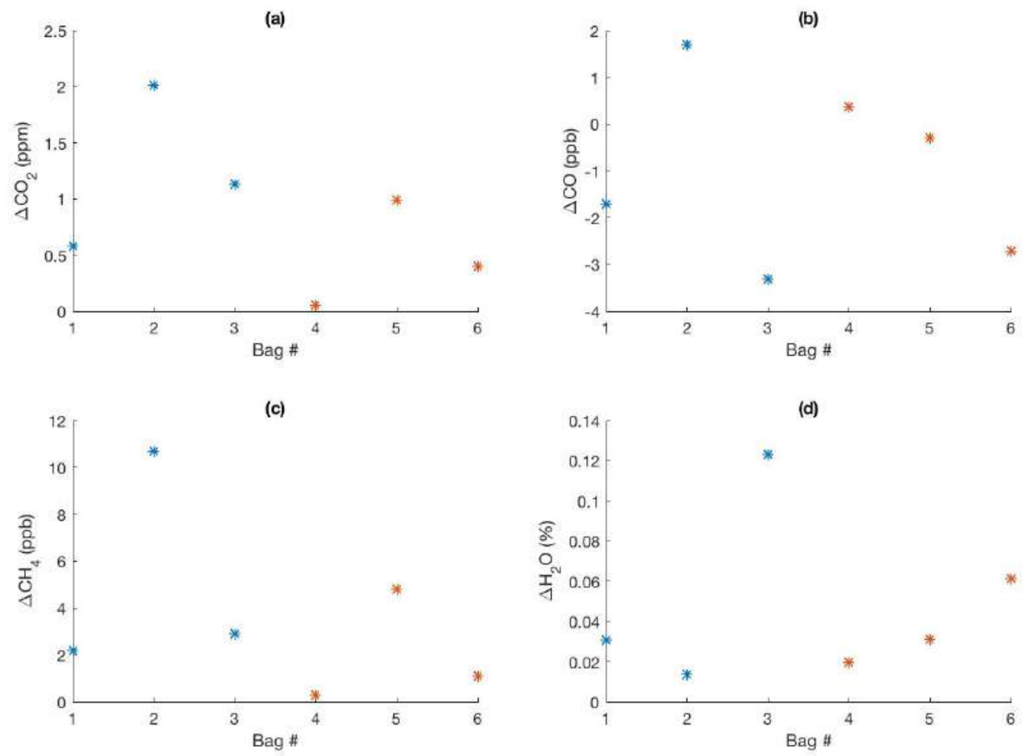


Figure 168: Obtained Variation in Concentration for (a) CO_2 in ppm, (b) CO in ppb, (c) CH_4 in ppb and (d) H_2O in $\%$.

The results were very good in general with the CO_2 concentration differences not higher than 2 ppm. The bags with the 0.5L sample gave bigger CO_2 concentration differences and higher humidity for all the tested times. For the bags that analyzed after 48 hours, the humidity was two times higher for the 0.5L sample compared to the 1L sample. If water goes through the walls of the bags at the same rate for both bags then it is normal that sampling bags with larger amounts of sampled air have lower humidity concentrations. Therefore, for better results, the air left in the sampling bags at sea level pressure must be the maximum possible.

O.4.1 Test 4: Low Pressure

Styrofoam

The same vacuum chamber was used as in Tests 18 and 29. The Styrofoam was measured on each side before it was placed in the chamber. It was then taken down to 5 hPa and held there for 75 minutes. It was then removed and the sides were measured again. It was found that there was no significant change in dimensions. The results can be seen in Table 80.

Side	Before (cm)	After (cm)
A	9.610	9.580
B	9.555	9.550
C	9.560	9.565
D	9.615	9.610
E	9.615	9.615
F	9.555	9.550
G	9.605	9.605
H	5.020	5.020
I	5.025	5.025
J	5.015	5.015
K	5.020	5.025

Table 80: Styrofoam Size Before and After Vacuum.

As some sides are measured slightly bigger after and some slightly smaller it is thought this is due to the measuring technique and not due to changes in the Styrofoam. It is thought the result from side A could be due to deforming the Styrofoam with calipers or a misread original length.

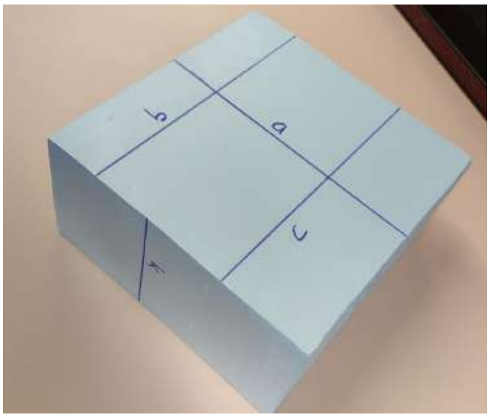


Figure 169: Picture Showing how the Styrofoam was Labeled for the Test.

Airflow

After the first airflow in vacuum test failed due to datalogging errors the airflow test was repeated. In this repeated test all of the Brain was placed into the vacuum chamber and one bag attached. It was not possible to attach more than one bag due to space restrictions. A view inside the vacuum chamber can be seen in Figure 170.

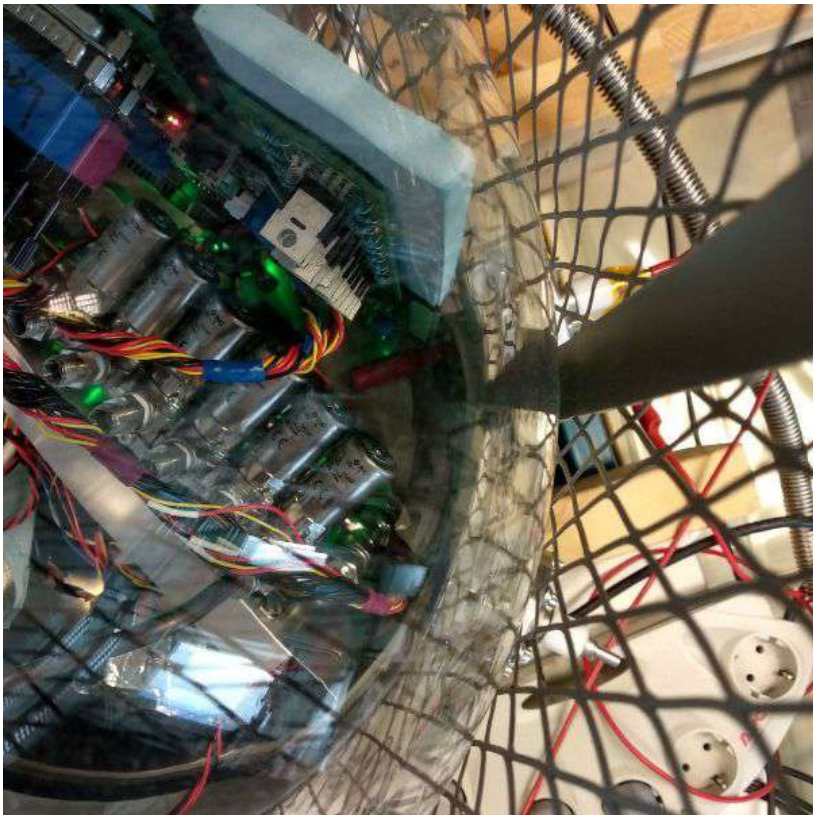


Figure 170: Picture Showing inside of the Vacuum Chamber During the Test.

To confirm the airflow rates the vacuum chamber was then taken down to from 400 hPa to 5 hPa in steps and the airflow rate logged. The results can be seen in Figure 171.

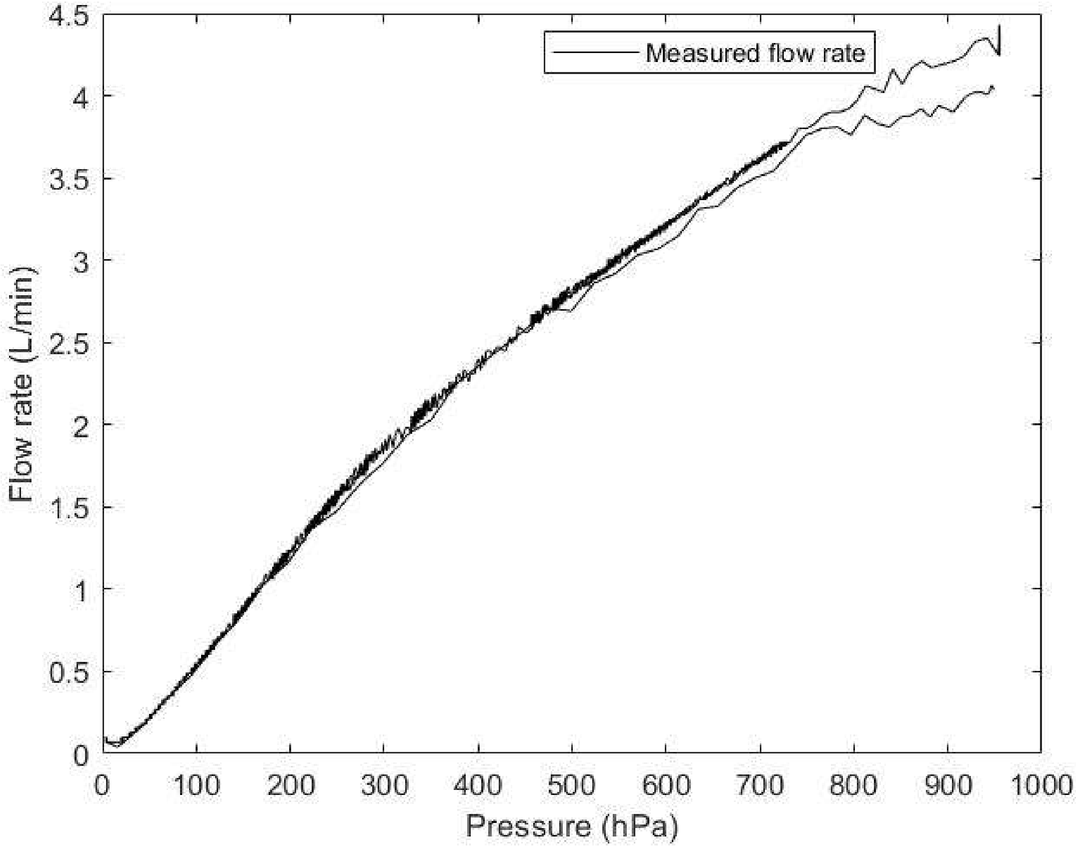


Figure 171: Graph Showing how the Airflow Rate is Changing with Ambient Pressure.

Sampling will take place between 200 hPa and 22 hPa, this area is seen in greater detail in Figure 172. From this graph it can be seen that the airflow rate is varying from 1.2 LPM to 0.1 LPM.

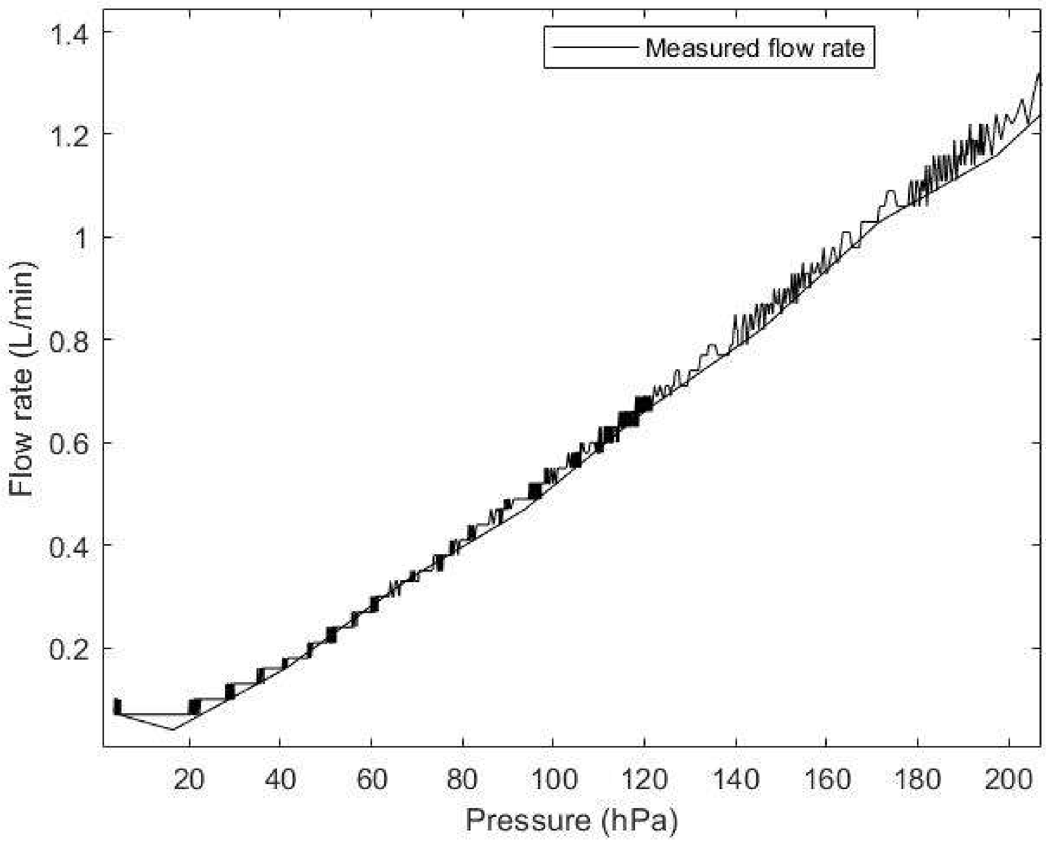


Figure 172: Graph Showing how the Airflow Rate is Changing with Ambient Pressure in the Sampling Region.

It was noted that the airflow rate seemed to be very low when compared to the rate at which the bag was inflating. For example for the first sampling point the flow rate was around 0.4 LPM and was filled for 44 seconds. This would imply that the bag was 10% full with 0.3 L, however from visual inspection it was clear the bag was at least 75% full. When the bag was brought back to sea level pressure the amount of remaining air in the bag was inspected. It appeared there was approximately 0.3 L left in the bag, as seen in Figure 173. This led to the conclusion that the airflow rate displayed is the equivalent airflow at sea level.

Figure 173: Picture Showing the Air Remaining in the Bag After Returning to Sea Level Pressure.

Software

With the same set-up as the airflow low pressure testing the software was tested to verify if it was operating as intended and that the conditions for stopping sampling were working.

First the software was run as it will be during flight. As the pressure inside the chamber was dropped it was possible to see through the LEDs on board the PCB the system going through the flight actions. When the first sampling altitude was reached the lights came on for the flushing valve and pump indicating the system was flushing. After one minute these lights went out and the first valve opened. For the first sampling point it was possible to see the bag inflate providing extra visual confirmation that the system is operating as intended.

The next check was to see if our conditions for stopping sampling were working. Testing with the initial sampling schedule meant that the time stopper always occurred first and worked well. The pressure threshold stopper also worked well with the system stopping sampling if the defined pressure range was left. Our third stopper is based on pressure and compares the pressure inside the bag to the ambient pressure to ensure we do not overpressure the bags. Interestingly it was found that this pressure was not being reached even after filling the bags continuously for three minutes, three times our time limit.

This shows that the maximum allowed pressure for the bags is not the pressure when the bag is 3L full but when the air in the bag has been compressed. This reduces the risk of bags bursting significantly.

Temperatures

As it is not possible to complete a thermal vacuum test in addition to the thermal testing temperatures were also monitored inside the vacuum chamber. Particular attention was paid to the CAC valve which will be on for the entire flight. From Figure 174 it can be seen that after 2 hours the temperature is leveling off at around 68°C. This is still well within the operating temperature range of the valve. In addition this was also held at 5 hPa which is a lower pressure than the minimum expected. However this is close to the melting point of the Styrofoam which is at 75°C so care must be taken to ensure there is no contact between the valve and Styrofoam. In the actual flight the valve is expected to be cooler than this due to the ambient temperature being lower.

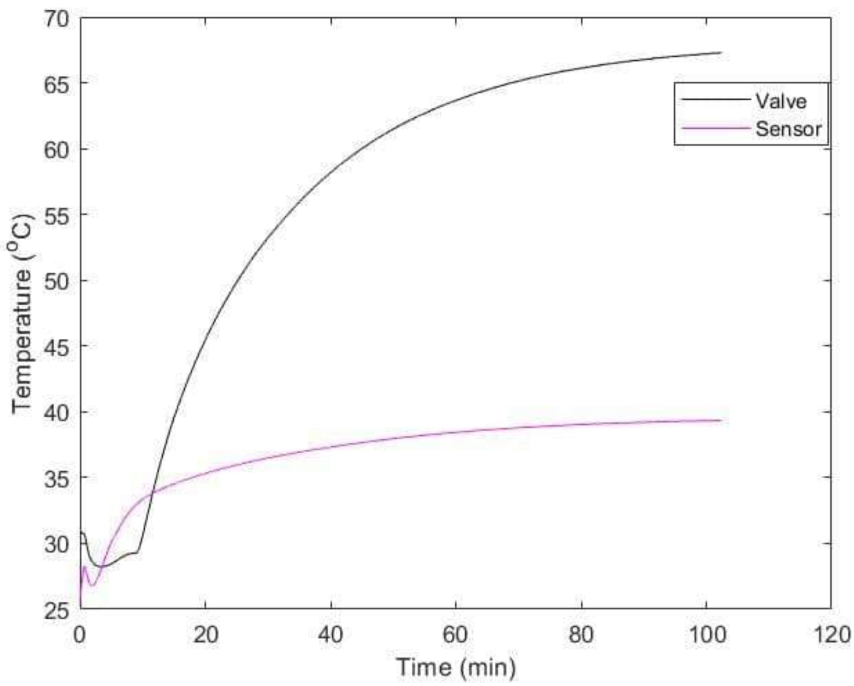


Figure 174: Graph Showing how the Temperature of the CAC Flushing Valve Changes over Time at 5 hPa.

The temperature of the pressure sensor, PCB, Pump and Manifold was also monitored with continuous use. After one hour and 48 minutes during the same test as the valve temperature the pressure sensor was found to reach 39°C. After one hour and 24 minutes during the flow rate monitoring test where the sensors, pump, and one manifold valve were on continuously the PCB temperature sensor was at 43°C, the pump at 42°C and the manifold at 33°C. As the pump will never be on for more than a few minutes at a time there is not any concern that this temperature will ever be reached during flight.

O.4.2 Test 24: Software and Electronics Integration

The different type of sensors were integrated one at time with the Arduino. The airflow sensor was first sensor to be integrated. The only problem with this sensor was the lack of calibration to give the correct data. Whilst at FMI this sensor was calibrated using another airflow sensor at FMI. The next sensor to be integrated was the temperature sensor. After several failed attempts to establish a connection to the sensor, a library, based on the information from the sensors datasheet was made. With this library communication was successfully established. During testing some problems were discovered with the temperature sensors as they stopped giving data back when exposed to colder temperatures. This was fixed by implementing a new piece of software code. Before the integration of the pressure sensor it had been expected the need of a self made library, despite this several changes was needed to the library to make the sensor responsive.

It was discovered that the pressure sensor on board the PCB wouldn't function while the other pressure sensors when connected to the SPI bus. Parasitic capacitance was suggested to be the culprit when looking on the SPI bus with an oscilloscope. During an telephone conference with our mentors another more reasonable theory was put forwards. Since the SPI was designed to function for short distances only the long cables connecting the outside pressure sensors caused reflections in the bus. The solution was to disregard the pressure sensor on the PCB since it was not a critical sensor.

When all the sensors had been integrated the sensors where tested together. The result was all the sensors, exept the PCB pressure sensor, working without interfering with each other.

O.4.3 Test 5: Thermal Test

The thermal chamber used was the one at FMI and Esrange. At FMI it could go down to between $-40°C$ and $-90°C$ and at Esrange it were tested down to $-60°C$. A few long run tests were done slowly going down to a temperature and stabilizing before lowering the temperature again to safely test that everything worked when it was below $-20°C$ outside and if it would handle a 4h $-40°C$ test. The long run test for $-40°C$ still needs to be done, because the temperature sensors gave an error and stopped showing data meaning the test was interrupted. With no temperature data the heaters could not be operated properly and the risk for damage was high enough to stop the testing to make sure no components were harmed.

To start with, only the AAC was put into the freezer. In the following Figures the vertical dotted line indicates where the sensor started to throw the error. The first test slowly went down to $-20°C$ before it stabilized, then it went down to $-30°C$ and then the communication received an error after a while as seen in Figure 175.

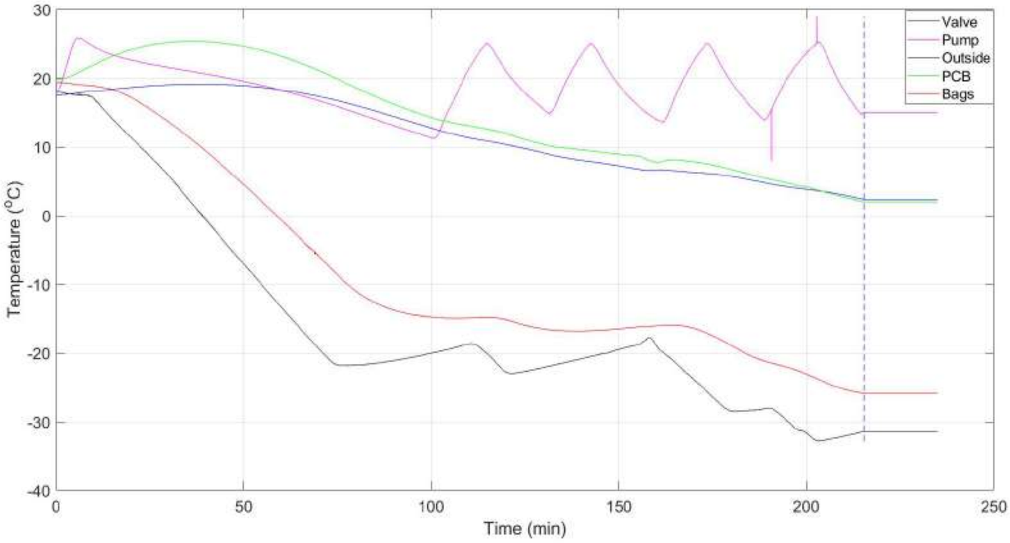


Figure 175: First Thermal Chamber Test.

The second test went straight down to $-30^{\circ}C$ and stabilized there to try long run test. After a while the communication got error again. The test can be seen in Figure 176.

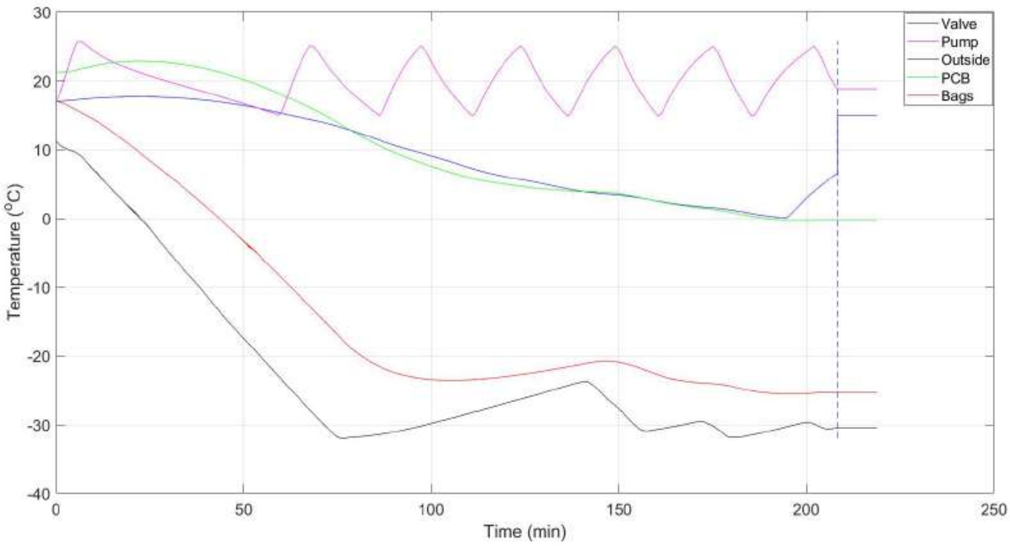


Figure 176: Second Thermal Chamber Test.

The third test went down to $-40^{\circ}C$ and was left to stabilize. After approximately half an hour the communication error happened again as seen in Figure 177.

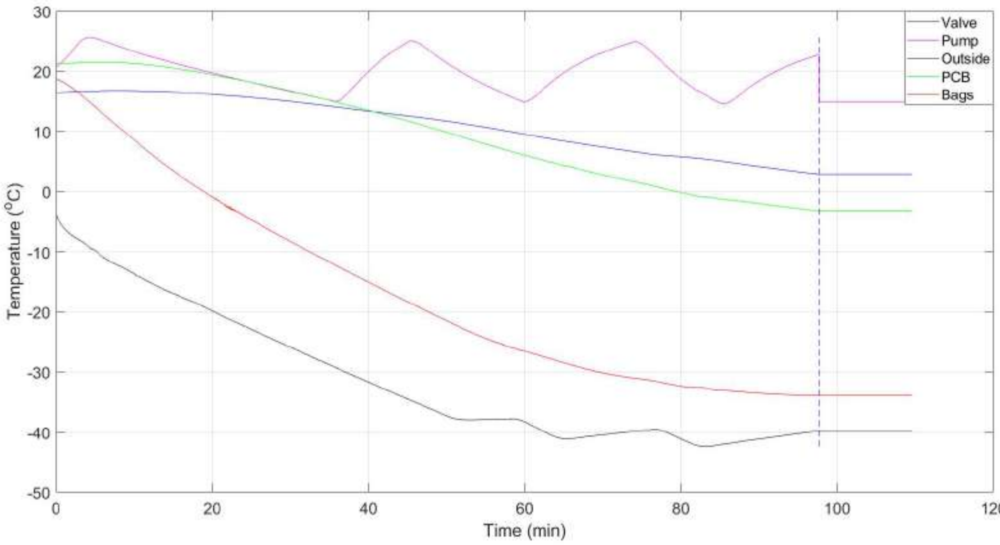


Figure 177: Third Thermal Chamber Test.

The fourth test was a repeat of the third test with $-40°C$ and left to stabilize and survived approximately 50min as seen in Figure 178.

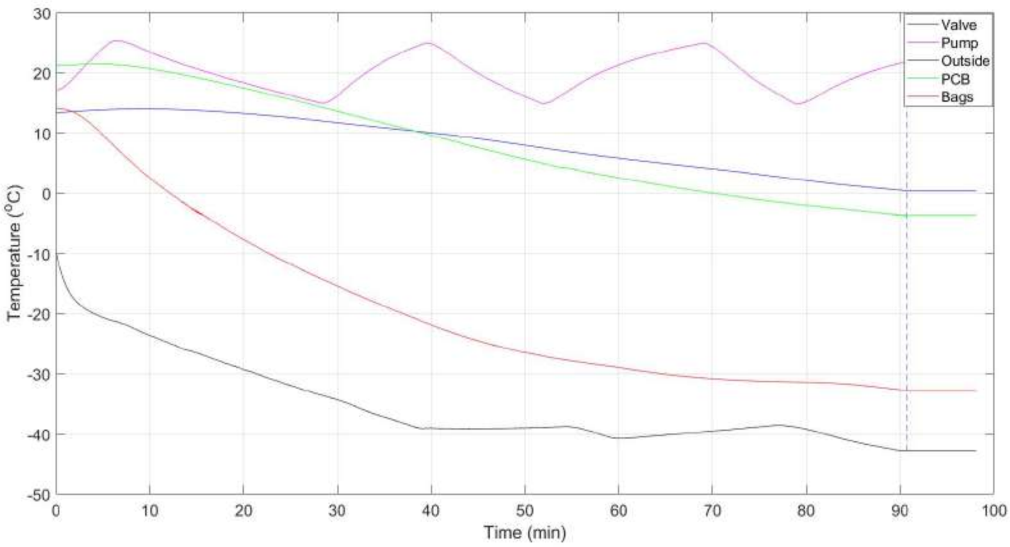


Figure 178: Fourth Thermal Chamber Test.

A separate test was completed afterwards with only the CAC inside the freezer and the AAC outside with cables going to the CAC. The freezer was at $-26°C$ and the communication error occurred as seen in Figure 179.

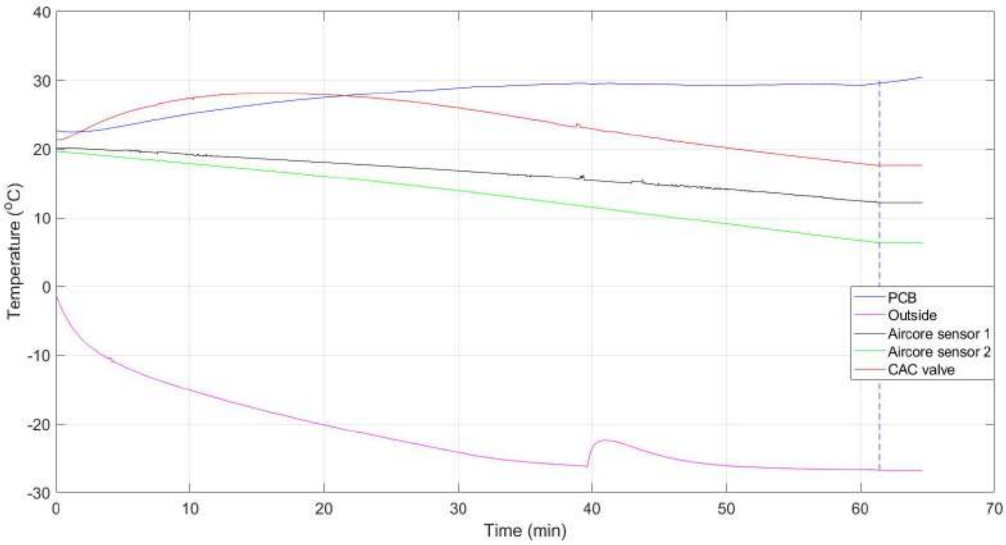


Figure 179: CAC Thermal Chamber Test.

The conclusion of the test is that the heating regulations for the pump and the manifold are working as they should keeping the critical components operating. It was concluded that the PCB is not the issue for the temperature sensors to give back error. The communication error was solved and a 8h freezer test were done at IRF to see if it could work in $-20°C$ temperature. At the same time three different resistors were put for the outside pressure sensors. The resistors produced 0.1W, 0.5W and 1W to the pressure sensors to determine the temperature difference from ambient temperature. In Figure 180 the temperatures is shown over time.

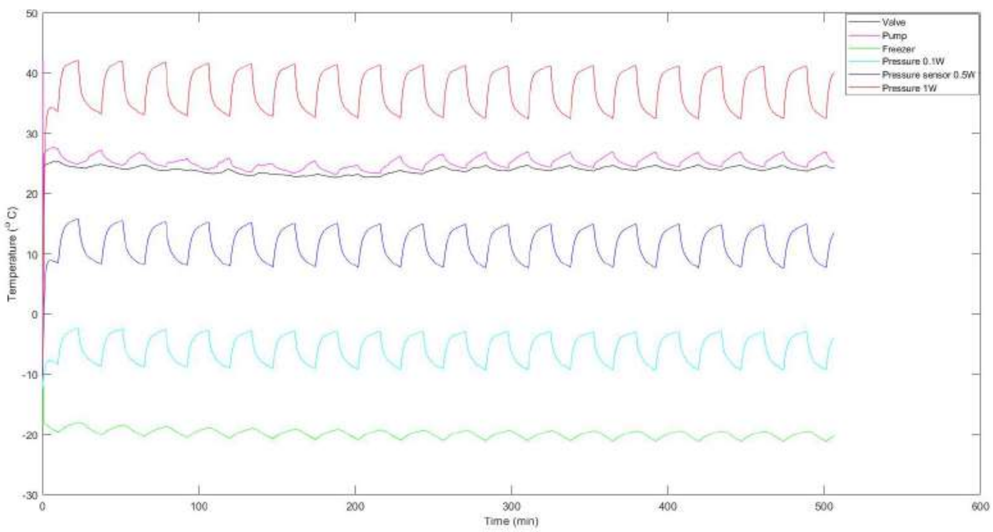


Figure 180: Freezer Test for 8h at IRF.

The average temperature difference between the pressure sensor and the ambient temperature was as can be seen in table 81.

Watt from resistor (W)	0.1	0.5	1
Temperature difference ($^{\circ}C$)	14.0488	31.336	56.9809

Table 81: Temperature Difference on Pressure Sensor from Ambient.

A final thermal test were done at Esrange. The test were 3h and 30min at $-50^{\circ}C$ where all functions were tested and then went down to $-60^{\circ}C$ to try the experiment a little more. In the end the test lasted 4h 40min.

As seen in Figure 181 the temperature of the pump (pink) and the valve (black) have their heating cycles fully working. After a little more then an hour the flushing were tested. Then soon after the pump and it can be seen that the temperature of the pump drop bellow zero. It were confirmed then if the pump is operating it can drop bellow zero and keep going. It were found out that when it were $-55^{\circ}C$ and colder the valve heater could not keep up fully and started to drop in temperature when the valves were not operating. Even while the temperature were dropping it were so slow and that it will not drop bellow operating temperature during flight and if the valves are operating they generate some heat as well.

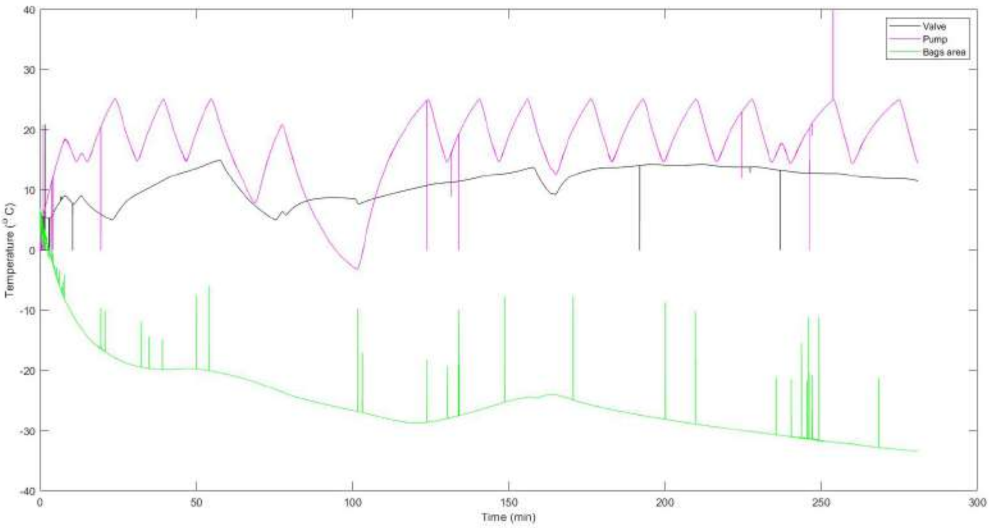


Figure 181: Thermal Chamber Test.

In Figure 181 it can be seen a lot of spikes and it is when the software returns an error value. It is not an issue because the error rate is so low and goes back to working directly after so it does not affect the heating system.

O.4.4 Test 20: Switching Circuit Testing and Verification

This has begun on breadboards with LEDs replacing the valves until the valves arrive.

So far DC-DCs have been set up and tested. Sensors have been connected electronically and the next step is to get them to communicate with the Arduino.

Mosfets connecting to the pump and the heaters have been tested for switching on and off with good results.

O.4.5 Test 32: Software Failure

So far testing has revealed that losing the SD card does not interrupt ground station data, it just means no data will be written to the SD card. However, if you reconnect the SD after removing it currently it will not connect back to the SD card and it as if the SD card has been permanently lost.

O.5 Test 33: Electrical Component Testing

The components were separately tested and later on tested together inside the full system. The separate component testing can be seen in Table 82. The results of these tests can be seen in Section O.5.1. There was also a full assembly off all components on the bench connected on a breadboard. This test was carried out with nominal results. Furthermore there were some PCB tests which can be seen in Table 83. The results of these tests can be seen in O.5.2

Complete	Test #	Test	Description
YES	1	Test Voltage divider (Airflow + Pressure sensor)	Test the airflow sense with voltage divider and check the voltage output with divider vs without to control that signal does not get interfered
YES	2	Test MOSFET	Test the MOSFETS by applying 3.3v to the gate from something else than Arduino
YES	3	Test LED Configuration	Test the resistance and zener diode configuration
YES	4	Test Valves with MOSFET	Test to open and close valves through the MOSFETS without Arduino 3.3v
YES	5	Test Pump + MOSFET	Same as valves but for pump
YES	6	Test DCDCs in parallel with LED	Test that the parallel configuration of the dcdc converters with the indication lights and make sure it works as expected
YES	7	Test interface connections	Test the dsub and power cables that will be inside the brain by checking for connectivity and wire resistances.
YES	8	Test Potentiometer trimming for DCDC	Test the DCDC trimming by using the potentiometers
YES	9	Test grounding for analog components	Test the grounding configuration for the analog components and compare it with non isolated ground wile turning on other power hungry components
YES	10	Heater testing	Supply 28.8v to the heaters in paralel and see if they work outside their limits described in the datasheet.

Table 82: Electrical Component Testing Detailed Descriptions

Complete	Test #	Test	Description
YES	12	Check conections	Check that all soldering points are connected to the right parts of the board
YES	13	Assembly	Solder everything in it's places and turn the board on and chech that everything is working nominaly

Table 83: PCB Tests with Detailed Descriptions

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O.5.1 Test results for Electrical component testing

- Test 1: The max output from the airflow sensor was not 10V as advertised, it was instead 10.82V. The resistors in the voltage divider will be changed accordingly to take care of this problem and not to damage the Arduino. There will be 240k Ohms on the upper part of the voltage divider and 100k on the bottom. This will limit the max output to approximately 3.2V which will be safe for the Arduino. Pressure sensor max output was approximately 9.54V at ground level. The sensor is sensitive to the voltage divider. It seems that a larger resistance lowers the output compared to an open circuit. After testing with three resistors at 330k, 100k, 33k and 3.3k Ohm resistor it was seen that using 330k Ohm the output was measured to 7V over the whole bridge. With the 3.3k Ohm voltage divider the output was measured to be 9.52V which is 0.2% below open circuit which is smaller than the measurement error of the sensor itself. Furthermore the output had a lot of very small spikes which gave a voltage ripple of 300-400mV, adding a 0.47uF capacitance in parallel to the output and ground decreased the ripple to 60-70mV. Larger capacitors did not lower the ripple although smaller capacitors increased the ripple. Furthermore the start up spikes of the senor has to be rectified, therefore a 1uF capacitor will be added to the sensor output on the wiring since there is no space dedicated for this on the main PCB. Furthermore, huge spikes of upwards to 30V peak to peak was discovered on turn on on the Vin on the pressure sensor. Therefore a 100uF electrolytic capacitor will be added in parallel to the 12 system
- Test 2: Using the MOSFET as a grounding switch and supplying 3.2V to the gate the resulting drain to source voltage was below 0.3V for components using 24V or 28V
- Test 3: 1k Ohm on 12V 3.9k Ohm for 24V as pull-up resistors
- Test 4: The circuit worked as expected. The circuit pulled 127mA at 24V 3.048W for one manifold valve. The valves on the tubing gave the same results
- Test 5: Supplying 3.2V to the gate on the MOSFET started the pump as expected.
- Test 6: The circuit functioned as expected. The indications are indicating each DCDC individually
- Test 7: All interface connections have been checked with good result by using the continuity measurement on a multimeter
- Test 8: Trimming works, extra resistors had to be added in series with the potentiometer to get the resistance required for the voltage output that was required. 26+390k Ohm for 24V. 15 + 32k Ohm for 12V
- Test 9: The proposed way of grounding analog sensors works. Although, if there is a faulty grounding somewhere else, the Arduino sits at risk since all the grounding current goes through the Arduino and might burn the Arduino
- Test 10: Using the heaters in parallel at 28.8V worked fine as long as they had some material to dissipate the heat into. Otherwise they are overheating. This is true at 28V as well which is the specified max voltage. Supplying 28.8V will not be a problem.

The heaters did use a little extra power. The specific power draws were: 28.62V and depending on the temperature the power draw was 0.37-0.36A. This results in a power draw of 10.59W which is 0.59W or 5.9% more than expected.

O.5.2 Test Results for PCB Testing

- Test 12: All connections were checked and it was discovered that some connections were not connected and some were faulty connected. There was one MOSFET gate pin that was not connected. The 28.8V power that goes to the heaters was connected to the 24V power. And the 24V power was not connected to the dc-dc. This was solved by adding a separate wire to connect the 24V power to one of the pins 24V pins on the D-Subs, since the D-Subs were connected together. The 28.8V power was solved by removing the cable from the d-sub and adding a separate connector that goes to 28.8V power. The MOSFET gate problem was solved by adding a wire from the correct Arduino pin to the corresponding MOSFET gate pin.
- Test 13: After the connections was checked and the problems resolved, the board was turned on. The functionality was checked and everything worked nominally.

O.5.3 Test 27: Shock test

The entire pneumatic system and electrical system was mounted in the AAC box along with the walls and styrofoam attached. It was then dropped from a height of approximately one meter three times. Nothing came loose or was damaged after this drop test. All electronics were verified to still work.

O.5.4 Test 9: Vibration test

The entire experiment was placed in the tailgate of a car, while the test was carried out on a 18 km long rough terrain. An emergency brake was also implemented during the test. The experiment's functionality and structural integrity were capable of handling the vibrations and the stopping force. No damages or issues were detected after this test.

O.5.5 Test 25: Structure test

A team member was placed on top of each box's structure, see Figure 183. Both the CAC and AAC box was able to fully support the member's weight without showing any instability or deflections. No damages or issues were detected after this test.

Figure 182: Structure Test for AAC Box

O.5.6 Test 12: Removal test

For a non team member to perform the removal of the CAC box based on the given instructions, it took that person 6 min and 25 sec. One problem that occurred during this test was that the person had problems to distinguishing the CAC from the AAC box. To resolve this the boxes will now have clear labels on them. The set up for this test can be seen in Figure **??**.

Figure 183: Picture Showing how the Experiment was Mounted on the Bench.

There were additional confusions during the test due to the fact the experiment was not actually fixed to the gondola and it had to be explained what was meant by gondola attachment points. The items to be unscrewed were also not yet clearly marked which also added time to the test. It is expected that the time will be lower for the recovery team due to this. Therefore the team finds this time to be satisfactory.

O.5.7 Test 2: Data collection test

The full software was run in auto mode to check everything operated as expected over a full test flight. At the end of the simulated flight the experiment was to shutdown automatically. This was tested both on the bench and in the vacuum chamber. In the vacuum chamber tests, see Section 5.3.6, the bench test, see Appendix O.5.8 and the thermal test, see Appendix O.4.3 data collection was also monitored. It was found that the physical samples were being collected properly and all the sensors were returning good data.

O.5.8 Test 7: Bench test

The experiment was run for 5 hours simulating 1 hour on ground, 1.5 hours in ascent, 2 hours in float and 0.5 hours in descent. The experiment was found to be operating as intended at all points. Additionally, the temperature sensors have been tested at ambient conditions for over 6 hours. No problems were found with the temperature sensors on the bench.

O.5.9 Test 16: Sampling test

The system was tested while already mounted as this test was pushed back due to the late arrival of the static pressure sensor.

The Arduino successfully controlled all valves and the pump and through the static pressure and airflow sensor readings alone it could be confirmed if a bag was sampling.