Risk Management Framework for Parachute Mortars on Sounding Rockets

Increasing the safety and functional performance of the parachute mortar

MOT2910: MSc Thesis Project

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by

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Cover: The parachute mortar assembled for ejection testing (May 12th, 2023).

TU Delft

Preface

I have been intrigued with parachute recovery systems ever since I joined Delft Aerospace Rocket Engineering. Throughout my studies in the Management of Technology program, I sought to find a way to combine project management aspects with technical systems and content. This thesis topic provided an excellent opportunity to explore and develop both these qualities.
Working on parachute systems has been a fascinating experience, as they play a crucial role in the success or failure of a mission, despite often receiving less attention on sounding rockets. Although the parachute mortar was already well developed within the Supersonic Parachute Experiment aboard REXUS (SPEAR), I aimed to take the design further and make it more accessible within DARE. The potential of this system as a robust and reliable deployment device inspired me to contribute my efforts to the successful recovery of many missions within our society. Improvements on parachuting systems are never ending, and so also on this mortar system. May it evaluate another ten times over, as long as it provides members with an educational experience.

I am deeply grateful for the unwavering support and motivation of my supervisor, Ming Yang. Despite my countless questions and ambitious plans, he patiently engaged in discussions and provided continuous encouragement. I would also like to extend my gratitude to Udo Pesch, as the chair of the thesis committee, for his meticulous reviews and invaluable feedback, which helped me maintain a high-level perspective throughout the thesis instead of getting lost in the technical details.

While the risk mitigation activities may only occupy a small portion of the overall pages of this thesis work, the redesign, production, testing, and launching of various systems constituted a significant part of the work. I want to express my sincere appreciation to Thomas, Ijsbrand, Oszkar, Anibal, and Andrew for their contributions in machining various hardware parts, enabling the successful execution of these tests, as well as all the team members involved in the design, construction, and launch of Py-Rocket.Special thanks to Claudio for stepping in to assist with the vibration test campaign, tricky snap rings, and post-processing the data plots. During all these activities, the vibration test campaign proved to be a tremendous learning experience, thanks to the guidance and expertise of Loris and Max, the exceptional operators and educators from ESA.

Lastly, I would like to express my gratitude to my family and friends for their unwavering support and motivation throughout this demanding period. A special acknowledgement goes to my boyfriend, who patiently answered my numerous queries about mortar systems, tests, failure modes, and CAD work, whilst being positively supportive of all my endeavours. Their collective contributions have been instrumental in the successful completion of this thesis research, and I am truly grateful for their presence in my journey.

Esmée Menting
Delft, June 2023

Executive Summary

The executive summary offers a concise overview of the thesis research conducted, focusing on enabling risk management for parachute mortars on sounding rockets from a socio-technical perspective. The study aimed to address safety and performance risks associated with these systems and bridge the gap between theoretical risk management methods and practical applications.

The research was initiated with a comprehensive review of the relevant literature, which identified several gaps in the existing knowledge. These included a lack of detailed coverage on risk identification, assessment, and evaluation in case studies, limited information on parachute mortar systems specific to sounding rockets, and a lack of application of socio-technical systems to technical subsystems in spaceflight.

The primary objective of this study was to develop a comprehensive risk management guideline specifically tailored for parachute mortar systems, integrating a socio-technical systems approach. The guideline aimed to be grounded in conventional risk management practices while being validated through a practical case study to ensure its feasibility.

Throughout the research, various results were obtained. The evaluation of conventional risk management methods, including ISO31010, industry practices and socio-technical views, led to the initial design of the risk management approach. This approach was then applied to a case study involving the DARE mortar, allowing for the reflection on each method's effectiveness. Key risks identified were related to the carbon fibre reinforced polymer (CFRP) canister of the mortar system and risks of underperformance due to pressure leaks in the system during flight. These critical risks were successfully reduced through redesign and testing activities in the risk treatment phase of the case study. The final Risk Management Guideline was developed by incorporating the lessons learned from applying the approach to the case study.

By applying the developed framework to a real-world scenario, this research went beyond theoretical considerations and demonstrated the practical applicability of the socio-technical system approach in mitigating risks associated with parachute mortars on sounding rockets. The combination of a practical case study, a socio-technical approach, and risk management on sounding rocket subsystems is considered novel and has the potential to advance risk management activities in this domain.

The research also identified several future research directions. These include performing more case studies on smaller technical subsystems using a socio-technical systems approach, exploring and establishing consensus on definitions and boundaries of socio-technical systems, integrating qualitative results of human reliability analysis with risk management methods, and defining objective methods for risk evaluation and establishing risk acceptance criteria.

Overall, this thesis research contributes to the field of risk management by addressing the unique challenges of parachute mortars on sounding rockets through a socio-technical systems perspective. The developed risk management guideline, validated through a practical case study, provides valuable insights and practical applications for mitigating risks in this specific context. It is anticipated that this research will facilitate further advancements in risk management activities for parachute mortars and socio-technical systems while also having the potential to be applied to other sounding rocket subsystems.

Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
ACH	Aircraft Hall
ASK	Artillerie Schietkamp (military shooting and exercise range)
ASPIRE	Advanced Supersonic Parachute Inflation Research Experiments
BEM	Ballistic Evaluation Motor
CEV	Crew Exploration Vehicle (Orion capsule)
CFRP	Carbon Fibre Reinforced Polymer
COTS	Commercially-off-the shelf
CPAS	CEV Parachute Assembly System
CSL	CanSat Launcher
DARE	Delft Aerospace Rocket Engineering
DOT	Design Option Tree
DUT	Device Under Test
EuRoC	European Rocketry Challenge
ESA	European Space Agency
ESD	Electrostatic Discharge
FTA	Fault Tree Analysis
FMEA	Failure Modes and Effects Analysis
FPS	Frames Per Second
GG	Gas generator
GMA	General Members Assembly
HRA	Human Reliability Analysis
IRM	Intermediate Rocketry Motor
LADT	Low Altitude Drop Testing
LAT	Lot Acceptance Testing
LDSD	Low Density Supersonic Decelerator
MPF	Mars Pathfinder Mission
MER	Mars Exploration Rover
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
NLR	Netherlands Aerospace Centre
NTC	Nitrocellulose
OSO	Operational Safety Officer
PRG	Parachute Research Group
PEPP	Planetary Entry Parachute Program
PLA	Polyactic acid
PPE	Personal Protection Equipment
PSF	Performance Shaping Factor
RCF	Rocket Check Form
RSO	Range Safety Officer
SCD	Science Centre Delft
SO	Safety Officer
SoTeRiA	Socio-Technical Risk Analysis
SPEAR	Supersonic Parachute Experiment aboard REXUS
SRP	Small Rocket Project
SRQ	Sub-research Question

Abbreviation	Definition
SSC	Swedish Space Corporation
SStS	Stichting Students to Space
SUPERMAX	SUpersonic Parachute Experiment Ride on MAXus
SPF	Single Point of Failure
TRP	Thermal Rocket Propulsion

Concepts

Concept	Definition
Sounding rocket	Rocket designed to take measurements and perform scientific experiments during its sub-orbital flight.
Recovery system	(Sub)system in a space vehicle which aims to land a payload safely in order to retrieve data and hardware or to execute a mission.
Drogue parachute	Small parachute which deploys first in order to slow down or stabilise the vehicle, or to pull out a larger main parachute.
Systems engineering	Systematic approach to develop complex systems, focusing on the integration and interfacing between various (sub-)systems.
Validation	The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers.
Verification	The evaluation of whether or not a system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process.
Risk	The combination between the probability (likelihood) that a scenario will happen and the (negative) consequences that the occurrence of the scenario will have on the system or mission.
Performance risk	The risk that a part or (sub)system will not function nominally, resulting in an undesirable outcome.
Safety risk	The risk that a person may be harmed during operations on or functioning of the (sub)system.
Safety zone	Designated area reserved for a rocket launch to ensure the safety of the general public, personnel and equipment.
Qualitative risk analysis	assesses risks without numerical input, but is evaluated verbally using qualifiers like high likelihood, low likelihood, etc.
Quantitative risk analysis	uses numerical (verifiable) data as input on assessing risk.
Plenum volume	volume in which the gas from the gas generator expands, between the canister and the sabot.
Ejection tests	Tests of the parachute mortar to confirm successful ejection, and optionally performance
Flight tests	Test of a (sub)system on a sounding rocket launch
Accident	An undesired event that results in injury
Incident	An undesired event that results in property damage or minor injury (cut, scrape), or debris exiting the safe zone of a test/launch
Launch window	The allocated time to perform final preparations on the sounding rocket before launching. Includes motor insertion, pyrotechnic insertion or connection, and final arming.
Intolerable risk	Risk that is so high, that it must be treated.
Tolerable risk	The risk is undesirable, but the resources required to treat the risk are balanced against the potential risk reduction.
Acceptable risk	Risks that are broadly accepted and do not require mitigation activities.

1 Introduction

1.1. The significance of parachute mortar systems

In the realm of high-altitude missions, the recovery of payloads poses a critical challenge that warrants thorough examination. Sounding rockets can reach great heights and rely on efficient recovery systems to receive flight data and salvage hardware for analysis and reuse. Among the various options available for parachute deployment, the parachute mortar system emerges as a method of remarkable performance and reliability. Its significance spans from historic missions such as Apollo to modern endeavours like the Mars 2020 Perseverance Rover, and has even found application in student rocketry. In this thesis, the intricacies surrounding parachute mortar systems on sounding rockets are explored. The main objective is to enhance their performance and safety through the lens of risk management, employing methodologies and guidelines adapted to this unique domain of engineering.

A sounding rocket is a suborbital launch vehicle designed to carry scientific instruments and experiments into the upper atmosphere or space for a short duration of time. Unlike orbital rockets that aim to achieve a stable orbit around the Earth or other celestial bodies, sounding rockets are primarily used for research, educational, and technological purposes. These rockets offer several benefits to society and scientific exploration. Firstly, they enable scientists and researchers to gather valuable data about various atmospheric phenomena, such as the Earth's upper atmosphere, auroras, cosmic rays, and microgravity conditions. For instance, the Swedish Institute of Space Physics (IRF), recently launched a scientific experiment on the BROR rocket from Esrange, Kiruna, aiming to study auroras in the ionosphere [91]. Secondly, these rockets serve as a platform for testing and validating new technologies and instruments before their deployment on larger space missions. Notable examples include the Black Brant series of sounding rockets utilised by various space agencies worldwide, such as NASA's suborbital rocket missions for studying astrophysical phenomena or the German Aerospace Center's TEXUS program for microgravity research. Lastly, sounding rocket launches contribute to the education and training of students and early-career scientists, allowing them to gain practical experience in designing, building, and conducting experiments in a space-like environment. For instance, both the REXUS/BEXUS programme and the NASA-sponsored High Altitude Student Platform (HASP) provide university students with the opportunity to fly their experiments on a sounding rocket, fostering hands-on experience and encouraging scientific inquiry [27] [22]. The knowledge gained from sounding rocket missions not only expands our understanding of the universe but also lays the foundation for future space exploration and technological advancements.

Recovery systems are implemented in sounding rockets for various reasons, such as retrieving valuable flight data that cannot be sent over a telemetry downlink or recovering and refurbishing hardware for analysis, display or reuse. High-altitude recovery systems generally consist of two or more parachute stages. Here a drogue parachute is deployed to stabilise and decelerate the vehicle such that the main parachute, the main decelerator, can deploy safely [35]. The deployment of these drogue parachutes is generally quite violent and can include extremely high (supersonic) velocities, high inflation loads, or instability of the vehicle.

Notable examples of parachute failure due to a slow deployment may include entanglement or inversion of the parachute, or lines being damaged due to a sideways deployment [13] [2]. A slow ejection from a vehicle travelling supersonically can also result in the parachute not deploying from its container or parachute bag at all due to the airflow around the vehicle [29]. Lastly, a slow parachute deployment significantly decreases the reliability of the deployment altitude and conditions as the vehicle can quickly descend multiple kilometres when travelling at supersonic speeds [35]. These conditions lead to the need for a fast drogue parachute deployment. Amongst the options for parachute deployment systems with a high ejection velocity is the mortar [30]. The parachute mortar design has been implemented in various missions worldwide, from the Apollo missions [78] to the Mars 2020 Perseverance Rover [83]. Although mortar systems are more frequently used in crewed vehicles or interplanetary missions, they can also be used on sounding rockets, which are designed to perform scientific experiments during their sub-orbital flight.

When rockets and spacecraft are launched and their operations start, there is little to no access to make adjustments or fix issues. This necessitates meticulous ground-based preparations to ensure the flawless functioning of all systems. One crucial aspect that cannot be understated is risk management in space engineering. Risk management plays a pivotal role in guaranteeing the safety, reliability, and ultimate success of rocket launches. By identifying, assessing, and mitigating potential hazards, risk management helps managers avert costly delays, injuries, and project failures [4]. It can be considered a fundamental part of the project life cycle, from initial planning and design to construction and operation.

Risk management in spaceflight often strongly ties into systems engineering, which is a multidisciplinary approach that focuses on designing, integrating, and managing complex systems to ensure their successful development, operation, and maintenance throughout their lifecycle. Validation and verification activities are integral components of systems engineering, encompassing the systematic processes and methods used to assess and confirm that a system meets its intended requirements, objectives, and performance criteria [38]. In this context, engineering risk management emerges as the linchpin process that facilitates a comprehensive understanding of the risks associated with a system and alignment with the system's intended purpose. By prioritising risk management, space engineering endeavours can effectively address potential challenges and instill a higher level of confidence in the overall mission's accomplishment.

Let us now consider risk management on parachute mortar systems. When reviewing the full sounding rocket, parachute mortars may not be the most critical subsystem to ensure a successful launch and mission execution. The scientific missions on sounding rockets predominantly perform their research during or shortly after ascent of the rocket. During these flight phases, the propulsion system and structural sections of the rocket could be the main cause of a catastrophic failure. Therefore, the significance of parachute mortars lies in the recovery of hardware and valuable data, as the successful retrieval of the rocket, experiments and their components remains vital for a considerable number of missions. In this context, the parachute mortar system plays a crucial role as a flight-critical element, as it enables the successful deployment of a (drogue) parachute and therewith the safe deceleration and stabilisation of the rocket during descent. Thus, effective risk management is of utmost importance to safeguard the reliable deployment and functionality of parachute mortars, reducing the risks associated with the recovery process and bolstering confidence in achieving all mission objectives.
Moreover, parachute mortar systems utilise pyrotechnics and is a high-pressure system after actuation, which can pose hazards to the operator during testing and/or final assembly. Given the inherent risks associated with these components, it becomes imperative to employ risk management practices. By implementing appropriate safety measures and protocols, risk management can ensure safe operations throughout the testing, handling, and assembly processes, significantly reducing the potential for personal harm or damage to property. To summarise, there is an unmistakable need for risk management on such a mission-critical system, to ensure safe operations, and increase confidence in a nominal in-flight performance.

1.2. System overview of a parachute mortar

The parachute mortar is essentially a short, smooth tube that is sealed at one end and attached to the rocket. When the parachute needs to be deployed, an electrical signal is sent to a small explosive charge at the sealed end of the tube. The explosion propels the parachute out of the tube and away from the rocket. A more detailed view of this system overview and an ejection test can be seen in Figure 1.1 [87] [43]. The working principle of the mortar is as follows; pyrotechnics in the power unit on the left side will create hot gas when ignited. This power unit consists of a pyrotechnic charge with electrical matches, a breech which forms the structural connection between the charge and the mortar tube, and an orifice (narrow opening) through which the gas enters the mortar tube.
When the hot gas expands it exerts pressure on the sabot, which is a sliding disk, that in turn exerts pressure on the parachute pack and the lid. The lid is constrained using shear rivets or pins, which shear off when a predetermined pressure is reached. At this moment the lid, parachute pack and sabot will be ejected from the canister at a high velocity. In nearly all parachute mortar systems the power unit uses a pyrotechnic charge to create pressure. Alternative designs use cold gas with the same result, however, these subsystems are not reviewed in-depth.

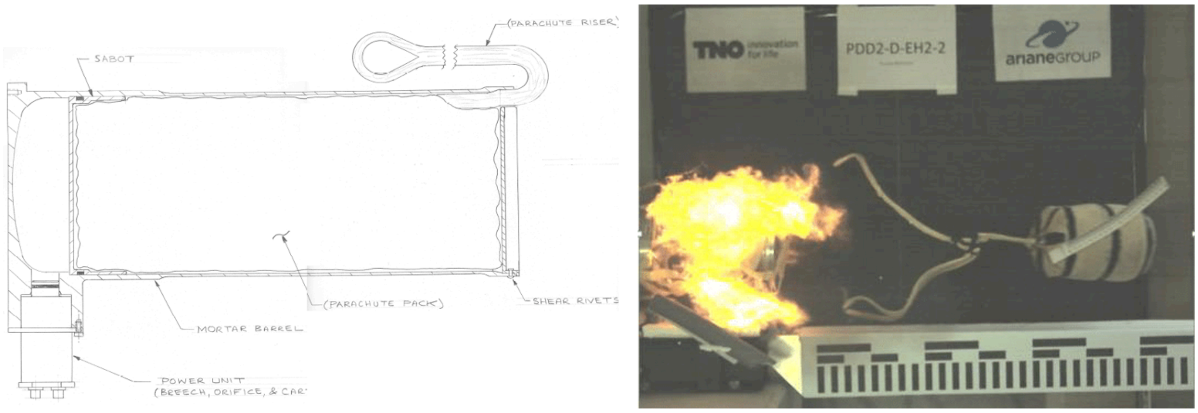

Figure 1.1: System overview of a parachute mortar [87] (left) and ejection test of the ExoMars2022 mortar design [43] (right)

1.3. Research relevance

1.3.1. Case study

The topic of this thesis originated from a practical problem encountered during the development and launch of a parachute mortar by the student team Delft Aerospace Rocket Engineering (DARE). Specifically, the parachute mortar was developed for the Supersonic Parachute Experiment Aboard REXUS (SPEAR) mission [47]. This parachute mortar design has undergone various V&V activities to increase confidence in a nominal performance [48]. Additionally, the SPEAR mission has recently been flown on REXUS28 to an altitude of 95.7km, where the parachute mortar demonstrated its functionality in flight by deploying a Hemisflo ribbon parachute at 38.5km altitude whilst travelling at Mach 2.9. However, various risks from a performance and safety aspect are still present within the system, which stem from the limited development time available. This prevented the team from conducting an extensive number of tests and fully understanding the system's functionality. To ensure the continued safe operation and increase confidence in the nominal performance of the parachute mortar for future missions within DARE, it is necessary to undertake further risk management efforts. This is especially crucial as new teams and inexperienced DARE members may be involved in the system's use in the near future. However, determining the best approach for conducting risk management on the DARE mortar is not straightforward. While a wealth of scientific research exists on risk management methods, it remains unclear which methods are most suitable for sounding rockets, specifically for the parachute mortar system, and how to practically apply these methods to the unique case of the DARE mortar. Addressing these challenges will involve exploring the suitability of different methodologies, identifying relevant risks, and establishing a comprehensive risk management process tailored to the DARE mortar system.

1.3.2. Scholarly relevance

Determining the best approach for tackling risk management in the context of parachute mortar systems on sounding rockets can be a complex task. The scientific and engineering domains offer a vast array of methodologies and frameworks for risk assessment and mitigation. However, these approaches often lack the specificity required to apply them effectively to the unique challenges presented by subsystems in the space sector. The challenge lies in finding concrete, real-world practices and guidelines that bridge the gap between theoretical frameworks and practical implementation. Currently, there is a limited availability of examples demonstrating the application of risk management methods to subsystems on sounding rockets, making it challenging to establish a clear structure for these efforts. Nonetheless, having an exemplar case where theoretical risk management models are successfully applied to a practical, detailed scenario would provide a solid foundation for building a comprehensive risk management process tailored to sounding rocket subsystems.

This thesis aims to evaluate and compare various risk methodologies to identify the most suitable approaches for managing risks associated with parachute mortars on sounding rockets. Building upon this selection, a real-world case study will be conducted to validate the selected risk management methods, demonstrating their practical implementation and effectiveness in identifying, assessing and mitigating risks. The insights gained from this analysis will provide valuable recommendations for the utilisation of these methodologies in practice, enabling improved risk management practices for parachute mortars on sounding rockets. Ultimately, this research endeavours to enhance the safety, reliability, and success of sounding rocket missions by optimising the risk management process for these critical systems.

The research conducted in this thesis holds significant implications beyond the scope of the DARE parachute mortar. The findings and methodologies developed can be readily applied if parachute mortars are implemented on other sounding rockets, for example on Muira 1 (PLD Space) or Barracuda (T-Minus Engineering). By leveraging the insights gained from this research, these organisations can lower development cost and time whilst enhancing their risk management practices to ensure the safe and reliable deployment of parachute systems on their respective rockets. Furthermore, the broader application of this research extends to comparable systems on sounding rockets that play a crucial role in mission objectives. For instance, other mechanical subsystems with actuation or movement can benefit from the developed risk management methodologies. Examples would include different parachute deployment systems, such as spring-based deployment systems or tractor rockets, rocket separation mechanisms like clamp bands or pusher plate systems, and numerous general actuators such as pyrotechnic bolts, frangible nuts or pin-pulling release mechanisms. By applying the selected frameworks and recommendations, these subsystems can be effectively assessed, mitigating potential risks and increasing the overall success and reliability of sounding rocket missions.

The research outcomes of this thesis therefore contribute to advancing risk management practices not only for the DARE parachute mortar, but also for a wide range of related systems within the sounding rocket domain. By embracing these findings, organisations and researchers in the field can further enhance the safety, operational efficiency, and mission success of their sounding rocket projects, ultimately fostering advancements in scientific exploration, data retrieval, and technology development.

1.3.3. Societal relevance

As described in section 1.1, sounding rockets serve as valuable platforms for atmospheric research, technology demonstration of spaceflight systems, and educational programs, each with distinct benefits for society.

1. Atmospheric research conducted using sounding rockets provides valuable insights into the Earth's atmosphere and its various phenomena. By carrying scientific instruments and experiments to high altitudes, these rockets enable researchers to study atmospheric composition, dynamics, and interactions with space. This research enhances our understanding of climate change, air quality, ozone depletion, and other crucial environmental factors. The data gathered from atmospheric research missions on sounding rockets contributes to the development of accurate models, forecasts, and mitigation strategies, leading to improved environmental policies and protection of natural resources.

2. Technology demonstration missions on sounding rockets play a crucial role in advancing spaceflight systems and technologies. These rockets provide a cost-effective means to test and validate new technologies, components, and materials under relevant space conditions. By subjecting these systems to the harsh environment of space, including extreme temperatures, vacuum, and vibrations, sounding rockets enable engineers and scientists to assess their performance, reliability, and durability. The knowledge gained from such technology demonstrations paves the way for the development of more robust, efficient, and innovative space systems, ranging from satellite components to propulsion systems, benefiting future space exploration, telecommunications, Earth observation, and even commercial applications.
3. Sounding rockets offer unique educational opportunities for students, researchers, and the general public. Educational programs involving sounding rockets provide hands-on experiences, fostering interest and engagement in STEM (science, technology, engineering, and mathematics) fields. Students and young scientists can actively participate in designing, building, and launching experiments on these rockets, gaining practical skills and knowledge in aerospace engineering and scientific research. The collaborative nature of sounding rocket projects encourages teamwork, problem-solving, and innovation. Moreover, the public engagement aspect of sounding rocket launches raises awareness about space science and technology, inspiring the next generation of scientists, engineers, and explorers. These educational benefits contribute to the development of a skilled workforce, scientific literacy, and societal appreciation for space exploration and research.

Numerous sounding rockets are equipped with a recovery system to retrieve valuable data sets, experimental hardware, and the launcher for potential reuse. However, when a recovery system fails, it can significantly impact the amount and quality of data obtained from the mission, thereby diminishing the associated societal benefits. The extent of these impacts varies depending on the mission design and the availability of alternative methods, such as telemetry, for receiving experimental data.

The successful recovery of sounding rockets plays a crucial role in retrieving valuable hardware and enabling its potential reuse. The development of reusable sounding rockets brings numerous benefits to the space sector, leading to a growing interest in this technology. First and foremost, reusability significantly reduces the overall cost of launch operations. By enabling multiple launches with the same vehicle, the expenses associated with manufacturing new rockets for each mission are substantially reduced. This cost reduction opens up opportunities for more frequent and affordable access to space, fostering innovation, research, and commercial activities. Moreover, reusable sounding rockets contribute to enhanced sustainability in space exploration. Reusing recovered hardware not only conserves valuable materials but also minimises the environmental impact associated with manufacturing new components. By reducing resource consumption and waste generation, successful recovery contributes to sustainable practises and aligns with the principles of a circular economy. Reusable launchers, by minimising the need for new rocket production, promote a more environmentally friendly approach to space activities.
Additionally, reusable sounding rockets offer greater flexibility and responsiveness in mission planning. With reusable launchers, researchers and scientists have the advantage of rapid turnaround times between launches. This allows for iterative testing, experimentation, and data collection, facilitating the advancement of scientific knowledge and technological development. The capability to conduct frequent launches also supports educational programmes and hands-on training, empowering students and researchers to gain practical experience in space-related disciplines. Overall, the transition towards reusable sounding rockets represents a significant step forward for the space sector. The cost savings, sustainability improvements, and operational flexibility offered by reusable launchers align with the industry's goals of expanding space exploration, fostering innovation, and making space more accessible to a broader range of stakeholders.
On the other hand, when recovery fails and subsystems crash in unintended areas and are not retrieved, it poses environmental hazards and disrupts the local ecosystem. The materials used in these subsystems, such as metals, plastics, and fibres, may have adverse effects on the surrounding environment, including soil contamination, water pollution, and potential harm to wildlife. The ecological damage caused by failed rocket recovery emphasises the importance of effective risk management on recovery subsystems to mitigate these environmental impacts. In summary, the successful recovery

of sounding rockets not only aids in the retrieval of valuable hardware but also promotes resource efficiency, reuse, and prevents environmental pollution and harm to local ecosystems.

The far-reaching societal impact that the parachute mortar system may have warrants a broader review than solely technical. The performance of the system can also impact and be influenced by various actors, such as the operator, launch provider and launch site operator. These parties all have effect on the risk management process as well, as they may influence the presence, probability and severity of risks, and they can be strongly affected by the negative consequences of insufficient risk mitigation. Due to these interactions, it is of interest to observe the system not purely from a technical engineering system perspective, but from a broader socio-technical system perspective. A socio-technical system perspective involves considering the interplay between technical elements, actors, and social elements to understand the complex dynamics and implications of the system.

A socio-technical view on risk management, incorporating not only technical aspects but also social and organisational factors, is also beneficial due to the inherent complexities and biases involved in risk analysis. Risk analysis is a subjective undertaking influenced by societal constructions, organisational priorities, and individual biases. These factors contribute to varying degrees of human bias and subjective representation throughout the risk assessment process. Consequently, risk assessments are not easily transferable across different environments, users, contexts, and organisations without considering the specific socio-technical construct in which they were conducted. To ensure a meaningful comparison of findings and results, it is essential to evaluate, describe, and review the organisational context and framing that shape the risk assessment. This is reflected upon in the ISO31000 risk management guideline, which highlights the importance of understanding the organisational context, because: "1) risk management takes place in the context of the objectives and activities of the organisation; 2) organisational factors can be a source of risk; 3) the purpose and scope of the risk management process may be interrelated with the objectives of the organization as a whole" [32].
Unfortunately, the socio-technical setting, analysis, and framework are commonly omitted or inadequately considered in many risk assessments, leading to potential misinterpretations and misapplications of the findings. Therefore, adopting a socio-technical perspective allows for a comprehensive understanding of risk, accounting for the intricate interplay between technical systems, human factors, and organisational dynamics.

1.3.4. Relevance to the Management of Technology (MoT) study programme

The research on risk management of parachute mortar systems in a socio-technical context is highly relevant to the Master of Science in Management of Technology (MOT). The MOT programme aims to educate students as technology managers and analysts in competitive and technology-based environments. The thesis research specifically addresses the challenges faced by companies in managing and utilising technology effectively. By examining the risk management of parachute mortar systems, the research investigates the intersection of technology, safety, and organisational factors. It provides insights into how technological decisions impact the overall mission, objectives, and strategies of a firm. Moreover, the research emphasises the importance of analysing and anticipating wider societal trends in the context of technological production and market dynamics. The study aligns with the MOT program's objective of developing students' abilities to analyse technologies and their commercial impact within the organisational context of a firm. The study aligns with the MOT program's objective of developing students' abilities to analyse technologies and their commercial impact within the organisational context of a firm.
The research on risk management of parachute mortar systems in a socio-technical context is highly relevant to the MSc programme Management of Technology (MOT). Risk management is an incredibly important aspect for every company venturing in technology development, as it allows a company to adequately identify and deal with potential risks. Once a risk has been identified, it is then possible to mitigate it, saving cost, time, and potential injury or damage. Therefore, risk management is a very applicable topic in the MOT programme by utilising technological expertise to advance a company's position. By examining the risk management of parachute mortar systems, the research investigates the intersection of technology, safety, and organisational factors. It provides insights into how the overall mission, objectives, and strategies of an organisation shape technological decisions and development. Through incorporating a socio-technical system view, this research further enhances the risk manage-

ment analysis by 'zooming out' to a broader picture to ensure all relevant aspects are included. The integration of non-technical and technical elements in the socio-technical system captures the intricate dynamics of real-world situations, an aspect that holds great significance within the MOT programme. Understanding the complexities of risk management in a socio-technical system enables addressing the challenging questions that companies face regarding technology development, utilisation, and strategic decision-making on the allocation of resources.

1.4. Research Outline

The thesis research encompasses several key components. It begins with a thorough literature review, which explores the topics of parachute mortars, risk management methods in engineering, and socio-technical systems. This review serves to gain a deeper understanding of the research landscape and identify any knowledge gaps. Based on the insights gained from the literature review, the research design of the thesis study is presented and discussed. This includes defining the main objectives, formulating research questions, and determining the methodology that will be applied.

The subsequent chapters focus on different aspects of the research. In chapter 4, the definition and system boundary of the socio-technical system are explored, as well as how they can be integrated into the risk management framework. Subsequently, a synthesised approach to risk management methods and practises specific to parachute mortars is developed based on conventional risk management methods, their usage in industry, and the inclusion of socio-technical aspects.

chapter 5 involves the testing and validation of the synthesised approach. A case study of the DARE parachute mortar is conducted to apply the approach and assess its effectiveness. The objective is to evaluate and mitigate safety and performance risks by implementing all phases of the risk management process, including preliminary risk treatment activities. The insights gained from this practical application are then used to refine and enhance the proposed risk management guideline.

The research is critically discussed in chapter 6, evaluating the construction of the synthesised approach and its application to the case study. It also compares and contrasts the findings with existing literature and research in the field, identifying strengths, limitations, and potential areas for further improvement. Finally, chapter 7 serves as the conclusion of the thesis research, summarising the key findings, contributions, and implications of the study. It provides a comprehensive overview of the research journey and offers insights into the broader significance of integrating socio-technical perspectives into risk management practises for parachute mortars.

The full outline of the thesis research is presented in Figure 1.2. By undertaking this comprehensive research, the thesis aims to contribute to the field of risk management, particularly in the context of parachute mortar systems. It seeks to provide valuable insights and practical guidelines for enhancing safety and performance, bridging the gap between technical and non-technical aspects within a socio-technical framework.

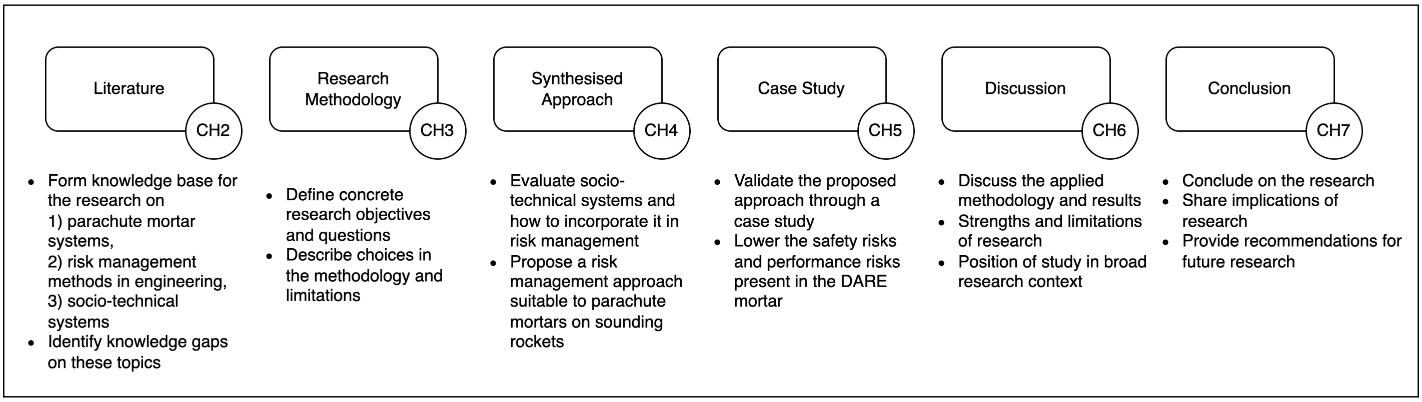

Figure 1.2: Outline of thesis research

2
Theoretical Framework

This chapter is dedicated to conducting an extensive literature review encompassing multiple topics that are highly relevant to the research undertaken in this thesis. The literature review encompasses four key areas: (1) an in-depth examination of various mortar system designs to facilitate comprehensive comparisons between the case study and industry examples, ensuring transparency in design and requirement variations; (2) an exploration of risk assessment methods in engineering disciplines, critically reviewing their applicability to the field of spaceflight; (3) an investigation into the risk management activities, including testing and flight qualification, conducted for diverse mortar systems; and (4) a study of the concept of socio-technical systems, elucidating its implicit advantages and its implementation within engineering projects and specifically within the spaceflight industry. By delving into these areas, this literature review aims to establish a solid foundation of knowledge and insights that will inform the subsequent analyses and discussions throughout the thesis. Furthermore, the chapter will conclude with a synthesis and review of the findings, highlighting the key contributions and implications of the reviewed literature.

2.1. Design of parachute mortars in space flight

Throughout this research on parachute mortars, information has been collected on the design and requirements of fourteen existing mortar systems. Requirements refer to the specific objectives, capabilities, and constraints that a spacecraft or system must meet in order to successfully accomplish its mission [38]. These requirements are established by the customer or mission stakeholders and can be divided into two main categories: functional and performance. Functional requirements are specific tasks or functions that a system must be able to perform, such as igniting a pyrotechnic charge or deploying the parachute. Performance requirements are specifications that define how well the system must perform these certain functions. For example; the maximum time between an electrical signal and ignition of the charge, or a minimum ejection velocity of the parachute pack. This set of requirements is then used as a basis for the design, development, testing, and operation of the spacecraft. It is important to note that the requirements are often iteratively refined and validated through the design, development and testing phases, and they are subject to change. This is perfectly demonstrated in the evolution of the requirements for the CPAS system, where all requirements were continuously evaluated and adapted throughout the project to ensure they remained useful and verifiable [45].

When reviewing all sources, a number of papers present the requirements that are imposed on the mortar system. The different sources that were reviewed showed great alignment in the requirements that are shown, which are described below in detail [43] [77] [84] [10]:

- Parachute pack size (diameter & length) and mass.
  The primary goal of the mortar is to house and deploy the relevant parachute. This can be a pilot chute, drogue or main parachute, with highly varying dimensions and weights. The total ejectable mass (parachute pack, mortar lid and sabot) influences the required pressure to achieve a certain ejection velocity. The packing density of the parachute pack ($\frac{kg}{m^3}$) is also relevant for the mortar

design. After mortar ignition, a low pack density will lead to more compression of the parachute before ejection, meaning more energy is required to achieve the same ejection velocity.

- Minimum ejection velocity:
  A minimum ejection velocity is primarily required by the necessity to inflate the parachute behind the body wake and before instabilities or entanglement occur, introducing a minimum distance within a restricted time [m/s]. This combination causes the requirement to be especially mission-specific, as it is dependent on vehicle aerodynamics and the deployment environment.
- Maximum reaction load:
  When the parachute is ejected, the impulse of the exiting mass creates an equal reaction load on the mortar subsystem and therefore the rocket. The higher the ejectable mass and/or the ejection velocity, the higher the reaction load will be. The mortar reaction force is a driving design load for multiple spacecraft, which therefore should be minimised.
- Maximum mortar weight or dimensions:
  This requirement is often of less importance than the others. However, it can occur, that a mission has tight constraints on volume and/or mass. In this case, the allocated mass or volume for the mortar can be a driving requirement for the design.

For each of the mortar systems described in detail in the collected sources, the (numerical) information that could be gathered on these requirements and the system design has been collected and is shown in Figure 2.1 [1].

Mission	Launch year	Ejection velocity [m/s]	Parachute pack mass [kg]	Reaction load [kN]	Mortar or parachute pack length [mm]	Mortar or parachute pack diameter [mm]	Mortar mass [kg]	GG pyro charge powder type	GG Pyro charge mass [g]
ExoMars 2020, PDD 1	[tbd]	*35-40*	*1.5-1.85*	*<12*	154 (P)	126 (P)	-	-	-
ExoMars 2020, PDD 2	[tbd]	*35-40*	*1.5-1.85*	*<15*	187.5 (P)	150 (P)	-	-	-
DC-9 & TA4E aircraft	-	36.1	15.9	28.4	412.7	310.3	8.26	M-2	28.014
PEPP	-	39.9	39.6	76.8	767.2	310.3	10.57	M-2	40.70
SPED II	-	42.9	56.1	109.1	793.4	374.6	37.24	M-5	67.5
Mars vehicle decelerator	-	33.5	44.0	53.3	541.0	374.6	10.07	PL6670	56.3
Mars Science Laboratory (MSL)	2011	*37-43*	60 53.5-59.5	*<176*	1044	500	*<24* *<28*	Wincherster 231 ball powder GD-OTS St. Marks Ball Powder	51.5 95
Mars Exploration Rover (MER)	2003	*30.5-42.7*	*16-18*	*<95*	570	278.8	*<7.4*	Winchester 231 ball powder	16.8
Viking mission	1975	*>28.7*	45.4	*<60.1*	565.4	377.9	9.30	PL6670	60
Mars scout Phoenix	2007	*Same design as MPF mortar except slight change in pyro charge*						Winchester 231 ball powder	12
Mars Pathfinder Mission (MPF)	1996	30.5-39.6	15.65	48.95	-	213.4	-	Winchester 230 ball powder	12
Orion (CPAS) drogue mortar	2014	*38.1-54.9*	*<36.3*	-	304.8 (P)	419.1	-	-	-
Mars 2020 (Perserverance rover)	2020	-	-	-	*150% of MSL mortar*		-	-	-
Low Density Supersonic Decelerator	2014	59.4	18.1	102.3	650	270	11.9	Black powder	60

Figure 2.1: Overview of mortar requirements or design specifications [43] [65] [77] [84] [72] [10] [88] [36] [83] [82]

As described in section 1.2, a parachute mortar consists of a number of subsystems. When reviewing the mortar systems listed in Figure 2.1, certain design choices or considerations are of interest:

- The **mortar tube** is in all cases made from aluminium. Three production methods are shown: two or three processed parts are either welded together or connected via fasteners with the implementation of seals, or the full tube is milled from a large slab. The latter is primarily implemented when mass requirements are strict, as the machining time and cost are high [77] [84].
- The **sabot** is in nearly all cases made from aluminium. Either the outside of the sabot or inside of the mortar tube is greased to reduce friction. In some instances, a "Sabot capture net" is implemented to mitigate the risk of the sabot colliding with the parachute pack after deployment. The capture mechanism generally consists of (a web of) Aramid tapes [83].
- The **lid** constraining the parachute pack inside the mortar has two design alterations. The most used design consists of an aluminium lid which is mounted with shear pins. Alternatively, no lid is present, but the pack is kept in place by restraint loops and ties made from Aramid tapes [82].
- **Shear pins** retaining the lid are mostly made from metal and must be able to withstand handling and launch loads. However, it is noteworthy that the shear pin strength should be as low as possible to minimise parachute compression before ejection [65].

[1] Requirements are indicated by the value having a range or minimum/maximum value and having an *italic* font. (P) indicates that the length refers to the parachute pack instead of the mortar tube.

- The **gas generator** or power unit consists of different subsystems: initiators, a pyrotechnic charge, breech and orifice.
  - The initiators are electrically powered squibs that house a small pyrotechnic charge, which ignite the larger charge. In all NASA missions the NASA Standard Initiators (NSIs) are implemented [6]. Generally speaking, the initiators are not developed as part of the mortar system, but either purchased commercially or already developed internally.
  - The pyrotechnic charge is the main source of pressure in the mortar. The type of powder implemented is dependent on what can be sourced at that time [87]. The volume of powder is a leading factor in the gas generator design.
  - The breech forms the structural integration between the charge, which is generally a separate part, and the mortar tube. This is regularly implemented to ease integration and operations. Although in Figure 1.1 it is located on the side of the mortar to increase accessibility, it is also often located on the bottom of the mortar tube.
  - The orifice is a narrow hole through which gases can escape from the gas generator into the mortar tube. This promotes a clean burn of the charge and prevents particles from exiting the mortar tube, which could damage the parachute pack after ejection. The main purpose of the orifice is to slow the gas flow and therefore pressure towards the mortar tube and sabot, leading to a more evenly distributed pressure over time. This lowers the reaction load of the full mortar system and is therefore an essential design parameter in meeting requirements on a maximum reaction load. The orifice is occasionally sealed by burst disks to ensure no degradation of the powder over time or atmospheric pressure during ignition, primarily relevant for interplanetary missions [84].

When studying the available literature as a whole, it becomes apparent that flight heritage plays a large role in the mortar design history. This can be seen especially in NASA missions, where mortar systems have developed from the Viking missions, to MPF, MER, Phoenix and MSL. The general technologies and system layout stay the same, and design changes are primarily iterative, such as changes in the production process, or focused on resizing the system to the mission.

By thoroughly reviewing the design parameters, a discrepancy can be observed between the gas generator design of the Mars Science Laboratory (MSL) mortar as reported in 2007 [77] and 2009 [72]. It is deemed likely that this indicates a design change throughout the development of the system, although this is not explicitly indicated.

Here, the first major knowledge gap is identified, as there is a limited availability of sources addressing mortar systems for sounding rockets. The reviewed sources on mortar systems primarily focused on large missions or rockets such as interplanetary (Mars) missions or manned spaceflight. These systems differ in two critical aspects. Firstly, the physical size of the system, including the mortar and parachute volume and mass, is significantly smaller for mortars on sounding rockets. The design characteristics of and requirements on the mortar evaluated in the case study will strongly deviate from the numbers presented in Figure 2.1. Secondly, larger missions have a higher budget allocated for risk reduction and the need for a high level of reliability. Consequently, it is necessary to consider that the risk management activities on these mortar systems, which are further discussed in subsection 2.2.2, may present different risks or variations in their severity and probability when compared to the case study at hand. Because in the context of sounding rockets, the available resources for risk reduction are considerably lower, this may pose restrictions on the risk management process that warrant further exploration.

2.2. Risk management on mortar systems

Before proceeding to examine risk management implementation for mortar systems, it is important to create an overview of the various risk management frameworks and methodologies that can be applied. subsection 2.2.1 will describe and review the relevant risk management phases and methodologies, whereas subsection 2.2.2 will analyse sources for how they have applied risk management to existing mortar systems.

2.2.1. Risk management methods

There are many types of risk recognised in the space sector; technical performance risks, cost risks, programmatic risks, schedule risks, financial risks, liability risks, regulatory risks, safety risks and supportability risks [38]. The scope of this research limits itself to performance risk and safety risk.
There are other areas that are related to or intertwined with performance and safety risk management. Firstly, when reviewing risk management in the space sector, this is strongly associated with systems engineering. NASA defines systems engineering as “a methodical, multi-disciplinary approach for the design, realisation, technical management, operations, and retirement of a system” [57]. Additionally, product assurance is identified as a part of or addition to risk management, as it aims to ensure a sufficient quality level for flight parts and systems [80].

In general, these four branches are in alignment. For example, increased efforts to flight qualify a system will often result in a lowered performance risk, which are the desired outcomes of these branches. But this alignment is not always the case, for example when comparing reliability and safety. An example is given by Roland and Moriarty on bullets and ammunition: increasing the handling safety, reducing the chances of ordinances going off unintentionally, will decrease its functional reliability [70]. More subtle contradictions can be found between systems engineering and risk management, whereas system engineering must balance all activities and budgets, meaning it cannot always prioritise risk management activities. For example, risk management activities may be limited due to resources being allocated elsewhere, or a design may be chosen with higher associated risks but desirable design characteristics or performance.
From here on out the focus will lie on performance and safety risk management, although it is highly intertwined with systems engineering and product assurance. Sources on general safety risk management, systems engineering and product assurance provide important insights which aid performance risk management as well. These concepts are not all clearly separated in literature and may flow into each other. It happens regularly that a certain methodology is mentioned in chapters on risk management, systems engineering and product assurance. The remainder of this section will describe the phases within risk management, and various methods that can be applied in each phase.

The risk management process can be described by five phases: risk identification, risk assessment, risk mitigation, risk monitoring and control, and risk communication [4] [38]. Various analyses or methods that can be applied during these phases are described in the following paragraphs.

Risk Identification

Risk identification starts with reviewing the technical documentation of the project and discussing possible risks with the project members. The project can also be checked against databases of lessons learned in previous, similar projects, where ”problem & failure reports” are stored [38]. Risks can also be identified or discarded based on heritage, however, it is important to be careful with these claims. In past projects there have been various parts labelled with a certain heritage whilst they underwent significant design changes [80]. Various analyses described in the risk assessment phase below can also be initiated to boost risk identification [86]. An Event Tree Analysis (ETA) can also be used to explore various causes (risks) that may lead to a certain event [4]. Lastly, interviews with key project personnel and independent experts are deemed the most valuable source of input within the risk identification phase [86] [38]. This argument is strengthened by a survey amongst engineering companies on frequently used tools for risk management, which shows that brainstorming is the most applied method in the risk identification phase [67].

Risk Assessment

Analyses performed during the risk assessment phase are designated to one of the following categories: qualitative risk analysis or quantitative risk analysis. The most implemented qualitative risk analysis is a risk classification matrix. Within this method, each risk is assessed based on its likelihood and consequences on a scale (for example 1-5). All risks are plotted in a matrix with likelihood and consequences on its axes [86] [38]. A clear example of this method can be seen documentation on the ASPIRE risk management efforts, where the likelihood ratings include well-specified definitions [85].
An alternative analysis is the Failure Mode, Effects (and Criticality) Analysis (FME(C)A). This provides a way of identifying what causes a component to fail, which effects and consequences this failure brings, and how critical the total risk is. The Goddard space flight centre has implemented the FMECA method on numerous projects with great success, and describes it as valid and usable for other methods [39]. Although this is a very valuable risk assessment method it is also incredibly time-consuming and therefore expensive [4].
The most frequently used quantitative risk analysis in spaceflight is the Fault Tree Analysis, which evaluates probability rates of an event and based on this is able to rank risks based on their criticality [86]. Alternatively, a Probabilistic Risk Assessment is a similar methodology which uses ETAs and FTAs as input and focuses primarily on the computation of the risk probabilities [4].
Nearly all projects combine qualitative and quantitative methods, as they both have their (dis)advantages. Qualitative methods are generally used at the beginning of the project and is cheaper to implement. Quantitative methods are more time-consuming, but sometimes required to distribute project resources across risks [38]. It is important to note that quantitative methods will only generate correct results when the input (e.g. probability estimation) is correct [86]. A study which compared quantitative risk analyses with data on actualised events shows differences in the results of two orders of magnitude [25]. However, quantitative analyses can provide new insights, and help with allocating focus on the risks with a higher probability [3].

Risk Mitigation

There are various ways to mitigate risk. Firstly, risk prevention aims to take proactive measures to prevent risks from occurring in the first place. For performance risks this is primarily possible in the design phase, where certain design choices can reduce the amount of risk present, for example, through implementing redundant systems [80]. For safety risk management, this could include activities such as training employees on best practises, implementing safety protocols, or conducting regular maintenance on equipment.
Risk control involves implementing measures to reduce the likelihood or impact of risks. This could include activities like running additional structural or performance simulations, performing a sensitivity analysis, or performing testing activities to confirm the system's functionality [38].
Alternatively, it is possible to accept risks. In some cases, it may not be possible to completely eliminate a risk, and the organisation may choose to accept the risk and put contingency plans in place to manage it [38]. Or risks are deemed so low that no mitigation strategy is required. A great example of the latter is provided by JPL on their missions, where different acceptable levels of risk are related to different project types [34]. For high priority missions such as Mars 2020, single points of failure (SPF's) are mission critical, but for cubesat missions SPF's are acceptable.

Risk Documentation and Communication

To monitor and control the present risks, documentation is of utmost importance. Various methods are possible, amongst which a risk register [60] or a Significant Risk List (SRL) [38]. These contain all relevant information on each risk: its title or ID, a description and/or root cause, categorisation (system, cause, affected resources), owner, assessment method, mission risk (likelihood & consequences), mitigation options, and milestones.
The NASA Risk Management Handbook provides various guidelines of risk communication. It is primarily important to put protocols in place on this phase, which describe the frequency and content of expected reports, and which stakeholders should be involved or updated with specific information [56].

To conclude this section, the literature identifies five distinct phases in risk management with various methodologies that can be applied within these phases. It can be seen that there is a higher number of sources that focus on the phases of risk identification, assessment and mitigation, than on risk monitoring, control and communication.

2.2.2. Existing cases of risk management applied to mortar systems

Having discussed the relevant risk management phases in subsection 2.2.1, the final section of this literature review addresses examples of how risk management is applied to mortar systems in existing missions. This will allow a connection to be made between theoretical frameworks and real-life practices. When reviewing the collected sources on risk management of parachute mortars, the vast majority describe different tests that were performed on the system. Although this forms an essential part of the risk mitigation phase, the documentation on mortar testing is mostly limited to a description of the test execution and results, without denoting the test purpose or which risks should be mitigated. But more importantly, most of the reviewed studies failed to touch upon other risk management phases such as risk identification and assessment.

The sources that do partly address risk management describe the following elements to consider. For the MSL program, the majority of risks were accepted based on comparable previous tests and analyses. However, during the LDSD test program, it turned out that a number of critical assumptions made on the parachute strength during inflation were incorrect, leading to parachute structural failure. A number of conclusions were drawn from the program and this newly acquired knowledge shaped the risk management process for the Mars2020 parachute system. The test program includes specific parachute mortar tests focused on parachute bag deployment and the ASPIRE high-altitude flight tests [81]. This example shows risk identification through a previous in-flight failure.
Development of the CEV Parachute Assembly System (CPAS) included a high number of flight and drop tests. Each drop test has a well-documented configuration, expected/experienced test conditions, and test goal. Amongst these test goals is the observation and/or evaluation of drogue parachute mortar deployment and pilot mortar deployment. The test matrices progress from concept demonstration to system development, to system qualification tests [21]. This example shows thorough documentation of the risk mitigation process. The level of detail in reporting likely comes from the need of human rating the Orion parachute system, and therefore also has a structured risk management process [40].
The NASA handbook on pyrotechnic design, development and qualification recommends implementing the Failure Modes and Effect Analysis (FMEA) throughout the full development process of pyrotechnic systems [6]. This source shows the first concrete methodology that can be applied to (a part of) the mortar system to manage risks.

It can be concluded that no literature is available on a thorough risk management approach, from start to end, for a parachute mortar system. However, valuable information can still be extracted from the available sources on the tests that were executed on mortar systems. These tests are divided into two categories: tests frequently performed throughout the development and qualification process of a mortar system and uncommon tests which are performed for specific missions or to mitigate explicit risks. Test that can be categorised as the former type are:

1. Nearly all mortar development projects start with the gas generator (GG) development. **Closed bomb tests** or closed tank tests are performed to determine the pyrotechnic performance in terms of pressure profile over time. The gas generator is screwed into a closed volume with pressure and/or temperature sensors. These closed bomb tests are also used to determine gas generator performance when under- or overloaded in terms of pyrotechnic mass.
2. Additionally, all projects perform **static deployment tests** of the mortar. The main purpose of these tests is to balance the reaction load and ejection velocity by adjusting the gas generator (charge and orifice). Occasionally these tests do not use a parachute assembly but a replacement slug which allows the project to maintain a high development pace, as there is less dependency on parachute progress [88]. As these tests are heavily embedded in the design phase of the system, they may not seem like risk mitigation activities. However, through these repeated tests the risks of insufficient ejection velocities or too high reaction loads are mitigated, as it sheds light on mortar over- or underperformance and validates any simulation or analysis performed on the system.
   During ejection tests, two methods can be used to determine the ejection velocity: recording by high-speed cameras [66] or integrating the reaction load over time (between shear pin break and significant drop) [65]. A similar test, but with different goals, is the **integrated deployment** test. Here the mortar system is integrated as similar to the flight configuration as possible, connected

to the parachute and surrounding structures. The goal is to observe interaction with the parachute pack, deployment from the parachute pack, and structural integrity of the mounting points. These tests are also performed to establish parachute release from the deployment bag after ejection [81]. One example of an integrated deployment test, of the Perseverance parachute mortar by NASA, can be seen in Figure 2.2.

Figure 2.2: Integrated deployment test of the Perseverance parachute mortar [source: NASA]

3. It is also important to perform GG firings and/or deployment tests in the relevant **environmental conditions** as expected in flight. During the Phoenix mortar development, the team noticed that tests for the Mars Pathfinder mission performed mortar tests in an uncontrolled earth atmosphere. This meant that the air below the sabot was oxygen-rich, as well as the surrounding air when the sabot exits the mortar tube, resulting in an overperformance of the pressure created due to a higher amount of oxygen present throughout the burn. To mitigate these skewed results, the Phoenix program started purging the volume below the sabot with nitrogen before testing [88] [82].
4. **Load testing** of components is executed to establish structural integrity of the mortar tube and/or GG. This can be done via hydrostatic tank tests for the mortar tube, a nondestructive test which pressurises the tube up to 125% of the maximum operating pressure. The GG assembly is load tested by overloading the pyrotechnic charge by 25% in terms of mass [82].
5. When the design of the system has been thoroughly tested and meets all requirements, parts are subjected to a **qualification testing** process to ensure they are fit for flight. Both the shear pins and gas generator components are subject to Lot Acceptance Testing (LAT) [2]. Shear pins from the lot undergo load testing until failure, whilst gas generator subassemblies are subjected to pressurisation tests or firings with increased pyrotechnic charge. A part of the lot is tested after undergoing different types of loading (vibration tests, thermal tests). An example of a LAT approach for the Viking cartridge is shown in Figure 2.3.

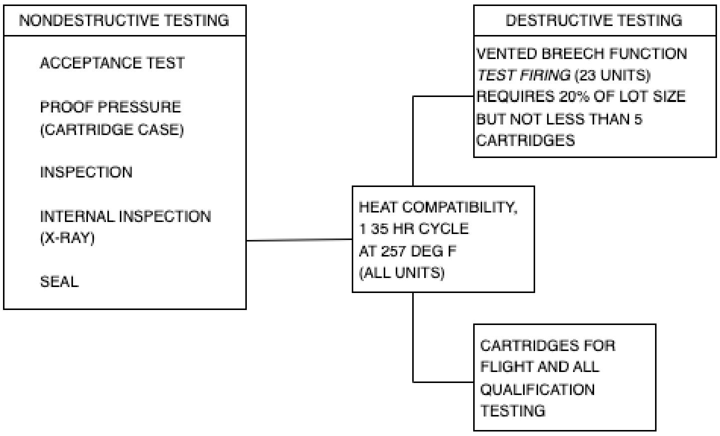

Figure 2.3: Lot Acceptance Testing (LAT) process of the Viking mortar cartridges [10]

[2] Lot acceptance testing (LAT) is a quality control process used to ensure that a batch or "lot" of parts meet the specified requirements and standards before they are deemed flightworthy. The results of these tests are then used to determine if the lot is acceptable for release or if further testing or corrections are needed.

The majority of missions implements LAT in their flight qualification process [43] [64] [77] [84] [10] [72]. As can be seen in Figure 2.3, the components undergo X-rays before and after various qualification steps of the LAT process. These X-rays are generally aimed at establishing the quality of welding joints, and are implemented in a high number of missions [64] [84] [10] [72] [41]. Occasionally, the LAT also contains destructive testing of a power unit assembly and multiple cartridges through hydrostatic burst testing. Here the operating pressure is increased to twice the nominal operating pressure [10].

6. The fully integrated mortar system is also subjected to **environmental testing**, such as vibration tests, thermal tests and/or an **ejection test** of either spare flight hardware or an identical system [43] [64] [77] [84] [72]. These tests aim to validate the system as a whole, as close to flight configuration as possible.

Besides well-known tests that are performed on many mortar systems, there are also rare tests or measurements described in literature. For the Orion and LDSD missions there was a desire to test packing, the deployment process, and the separation from the deployment bag, without having to carry out repeated pyrotechnic mortar tests [36] [82]. This also allowed for parachute deployment testing to run in parallel with earlier stages of pyrotechnic mortar development. Within the LDSD testing phase this accelerated the iterative design of the parachute bag [89].
For the MLAS test (Orion capsule pad abort system) integrated mortar tests were performed not only to gain experience with the parachute rigging [3] but also to confirm that the mortar would be able to penetrate a thick layer of foam and tape which was placed over the subsystem [73]. Such a mission specific design and risk generally warrants additional testing.
Additionally, it can be of interest to deploy the parachute in an airstream whilst observing the interaction between mortar deployment and parachute inflation. This is primarily to ensure proper line stretch, bag release and inflation. For this reason, mortar deployment tests were performed in large-scale wind tunnels at NASA Ames for the Mars Science Laboratory and Mars2020 missions [1] [81]. These wind tunnel deployment test aid in the iterative design of parachute bags and packing methods.
A number of in-flight test programs were started to generate new insights on supersonic parachute behaviour, such as PEPP, ASPIRE and LDSD [55] [58] [82]. Although incredibly valuable in terms of the data they generate, these in-flight tests are extremely costly, especially when select environmental conditions are necessary such as low air pressure or supersonic velocities at parachute deployment. In these programs the primary focus lies on the parachute deployment and inflation, as these are influenced most by complicated body-parachute dynamics or unpredictable aerodynamic motions. This makes parachute deployment and inflation incredibly difficult to mimic during ground testing or to capture in simulations and analyses. Although the mortar system is not a focal point of the test, they are implemented in most in-flight test vehicles, including the programs mentioned above. This provides a valuable in-flight test opportunity for the mortar system.
Lastly, in-flight testing may also be performed as the ultimate validation of a fully integrated recovery system. For this purpose Low Altitude Drop Tests (LADTs) are performed, which were done during the Viking and CPAS programs [10] [41] [21].

This section has reviewed the risk management activities that are performed on various mortar systems in spaceflight. The mitigation activities are clearly represented as the focus lies on tests that are performed on the systems. There is a high repetition visible throughout sources on the execution of a few key tests that are regularly performed, indicating agreement on their importance. Occasionally there is a short notion on the risks that are mitigated through certain tests, for example by testing in environmental conditions which mentioned a risk of under-performance (in terms of ejection velocity) when deployed at Mars in a less oxygen-rich atmosphere. However, information on risk identification and assessment as well as monitoring, control and communication are severely lacking.

[3] Rigging: the process of attaching the parachute to its relevant attachment points on the rocket and routing cables, such as the parachute riser, through the vehicle.

2.3. Socio-Technical Systems

In modern engineering and organisational contexts, the concept of socio-technical systems has gained increasing attention as a powerful framework for understanding and addressing complex problems. Socio-technical systems represent an integrated approach that recognises the intricate interplay between social and technical elements within a given system. By considering both the human and technological aspects as interconnected and mutually influencing, socio-technical systems provide a holistic lens through which to analyse and design complex systems in various domains.

At its core, the concept of socio-technical systems acknowledges that the success and effectiveness of a system depend not only on its technical components but also on the social structures, interactions, and human factors that shape its operation. In other words, the performance and outcomes of a system are influenced not only by the technology it employs but also by the people who interact with and operate the system, and it requires ”the joint optimisation of the technical and social aspects” [16]. This includes aspects such as organisational structures, communication networks, decision-making processes, and the socio-cultural context in which the system functions. By considering the social dimension in connection with the technical aspects, a more comprehensive understanding of the system’s behaviour, strengths, and weaknesses can be attained. This understanding enables the identification of potential conflicts, dependencies, and trade-offs that may arise between the social and technical components of the system.

The aim of the literature review on socio-technical systems is three-fold; 1) finding a definition of a socio-technical system which will clarify whether the parachute mortar ought to be characterised as socio-technical system, and enable establishing a system boundary of the parachute mortar socio-technical system, 2) an approach on how to analyse a subsystem, such as the mortar, from a socio-technical system perspective, and 3) identifying examples of how a socio-technical system approach was applied in the spaceflight or engineering sector, to serve as example for the parachute mortar analysis.

2.3.1. Lack of consensus in literature on socio-technical systems

When reviewing various sources on socio-technical systems, a number of challenges become apparent in the use of definitions and analyses in this approach, which are described below.

- The concept of socio-technical systems originally focused on the influence of worker interactions on a company’s success, emphasising working conditions, personal development, and creativity. This emphasis can be found in earlier sources, which primarily examined the impact of social and technical factors on organisational performance [54] [71]. Over time, however, the concept has evolved to encompass broader societal and human perspectives, extending beyond the workplace to consider the interactions between technology, organisations, and society as a whole.
- The term ”socio-technical system” is often used as a buzzword in papers, suggesting a broader perspective without further elaboration. In these cases, authors mention the term without providing a detailed explanation or exploring its implications. When the term ”socio-technical” appears less than ten times in a paper, this is often the case, and these sources are not reviewed in-depth.
- Multiple papers claim to adopt a socio-technical system approach in their analysis of a specific case, but they fail to provide a clear definition of what they consider to be a socio-technical system or how they employ this approach. This lack of explicit definition and description hinders the reader’s understanding of how the socio-technical system perspective is applied in the research, resulting in a superficial understanding of the concept, consequently limiting its practical application and impact. Papers on various socio-technical systems in space engineering, such as ground stations [42] and future Martian colonies [9] do not thoroughly explain why these systems are categorised as socio-technical, or what constitutes their analyses to be from a socio-technical view. Although Griffiths et al. provide highly detailed analyses and descriptions, no explanation is given on what is meant by employing a ”socio-technical view” [26].
- The absence of strict criteria for defining socio-technical systems contributes to the challenge of interpretation. Different sources offer varying definitions and perspectives on what constitutes a socio-technical system, sometimes solely depending on the scale and complexity of the context being examined, as observed by Kroes et al. [37]. Consequently, the understanding of what is or is not a socio-technical system can vary widely across studies and researchers. The lack of

consensus and agreement on a single definition further complicates the establishment of a unified understanding of socio-technical systems.

- Another challenge lies in the absence of specific and standardised methods for analysing socio-technical systems. Various sources employ different analytical methods to investigate or design socio-technical systems, resulting in a lack of consistency and comparability across studies. Researchers often adapt or develop their own analytical approaches based on the specific context and research objectives. Although the analysis of which elements make up the socio-technical system and the relationships between them is regularly used, there are no standard methods on how to evaluate this (deciding which elements are inside/outside the socio-technical system boundary) or on how to display the analysis. This lack of methodological consistency makes it challenging to determine which analytical techniques are most suitable or effective in analysing socio-technical systems and how they should be applied, hindering the advancement of the field and consistent application of the concept.

It is important to acknowledge these challenges and strive for greater clarity, consistency, and standardisation in the study of socio-technical systems. Researchers can benefit from addressing these issues by providing explicit definitions, clearly describing their approach, and establishing a more robust methodological foundation for analysing and understanding socio-technical systems.

2.3.2. Definitions on socio-technical systems

Despite these challenges, four views on the definition or system boundary of a socio-technical system were collected that describe their stances more clearly, which will be discussed in further detail.

1. Kroes et al. describe the socio-technical system boundary to include ”anything in the system that is necessary for performing its intended function and that may be the object of design” [37]. In some cases, this includes human agents and/or social institutions. An example is given using the aviation industry, as shown in Table 2.1.

	Without agents	With agents
Without social institutions	Tyre of landing gear	Aeroplane
With social institutions	?	Civil aviation

Table 2.1: Type of engineering systems [37]

   Engineering systems in the third category (”Civil aviation” in Table 2.1), which require agents and social institution(s) to function, are described as socio-technical systems. Although systems category two (”Aeroplane” in Table 2.1) would not constitute a socio-technical system, the paper describes that both this and the third category are hybrid systems, containing different kinds of elements and relations than a purely engineering system in category 1 (”Tyre of landing gear” in Table 2.1).

2. Ottens et al. [59] argue that socio-technical systems encompass a combination of technical elements, actors, and social elements. While technical elements like hardware and software are easily identifiable, the inclusion of social elements introduces a new dimension to system analysis. Within socio-technical systems, technical elements are the tangible components such as vehicles, infrastructure, and software. Actors, on the other hand, refer to both individual human beings and organisations, which can act as legal bodies. These actors interact with the technical elements and are subject to the laws of nature. However, unlike technical elements, actors also consider individual intentions and social rules in their behaviour. This interaction between technical elements, actors, and social elements is visually represented in Figure 2.4.

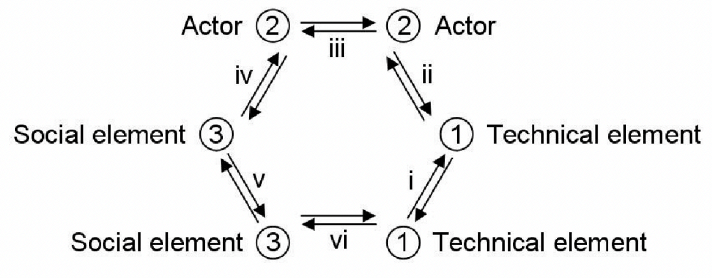

Figure 2.4: Elements (1-3) and relations (I-VI) in a socio-technical system [59]

These social elements introduce a different set of considerations. They encompass non-technical influences that affect decision-making in system design. Factors like personal relations, organisational setups, government policies, and legal regulations significantly impact the overall functioning of the system. Understanding and modelling these social elements pose challenges as they are intangible and difficult to quantify. Unlike technical elements that can be readily pointed to, social elements require a more nuanced approach.

3. Schöttl and Lindemann evaluate the concept of complexity within socio-technical systems, combining characteristics from system theory and psychology [75].

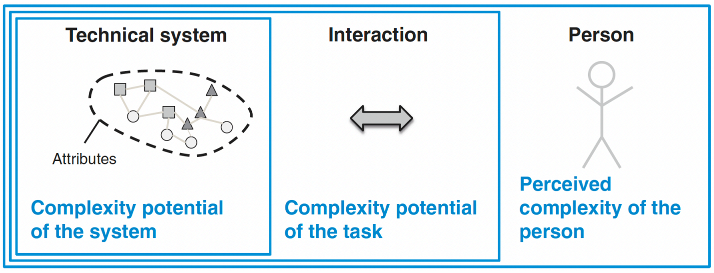

Figure 2.5: Representation of complexity in a socio-technical system [75]

The quantified complexity level is built up from three aspects: 1) the technical system, containing the system properties and changes, 2) the interaction, including the complexity of the task, instructions and time pressure, and 3) the person, with a given experience and mental flexibility. A visual representation of these aspects can be seen in Figure 2.5.
No specific definition of a socio-technical system is stated, but from the detailed description of the possible complexity in a socio-technical system some notions can be extracted. The socio-technical system at least consists of the technical subsystem, interactions and persons, as their individual complexity build up the complexity of the socio-technical system. It presents some parallels to the description by Ottens et al. [59], where a socio-technical system consists of technical elements, actors and social elements. However, this view focuses more on the performance of certain tasks. In an engineering system, one can imagine these tasks to include the design, production, testing and operating of certain subsystems.

4. Bauer and Herder describe a system as socio-technical system when "technological components and social arrangements are so intertwined that their design requires the joint optimisation of technological and social variables" [5]. Hereby, they also provide a possible selection criteria on the various elements: an element is part of the socio-technical system, provided that if the actor and/or material artefact is not analysed, the system will not function. This source does not mention the third dimension of social elements, however, the 'social subsystem' described in the paper seems to include both actors and social elements in the way that they are described by Shöttl and Lindemann [75].

2.3.3. Analyses conducted on socio-technical systems

When reviewing the analyses that are performed on real-world case studies, the following examples are of interest:

- Most papers that view an engineering system from the socio-technical system perspective include one or more analyses that aim to identifying the various elements in the socio-technical system, as well as describing the relationships between them [26] [79] [18], [52]. This is generally done in a figure, where blocks represent the different elements in the socio-technical system and (annotated) arrows the relationships between them. However, there is little to no information on how to decide whether an element falls inside or outside the system boundary, as described in subsection 2.3.1. Examples of these analyses can be seen in Figure 2.6.

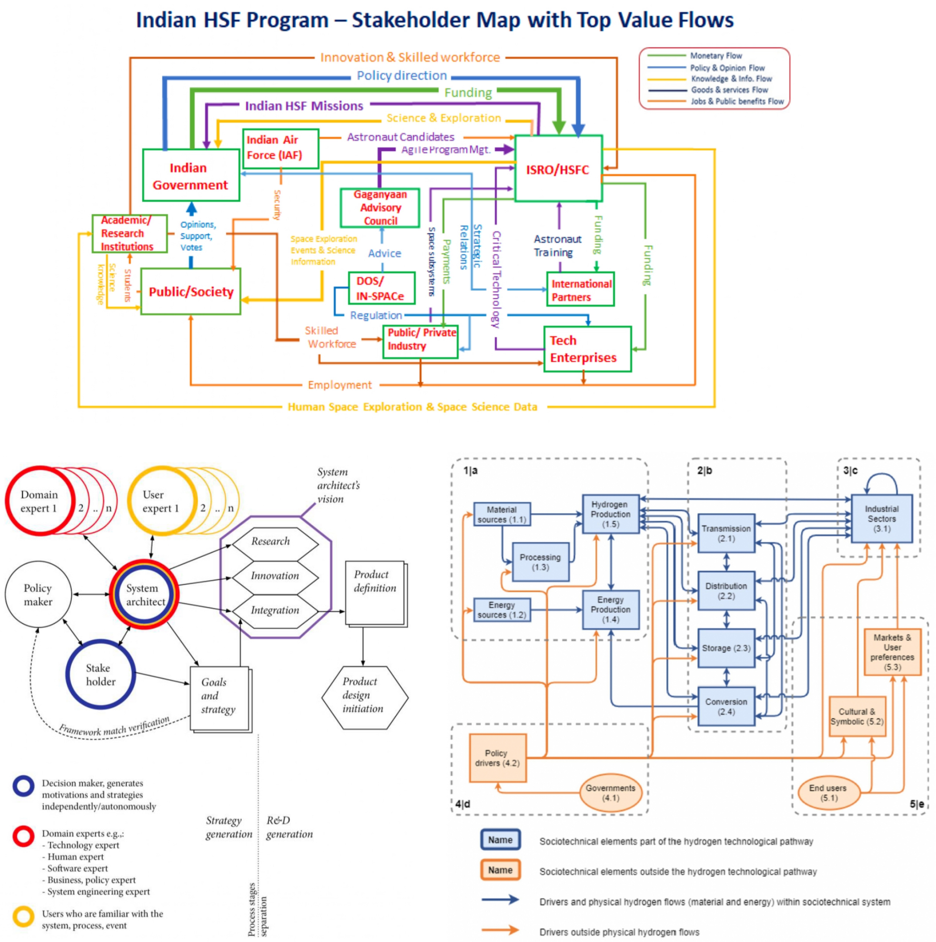

Figure 2.6: Analyses of socio-technical systems by Sundararajan [79], Griffiths et al. [26] and Doule [18]

- A value chain analysis was conducted on the socio-technical system by Griffiths et al. [26].
- A socio-technical context can be incorporated in design trade-offs or a system review [26]. Griffiths et al. provide the most straightforward and transparent examples on how to apply a socio-technical system view to an engineering system. On various design trade-offs and decisions, any socio-technical aspects or views are described and taken into account.
- Mindock and Klaus focus on evaluating various factors that can be used in Human Reliability Analyses (HRA) [50]. This is visualised in Figure 2.7. This research provides an interesting example of the combination of and overlap between a socio-technical system view and risk management.

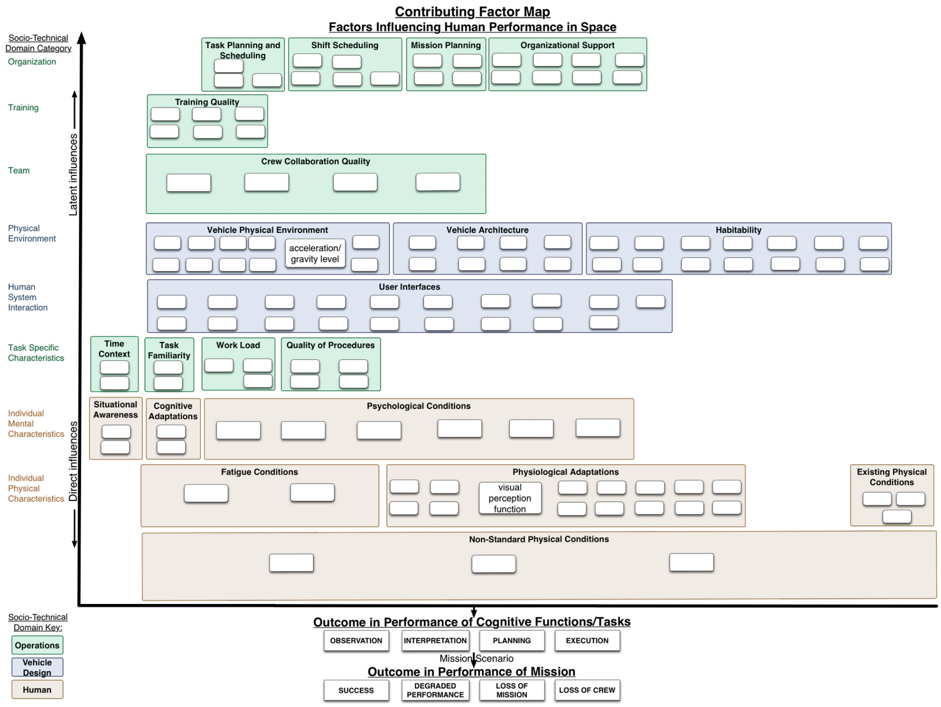

Figure 2.7: Contributing factor map: Factors influencing human performance in space [50] [49]

2.3.4. The implementation of socio-technical systems approach in spaceflight

The application of a socio-technical system approach in the context of spaceflight has garnered some attention, albeit examples in this domain are relatively scarce. Existing instances of the socio-technical system approach applied to spaceflight predominantly concentrate on specific tasks or areas where the human factor holds significant influence. These areas are described in Table 2.2.

Topic	Source
The operations of ground control centres, which rely heavily on human operators	Martinie et al. [42]
Human spaceflight simulators, which evaluate human interaction during spaceflight missions	Doule [18]
The in-flight performance of the crew, assessing the human reliability of astronauts	Mindock and Klaus [50]
General organisation of a human spaceflight program, including public opinions, funding and government policies	Sundararajan [79]
Modeling future spaceflight efforts, such as colonisation on Mars	Braddock et al. [9]

Table 2.2: Examples of socio-technical systems in spaceflight

However, the comprehensive examination of spaceflight systems from a socio-technical perspective, particularly from the standpoint of technical engineering systems, remains less explored and warrants further investigation.

The contributing factors by Mindock and Klaus (see Figure 2.7) do provide an interesting detailed practical example of the application of a socio-technical system. For example, they also mention a number of task specific characteristics (time context, task familiarity, work load and quality of procedures) that are relevant factors to assessing the systems complexity as described by Shöttl and Lindemann [75]. The majority of the contributing factors described may be applicable to the parachute mortar case as well.

2.4. Key findings and insights

In conclusion, this literature review aimed to provide an overview of theoretical frameworks and practical examples of risk management in spaceflight, specifically focusing on mortar systems. Additionally, the concept of socio-technical systems was explored to understand the potential benefits of a broader perspective on risk management. The findings of this review will serve as a foundation for the subsequent research conducted in this thesis, where a risk management approach will be developed based on existing frameworks and practical examples. This approach will subsequently be applied to the DARE mortar system as a case study.

The review highlighted the consistency in the design and breakdown of mortar systems across various sources, with differences primarily related to scaling. However, it is important to note the limited availability of literature specifically addressing mortar systems for sounding rockets, which may result in different risks or varying severity and probability compared to the case study. This identified a significant knowledge gap that needs to be addressed.

The findings of this literature review revealed that the design of the mortar system itself remains consistent across most sources, encompassing materials, system breakdown, part functionality, and part design. As the scaling of the system or different environmental conditions can heavily influence the risks present, a good understanding of the requirements and design variations of the reviewed mortar systems allows for meaningful comparisons between different implemented risk methods. The first knowledge gap is identified, where nearly all sources describe the design and/or risk management activities on interplanetary missions or manned spaceflight. This has a number of implications when comparing it to parachute mortars on sounding rocket, namely differing masses, volume, requirements on the system, required reliability, and resources available for risk mitigation.

The risk management methods reviewed indicate that the process consists of five phases: risk identification, assessment, treatment, monitoring and control, and communication. A focus lies on the first three phases when reviewing sources on risk management in spaceflight. The most important method to identify risks is interviews with project members and independent experts. Within risk assessment, both qualitative and quantitative methods can be implemented for a balanced result.

When reviewing practical examples of risk management on mortar systems, sources primarily address the performed tests on the system. The types of tests that were performed throughout different spaceflight missions show a high consistency. This presents the second crucial knowledge gap; it is evident that there is little to no information available on risk identification and risk assessment of parachute mortar systems. Within the reviewed literature, the focus lies primarily on mitigation methods and testing. There is a need to conduct more research in these areas to improve the understanding of the full risk management process for smaller systems such as parachute mortars on sounding rockets.

The concept of socio-technical systems has gained attention as a framework for understanding complex problems in engineering and organisational contexts. Socio-technical systems recognise the inseparable link between social and technical elements in a given system, providing a holistic lens to analyse and design complex systems. Four definitions of socio-technical systems have been reviewed in detail: Kroes et al. define it as anything necessary for performing a system's intended function; Ottens et al. emphasise the combination of technical elements, actors, and social elements; Schöttle and Lindemann highlight complexity within socio-technical systems; and Bauer and Herder reiterate the joint optimisation of technological and social variables. While examples of applying socio-technical systems to spaceflight exist, they often focus on areas with a high human factor such as ground operation centres or crewed flight. However, a comprehensive review of technical rocket subsystems in spaceflight from a socio-technical perspective is limited, which presents the third meaningful knowledge gap. The literature review highlights challenges in achieving consensus, providing clear definitions, and using standardised analytical methods for socio-technical systems. It emphasises the need for explicit definitions, clear descriptions of approaches, and methodological consistency. Further research is needed to fully leverage the socio-technical system approach in understanding and optimising spaceflight systems.

In summary, the literature review encompassed various examples of mortar system designs, tests, and theoretical frameworks for risk management. However, the identified knowledge gaps emphasise the need for additional research to address other risk management phases such as risk identification and assessment of parachute mortar systems. Secondly, performing risk management on a mortar system on sounding rockets provides a new and unique source of information on this topic. Lastly, a socio-technical system perspective can offer unique insights, however not many examples are available on applying this approach. By filling these gaps, future studies can contribute significantly to enhancing risk management practices in this domain, ensuring safer operations and bolstering confidence in achieving mission objectives.

3

Research Methodology

3.1. Research problem

The literature research described in chapter 2 reviewed conventional risk management methodologies that are used in space engineering, and practical examples of how risk management has been applied to existing mortar systems, as well as the concept of socio-technical systems. Throughout this review, three knowledge gaps were identified in the available literature on risk management of mortar systems:

1. There is extremely little available literature on risk management for parachute mortars in **sounding rockets**. All research presented is on mortar systems for interplanetary or human spaceflight missions. These missions differ to sounding rockets on a number of items: a higher mass and volume of both the (drogue) parachute and mortar system, a significantly higher reliability is required, and more resources are available in terms of budget, manpower and project duration. Therefore, the risk methods and activities presented on these mortar systems may vary greatly from those that can or should be applied to mortar systems on sounding rockets.
2. The existing literature on risk management activities performed on mortar systems focuses strongly on mitigation activities such as (re)design or testing. There is little to no information available on the **risk identification and assessment** phases. Without these crucial phases it is particularly difficult to decide which risk mitigation activities must be concluded for mortar systems on sounding rockets, as risk identification and assessment may strongly vary depending on the required reliability and environmental conditions.
3. While there are examples of applying the socio-technical systems approach to spaceflight, these applications predominantly focus on areas with a significant human factor, such as ground operation centres and crewed flights. However, there is a substantial knowledge gap when it comes to the implementation of the **socio-technical system approach on technical rocket subsystems** in spaceflight. The current literature lacks a comprehensive review of technical rocket subsystems from a socio-technical perspective, leaving a significant gap in understanding and analysing the intricate interplay between social and technical elements in these subsystems. Further research is needed to bridge this gap and explore the application of the socio-technical system approach to sounding rocket subsystems.

The practical case of the parachute mortar in DARE demonstrates the need for a risk management approach that bridges the gap between generic theoretical models of risk identification, assessment and mitigation, and their workable application to an actual system. The wide influence of the parachute mortar system on the operator, launch provider, launch site operator, society and other stakeholders warrant a socio-technical approach to reviewing this system. Although the current research focuses on parachute mortar systems, the general methodology followed and lessons learnt may be applied to comparable mechanical subsystems in sounding rockets.

3.2. Research design

This section presents the research design employed in this study, offering insights into the research objectives, scope, research questions, and applied methods. By delineating these essential elements, a solid framework is established to guide the research process and provide a clear direction for investigation.

3.2.1. Research objective

The main objective of this study is to develop a guideline on how to apply risk management methodologies on parachute mortar systems in sounding rockets. The following sub-objectives are required to achieve the main objective of this study:

1. To identify the elements that make up the socio-technical system of the parachute mortar on sounding rockets.
2. To identify the hazards present in a parachute mortar system on sounding rockets during testing, pre-launch operations, and the launch itself.
3. To identify risk management methodologies implemented in space engineering and evaluate their suitability to parachute mortars on sounding rockets.
4. To construct an approach for risk management of mortar systems on sounding rockets through selecting applicable risk management methods.
5. To apply this approach to the case study, in order to identify and assess the risks present in the DARE parachute mortar and present a risk treatment strategy.
6. To perform select mitigation activities on the DARE mortar case study to reduce the current level of safety and performance risk.

3.2.2. Scope

The scope of the research is restricted as follows:

- The evaluation is restricted to the topic of pyrotechnic parachute mortars on sounding rockets;
- The research incorporates a socio-technical systems approach. The boundary of the socio-technical system will be established in subsection 4.1.3.
- Risks regarding the in-flight performance of the system and safety throughout pre-launch or testing operations;
- The scope of the research is limited to one launch per set of hardware, excluding refurbishment and reuse of flown subsystems.

The scope of this research entails some limitations. The current focus of the research lies on performance and safety risks, although other types of risks, such as those related to project time and cost, are also significant. Within the case study, these risks may be predominant in some scenarios as the project timeline and budget are severely constrained.

Additionally, the study considers one launch per set of hardware, while in reality, select DARE teams reuse a significant portion of their hardware over a long period of time. This introduces additional risks associated with reuse, such as damage which cannot be detected through visual inspection and fatigue.

Reusability and refurbishment are currently popular topics in the spaceflight industry, with increased research into technologies and development of launch vehicles to enable reusable launches, such as Vega C, Callisto, Muira-1, and ReFEx [17] [19] [24] [69]. However, these developments are recent, and there is still a long way to go in terms of research on refurbishment costs, risks of reusing hardware, and which parts or subsystems form the key constraint in reusing a sounding rocket. Information on reuse of hardware in the case study of DARE is also scarce. Therefore, this is currently not evaluated, but holds significant potential as an area for future research.

3.2.3. Research questions

The purpose of this study is to develop a guideline, describing how existing risk management methodologies can be applied to parachute mortar systems in sounding rockets. In order to achieve the research objective, the research question is formulated as follows:

What are the design characteristics of a risk management guideline that enables the reduction of safety and performance risks of parachute mortar systems in sounding rockets?

To answer this question, the following sub-research questions (SRQs) may be addressed:

1. What technical elements, actors, and social elements build up the parachute mortar socio-technical system?
2. How does the implementation of a socio-technical system view adjust the scope of a risk management analysis?
3. What combination or adaptation of conventional risk management methodologies is suited for identifying, assessing, and mitigating safety and performance risks of parachute mortar systems in sounding rockets?
4. If the synthesised approach is applied to the DARE mortar case, what practical implications and limitations arise, and how can the approach be further enhanced for improved effectiveness?

3.2.4. Research methods

To answer the sub-research questions, various research methods are applied, which are schematically represented in Figure 3.1. Each method is described in more detail below.

Literature Review: In the initial stage of the research, the method of literature review is applied to conduct a comprehensive examination of existing literature on socio-technical systems and risk management methods. This involved systematically searching and analysing relevant scholarly articles, books, reports, and other sources to gather a wide range of insights and perspectives. By employing detailed search criteria and selection criteria, which can be found in Appendix F, the review ensured a comprehensive coverage of the subject matter. The collected information was evaluated to identify commonalities, key concepts, different perspectives and gaps in the existing knowledge. This process not only provided a theoretical foundation for the study but also helped shape the research direction and refine the research questions. The literature review allowed for a holistic understanding of socio-technical systems and risk management methods, enabling the development of robust approaches for determining the system boundaries of a socio-technical perspective and conducting effective risk management on parachute mortars in the context of sounding rockets. The findings of the literature review are described in chapter 2. One advantage of this method is its ability to draw upon a vast body of knowledge and expertise from various disciplines, enriching the study with diverse perspectives. However, a limitation of the literature review is that it relies on existing published works, which may have inherent biases or limitations, as demonstrated by the knowledge gaps described in section 3.1. Despite this, the thorough analysis of available literature and the identification of gaps have important implications for future research directions in the field of parachute mortars and spaceflight technologies.

Research Synthesis: the method of research synthesis was employed to integrate and consolidate existing knowledge, theories, and concepts from the literature on socio-technical systems and risk management methods. By bringing together diverse perspectives and insights, this approach aimed to create a novel framework or approach that addresses the specific research sub-questions: 1) how to establish the boundary of the parachute mortar socio-technical system, and 2) what combination of risk management methods is suitable for the parachute mortar system. The research synthesis process involved systematically reviewing and analysing relevant literature to identify key elements, principles, and best practices in the field. These findings were then synthesised and organised into a coherent framework or approach tailored to the unique context of parachute mortar systems. The research synthesis method allowed for a comprehensive exploration of available knowledge, enabling the development of practical and effective solutions. The results and outcomes of this method can be found in detail in chapter 4, where the newly developed framework and methodology are presented, providing valuable insights for the field of parachute mortars and contributing to the broader domain of socio-technical systems and risk management methods.

Case Study: To rigorously test and validate the synthesised approach, a comprehensive case study will be conducted on the parachute mortar in the Supersonic Experiment Aboard REXUS (SPEAR) of Delft Aerospace Rocket Engineering (DARE). This method entails an in-depth analysis and examination of the real-world example to gain practical insights into the application of the developed approach. The case study will involve collecting and analysing data from multiple sources, such as interviews with key stakeholders, observations of the parachute mortar system in operation, and thorough document analysis of relevant technical specifications, design documents, and operational procedures. By delving into the specific context of this DARE parachute mortar, the case study will provide invaluable insights and practical guidance for future engineers and researchers seeking to implement the synthesised approach. The step-by-step example will illustrate how to effectively apply the approach in a real-world setting, highlighting its strengths, limitations, and potential areas for improvement.
Advantages of the case study method include its ability to provide rich and detailed information about the specific case, allowing for a deep understanding of the intricacies and complexities of the parachute mortar system. Through the collection of qualitative data from interviews and observations, the case study enables researchers to capture nuanced perspectives and contextual factors that may influence the application of the synthesised approach. However, it is important to acknowledge some limitations and potential disadvantages of the case study method. The case study is performed on the parachute mortar system used in the SPEAR mission, which has its own specific requirements, objectives, and limitations. It is important to recognise that future missions using the mortar system may have different considerations and factors that can influence risk identification and assessment. Therefore, results of the risk management process in the case study may not be generalisable to other contexts. However, the risk management guideline can still be followed, and the detailed results of the case study can provide an inspiration to other organisations or missions. The relatively narrow focus of the case study, namely on parachute mortars on sounding rockets, also limits the scope of the findings, highlighting the need for caution when drawing broad conclusions to other technical subsystems.
Nevertheless, the implications of the case study extend beyond the immediate research project. The knowledge gained from the case study can inform decision-making processes on risk management, guide the development of best practices, and contribute to the continuous improvement of parachute mortar systems on various sounding rockets. Overall, the case study method serves as a powerful tool for examining the practical application and effectiveness of the synthesised approach, providing a valuable bridge between theoretical concepts and real-world implementation. Its findings contribute to advancing the understanding and optimisation of socio-technical systems and risk management practices in the context of parachute mortars.

Interview: two qualitative, semi-structured interviews were conducted with experts on parachute mortar systems. The decision to conduct semi-structured interviews for this research is driven by specific considerations. Firstly, the limited availability of experts in the field restricts the feasibility of conducting a large-scale survey or a comprehensive quantitative interview study. With only a small number of interviews possible (two in this case), a qualitative approach allows for in-depth exploration and understanding of the subject matter. Secondly, the research objective involves gaining insights into the risk management methods employed in industry, where specific approaches may vary. By adopting a semi-structured interview format, the research can maintain flexibility in the questioning process, enabling participants to provide nuanced and varied responses. This approach aims to capture a comprehensive range of perspectives and avoid prematurely narrowing the investigation, ensuring valuable information is not overlooked.
The interviews were conducted via online video calls of one hour. The responses were transcribed during the interview and post-processed afterwards. The purpose of these interviews was twofold: to evaluate which risk management methods are used in industry and how they are implemented (supporting SRQ3), and which performance and safety risks are deemed most important to the experts (supporting SRQ4). A limitation of interviews is the possible subjectivity of the interviewer. An attempt to mitigate this was made by ”interviewing the investigator” as described by Chenail [15]. This also aided in identifying whether the posed questions were sufficiently clear, and collecting possible probing questions, contributing to the questioning technique of the interview [76]. To prevent interpretation bias, the interview transcript has been sent to the interviewees for review and acceptance. One limitation of the interview method employed in this study is the small sample size, with only two interviews conducted. This relatively low number restricts the ability to balance out potential personal biases of the

interviewees by comparing multiple results. However, it is important to note that this limitation arises from the scarcity of experts in the field of parachute mortar systems. The domain of Entry, Descent, and Landing technologies in spaceflight is highly specialised and encompasses a small community of practitioners. Despite this limitation, the insights gained from these interviews remain valuable in providing a preliminary understanding of risk management methods within the specific context of parachute mortar systems.

Experiments: during the research, a series of experiments were conducted aiming to mitigate safety and/or performance risks of the parachute mortar. The experiments closely tie into the case study, as the risk identification, assessment and evaluation methods performed on the DARE parachute mortar decide which risk mitigation activities, such as experiments, should be performed. Ejection tests, a flight test, and vibration tests were performed to comprehensively evaluate the functionality, performance, and possible vulnerabilities of the (redesigned) parachute mortar. These experiments allowed for direct observation and manipulation of variables, enabling iterative testing of different design changes. Visual observations and video footage were collected, and in some experiments accelerometers were integrated. Despite the advantages of providing evidence-based data and allowing for flexible iterations, it should be noted that all experiments required a substantial time investment. The monetary costs were kept to a minimum as the case study specifically focuses on a student society with limited financial resources. The experimental method provides data which allows for informed decisions and improvements to enhance the safety and performance of the parachute mortar.

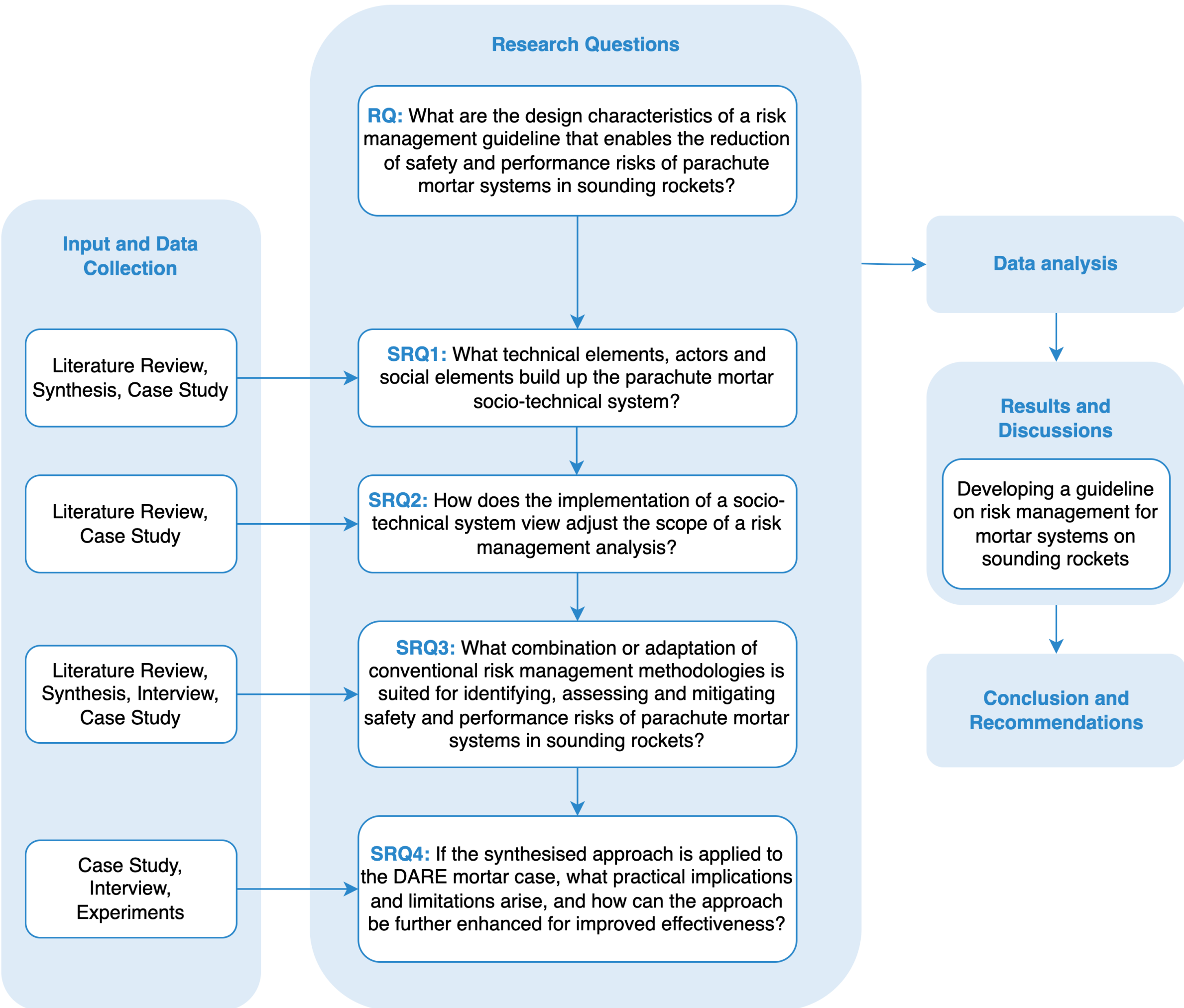

Figure 3.1: Research methodology applied in thesis

4

Synthesised Approach

4.1. Socio-technical systems

4.1.1. Selection of concept definitions

The four definitions discussed in section 2.3 can be evaluated based on their suitability to the parachute mortar system:

1. According to the first definition by Kroes et al. [37], the parachute mortar would not qualify as a socio-technical system since it lacks social institutions alongside its agents. Figure 4.1 draws a parallel between the aviation example provided by Kroes et. al and the parachute mortar case. Notably, the size and complexity of the subsystem play a significant role in determining its classification as a socio-technical system, and the parachute mortar falls short in comparison to the broader aviation industry, or the full sounding rocket system.

	Without agents	With agents
Without social institutions	Tyre of landing gear	Aeroplane
With social institutions	?	Civil aviation

	Without agents	With agents
Without social institutions	Parachute	Parachute mortar
With social institutions	?	Sounding rocket

Hybrid systems containing different kinds of elements and relations

Socio-technical system

Figure 4.1: Type of engineering systems, example by Kroes [37] (left) and parallel on parachute mortar systems (right)

2. The second definition by Ottens et al. [59] provides valuable insights into the elements encompassing socio-technical systems, such as components, people, organizations, relations, and legislation. However, it does not offer clear guidelines on determining the inclusion or exclusion of specific actors or social elements within the system boundaries.
3. The third definition by Schöttl and Lindemann [75] proves more useful in evaluating the complexity of the socio-technical system rather than delineating its boundaries. The source conveys the impression that only persons directly involved with the system, such as designers and operators, are included in the system. This potentially excludes other actors such as the launch site operator.
4. The fourth definition by Bauer and Herder [5] mentions a clear criterion for determining inclusion in the socio-technical system. It states that an element is considered part of the system if its omission would render the system non-functional. However, this criterion still entails subjectivity, necessitating a clear explanation for the inclusion or exclusion of specific elements.

By critically examining these definitions, the second and fourth definitions are combined to shed light on the socio-technical system boundaries of the parachute mortar system. Together they provide an extensive overview of possible elements to include, as well as a selection criteria guideline that can be applied to decide whether an element falls inside or outside the system boundary.

4.1.2. Approach to establish a socio-technical system boundary

Taking into account the selection of definitions made in subsection 4.1.1, an approach is designed to establish a boundary of a socio-technical system. This is graphically represented in Figure 4.2.

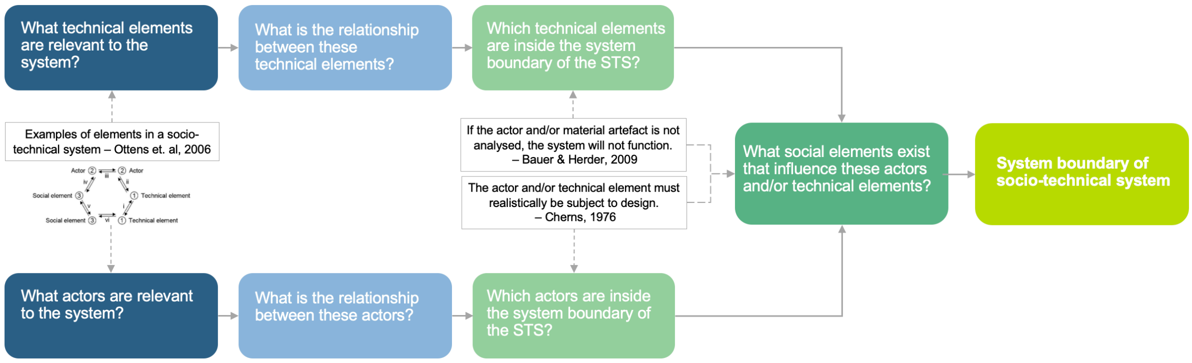

Figure 4.2: Synthesised approach to establish the boundary of a socio-technical system

The following steps are followed:

1. All potential technical elements and actors of the socio-technical system are listed. Inspiration is given by Ottens et al. [59] on the type of elements available, which should be exhausted. A literature search on the system can provide input on technical elements and actors associated with a system.
2. Relationships may be indicated between identified technical elements. This allows for easier observation on how an element influences the system as a whole, enabling the next step. The same can be done for the identified actors. However, this step is optional, as it will require significant analysis time to compute in case many technical elements or actors are identified.
3. The strength of the approach lies within providing an explicit method to select whether technical elements or actors fall within our outside of the socio-technical system. To this purpose, two criteria are imposed:

    - *If the actor and/or material artefact is not analysed, the system will not function* (Bauer & Herder [5]). Meaning, the functioning of the technical element or actor **has** to be designed in combination with the socio-technical system, otherwise it would result in a significant performance reduction of the system. Let it be clearly stated that the compliance to this requirement and therefore selection of the socio-technical system boundary is, in part, still a design choice. For technical elements this is very similar to the design choices made in engineering systems on where the interfaces lie between different subsystems. For actors, an initial judgement of this criteria can be made on previous experiences with or estimated influence and interest of the actor. Evaluation of and iteration on the system boundary is possible, an even recommended, as the elements and relationships may change over time. It is most important that a clear decision is documented on whether an element is included/excluded from the socio-technical system, and which reasoning was applied to reach this determination.
    - *The actor and/or technical element must realistically be subject to design* (Cherns [16]). Meaning, challenges that arise in the technical elements or actors can be addressed by adjusting the system design, communication between actors, or contributing factors to human performance. If the technical element or actor cannot be influenced, it imposes a constraint on the socio-technical system, but is not an element within it. This criteria has been added to the approach in order to exclude constraints, as they presumably do not change and therefore have limited influence on the risk management process. The compliance to this criteria will be more case-specific as it partly depends on relationships between actors and technical elements.

    A technical element or actor must meet both criteria before it is included in the socio-technical system boundary.

4. Lastly, the social elements which influence these technical elements and actors are identified. They are also evaluated against the two criteria mentioned above. The reason why this step is separated, is to prevent identifying many social elements that influence technical elements or actors that lie outside of the socio-technical system boundary, and therefore will also lie outside of the socio-technical system boundary.
5. The full overview of technical elements, actors and social elements that meet the imposed criteria, amount to the full socio-technical system.

4.1.3. The socio-technical system boundary of the parachute mortar

The system boundary of the parachute mortar socio-technical system will now be established by applying the synthesised approach as described in subsection 4.1.2.

The potential technical elements and their relationships are identified, which can be seen in Figure 4.3.

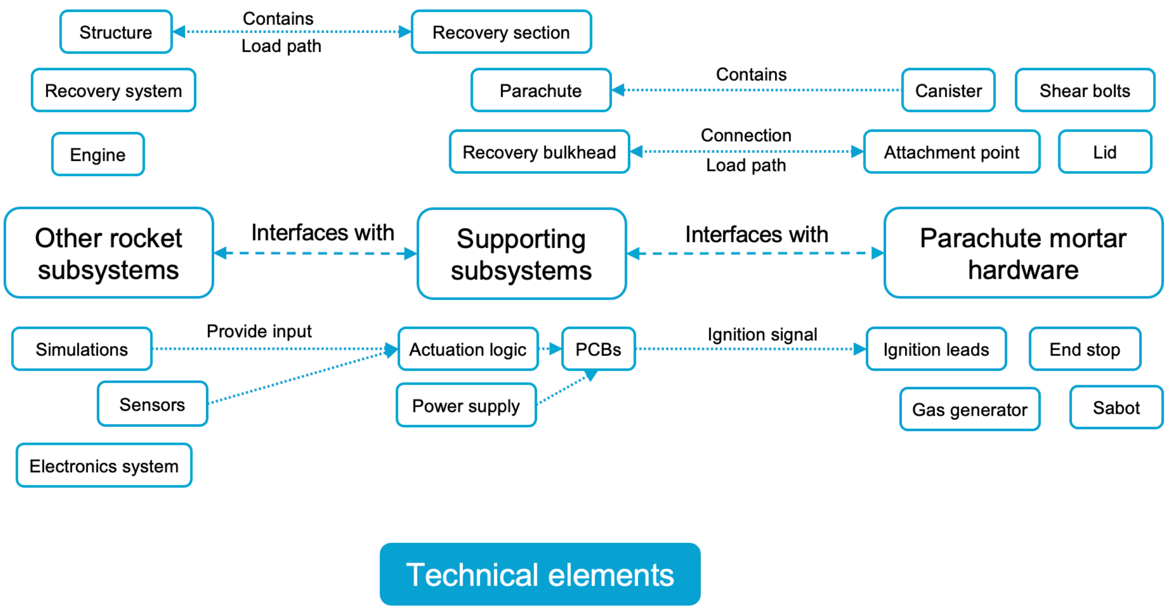

Figure 4.3: Identified technical elements relevant to the parachute mortar system

These technical elements can be evaluated based on the two imposed criteria. In principle, all these elements are part of the sounding rocket, and can be subject to design if the full rocket is developed and built by one organisation. Therefore the elements comply with the second requirement. This may not be the case if, for example, the parachute design (and therefore volume and mass) are rigidly fixed by external parties or mission objectives.
The selection is then based on compliance to the first requirement: the functioning of the technical element or actor **has** to be designed in combination with the socio-technical system, otherwise it would result in a significant performance reduction of the system. For the current level subsystem, this is interpreted as: all elements for which a well-written interface document suffices to achieve normal performance, fall outside the socio-technical system boundary. Elements which, if changed, immediately and strongly influence the design of multiple other elements in the socio-technical system, fall within the system boundary. All elements of the parachute mortar hardware are included in the socio-technical system, as each of them has an immediate and strong effect on nearly all other parts. The three interfaces between the parachute mortar hardware and supporting subsystems are still evaluated based on this interpretation:

- The interface between mortar canister and the parachute. Three main variables of the parachute design influence the mortar system: its mass, volume, and packing density. Combined with performance requirements, such as a minimum ejection velocity and/or maximum reaction load, this influences the mortar design in terms of dimensions and required pressure created by the gas generator. This is immediately a difficult interaction to assess, as on one hand the parachute subsystem is generally developed separately from the parachute mortar, but any significant design changes in the parachute do influence the mortar subsystem heavily. This can be seen in the Mars Exploration Rover (MER), where an increase in parachute mass led to significant redesign of the mortar subsystem Appendix B. The inclusion or exclusion of the parachute in the socio-technical system may then be based on the confidence in the parachute mass, volume and packing density estimations.

- The attachment point of the mortar system presents a unique challenge as it heavily relies on the specific design of the system. The integration and attachment process may require ongoing interaction with the parachute mortar design, making it necessary to consider the attachment point within the socio-technical system. However, this determination must be made on a case-by-case basis, considering the specific requirements and characteristics of each design and evaluation the design's dependencies and interactions. Currently, the connection for the attachment point is assumed to be relatively simple, involving methods such as bolting or gluing, meaning that some attachment part on the mortar hardware is directly connected to a structural (recovery) bulkhead. This indicates that the mortar attachment point will be inside the boundary of the socio-technical system, whereas the bulkhead will fall outside this boundary.
- The connection between the electronics subsystem, responsible for sending the ignition signal, and the ignition leads primarily relies on cabling. Documenting and regularly verifying the requirements for the ignition signal, such as voltage, amperage, and pulse duration, can be easily accomplished. The routing of the cables within the sounding rocket typically involves collaboration between members of the electronics and mechanical design subteams. While the division of responsibility may not always be well-documented, there are numerous feasible solutions available, minimising any notable impact on the system's performance. Therefore the ignition line will fall outside the socio-technical system boundary.

This places the boundary of the socio-technical system around the parachute mortar hardware, excluding any supporting subsystems. As mentioned earlier, this is a design choice. The parachute could also be included in the system, or the attachment point of the mortar could be excluded. Evaluation over time must show which boundary of the parachute mortar social-technical system is appropriate.

The potential actors in the socio-technical system are listed in Table 4.1.

Actor	Description
Launch provider	Company or organisation that provides the sounding rocket
Launch site operator	Company or organisation that mans the launch site and is responsible for range safety
Vehicle operator	Individual(s) who assemble the sounding rocket subsystems, specifically, the parachute mortar. Requires shotfirer license to handle explosives
Client	Customer of the sounding rocket, pays for (a part of) the launch cost, often flies a payload or performs an experiment with the sounding rocket
Suppliers	Provide raw or processed materials
Investors/Government funding	Provide monetary support
Other launching parties	Other launch providers which will launch a sounding rocket from the site
Safety range inhabitants	In case of landbound launch sites, permanent inhabitants, in case of seabound launch sites, boats in international waters
Society	The public

Table 4.1: Identified actors relevant to the parachute mortar system

The assessment of whether each actor complies with criteria 1 (influence on system functioning) and/or criteria 2 (subject to design), can be found in Table 4.2. Following this assessment, the boundary of the socio-technical system can be drawn around the launch provider, launch site operator, and vehicle operator. As mentioned earlier, this is a design choice. For example, if the client has a high interest in and influence on the mortar subsystem, the client can also be included in the socio-technical system boundary.

Actor	C-1	C-2	Commentary
Launch provider	Y	Y	The launch provider has a strong influence on the full development and use cycle of the system, including decisions on how much effort is spent on risk mitigation, which greatly effects the performance of the system.
Launch site operator	Y	Y	The launch site operator has the final go/no-go on the launch of any sounding rocket and/or subsystem. They also prescribe the working conditions and regulations during the launch campaign. The decisions made by the launch site operator can be subject to design, depending on fostering relationships.
Vehicle operator	Y	Y	The vehicle operator assembles the system, and any deviation from the standard assembly and integration may cause underperformance of the system. The selection of vehicle operator and the conditions in which the assembly and integration take place are all subject to design.
Client	N	Y	Although the relationship with the client and launch contracts are subject to design, they generally do not specifically influence the mortar subsystem. The focus of the client is on the full sounding rocket and/or launch, not on subsystem level.
Suppliers	N	Y	Although relationships and contracts with suppliers are subject to design, for all parts currently present in the parachute mortar system there are multiple suppliers available. This means the analysis of suppliers is not required to enable successful system performance.
Investors/Government funding	Y	N	The presence or absence of funding for technology development and/or specific launches may strongly influence the level of risk mitigation that can be achieved, and therefore the performance of the system. The applicability of this criteria depends on the overall financial situation of the launch provider and the project in full. However, the general system through which funds are obtained (grant applications, etc.) is not subject to design.
Other launching parties	N	N	Other launching parties have no influence on the parachute mortar subsystem design, and are not subject to design.
Safety range inhabitants	N	N	Safety range inhabitants have no influence on the parachute mortar subsystem design, and are not subject to design.
Society	N	N	Society has no influence on the parachute mortar subsystem design, and is not subject to design.

Table 4.2: Identified actors relevant to the parachute mortar system

The potential social elements in the socio-technical system are listed in Table 4.3.

Social element	Description
Legislative bodies	Laws on handling, transport or purchase of pyrotechnics Laws on what hazard can be imposed on inhabitants of the launch site safety range
Relevant standards	Standards often used in the space engineering industry (voluntarily), such as ECSS, ISO, IEEE
Financial structure	Which actor(s) are paying for which part of the launch and/or system. Have certain deliverables been agreed upon

Table 4.3: Identified social elements relevant to the parachute mortar system

Based on the assessment outlined in Table 4.4, it is concluded that all identified social elements are excluded from the socio-technical system as they do not meet either criteria 1 (influence on system functioning) or criteria 2 (subject to design).

Actor	C-1	C-2	Commentary
Legislative bodies	Y	N	Although legislative bodies have a strong influence on the design and logistics of the system, legislation on mortar systems is not subject to design. The sounding rocket industry and specifically Entry, Descent, and Landing (EDL) sector is extremely small and cannot influence legislation on pyrotechnic handling or limits on imposed risks/hazards.
Relevant standards	N	N	Standards are used in various engineering disciplines, but they are not obligatory to implement.
Financial structure	N	Y	The financial or funding structure of the sounding rocket that is being launched influences the involvement and relationship of/between the launch provider, launch site operator, and client, but does not inherently influence the parachute mortar system.

Table 4.4: Identified social elements relevant to the parachute mortar system

To summarise, the socio-technical system of the parachute mortar includes the following elements:

- Technical elements: parachute mortar hardware.
- Launch provider: company or organisation that provides the sounding rocket.
- Vehicle operator: individual(s) who assemble the sounding rocket subsystems, specifically, the parachute mortar.
- Launch site operator: company or organisation that mans the launch site and is responsible for range safety

4.1.4. Analysing the parachute mortar socio-technical system

The analyses that are presented in literature, as described in subsection 2.3.3, will be performed and evaluated in order to assess their benefits and limitations.

Relationships between elements in the socio-technical system

There is no definitive approach to conducting this analysis, however, the following points hold significance:

- The aim of the analysis is to create a clear overview of the elements in a socio-technical system and the relations between these elements. A clean, ordered visualisation should be pursued.
- Aspire consistent modelling and graphical representation between sources, to allow for ease of interpretation and building a foundation around the analysis.
- Document the steps taken and assumptions made whilst conducting this analysis.

The steps taken to perform this analysis are as follows:

- Each element in the socio-technical system is displayed in a box field.
- A double-headed arrow is placed between all possible combinations of 2 elements, indicating their relationship.
- Each relationship between two elements is reviewed, and the methods by which these elements influence each other are written next to the arrow.
- If the relationships clutter the visualisation, they can be replaced by numerical indicators and a separate legend describing the relationships in more detail.

The analysis as performed for the parachute mortar system, taking into account the socio-technical elements as determined in subsection 4.1.3, is shown in Figure 4.4.

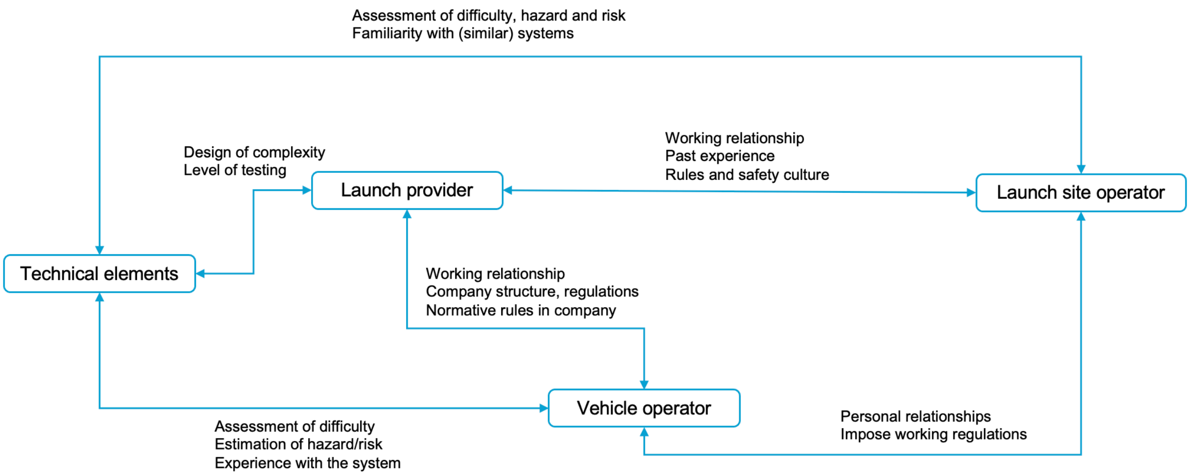

Figure 4.4: Relationships between elements in the parachute mortar socio-technical system

Two improvements that can be made on this analysis are; 1) indicating the strength or significance of a relation by increasing/decreasing the arrow width, and 2) specifying the direction of influences/relationships between two elements, by separating each double-headed arrow into two single-headed arrows.

To gain deeper insights into the factors that drive the actions of various actors, an overview can be created which identifies the internal and external influences shaping their behaviour. An example of such an analysis can be seen in Figure 4.5.

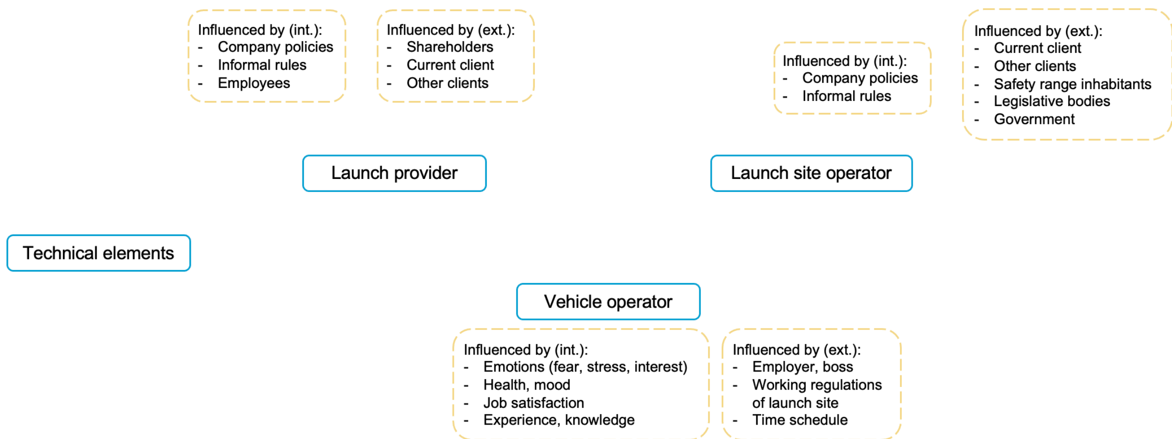

Figure 4.5: Internal and external influences on actors in the parachute mortar socio-technical system

Value chain analysis

Value chain analysis is a strategic management tool used to examine and evaluate the activities and processes involved in the life cycle of the parachute mortar subsystem. The value chain represents the sequence of activities from the design and development to the manufacturing, testing, deployment, and maintenance of the parachute mortar. By breaking down the value chain into its primary and support activities, organisations can analyse each activity's contribution to the overall value creation and identify opportunities for improvement. Advantages of a value chain analysis include:

- Cost optimisation: The analysis helps identify cost drivers throughout the life cycle, enabling organisations to focus on cost reduction efforts and optimise resource allocation.
- Performance enhancement: By understanding the value-adding activities and their interdependencies, organisations can streamline processes, enhance efficiency, and improve the overall performance of the parachute mortar subsystem.
- Supplier and partner collaborations: Value chain analysis allows organisations to evaluate the relationships with suppliers, contractors, and partners involved in different stages of the life cycle. This facilitates effective collaboration, quality control, and timely delivery of components or services.
- Lifecycle management: The analysis provides insights into the entire life cycle, from design to retirement or disposal, allowing organisations to identify opportunities for innovation, sustainability improvements, and lifecycle cost management.

Disadvantages of a value chain analysis include:

- Complexity: Analysing the complete life cycle of the parachute mortar subsystem can be complex and time-consuming, especially considering the various stages and interactions involved.
- Data availability: Obtaining accurate and comprehensive data for each stage of the life cycle may pose challenges, requiring collaboration and data sharing among different teams or stakeholders.
- External factors: While value chain analysis focuses on internal activities, it may not fully capture external factors such as market dynamics, regulatory changes, or geopolitical influences that can impact the life cycle of the parachute mortar subsystem.
- Subjectivity: The analysis requires subjective judgements and interpretations, which may vary based on the perspectives and biases of the individuals conducting the analysis.

A generic value chain analysis of a parachute mortar subsystem can be seen in Figure 4.6.

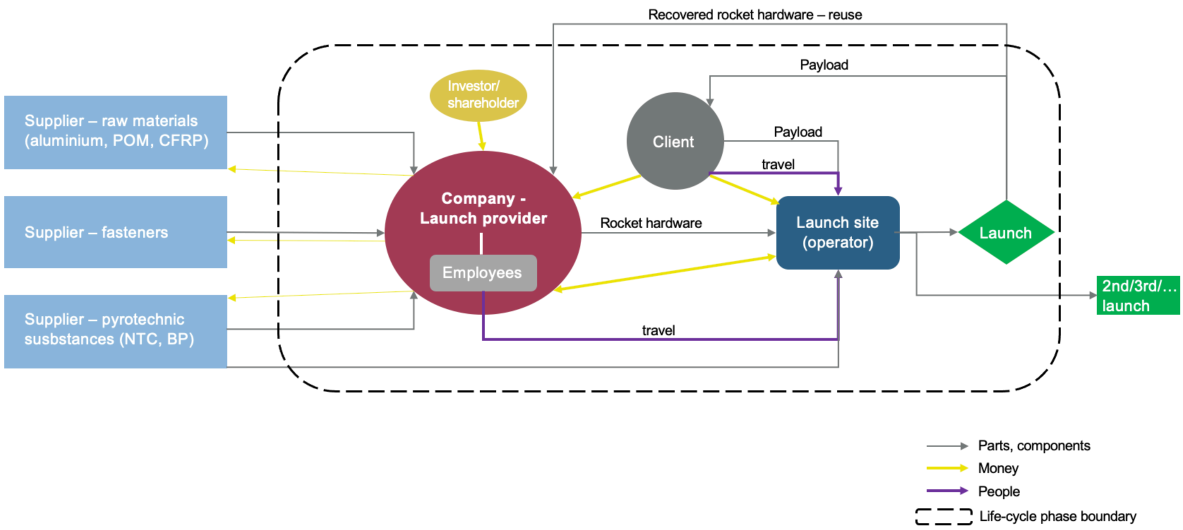

Figure 4.6: Value chain analysis on the parachute mortar system

This analysis is primarily interesting if some of the flows of employees/members, money, or hardware can be quantified.

Integration of socio-technical analyses and risk management methods

From the analyses on socio-technical systems from literature, two can be integrated into the risk management approach in this research.

- Incorporating a socio-technical context in the design and risk management considerations, as done by Griffiths et al. [26].
- Performing a Human Reliability Analysis, where various factors from elements of the socio-technical system influence the risk assessment. These factors are described by Mindock and Klaus [50].

These incorporation of the socio-technical view will come back later in the research via these methods.

4.1.5. Stakeholder analysis

Even though some stakeholders may fall outside of the system boundary of the socio-technical system, and they are not subject to design, it is still recommended to analyse the interests of and relationships between various stakeholders.
A power-influence matrix is a stakeholder analysis tool that helps identify and prioritise stakeholders based on their level of power and influence over a project or organisation. It involves mapping stakeholders on a grid, with power on one axis and influence on the other. The advantages of using a power-influence matrix include providing a visual representation of stakeholder dynamics, aiding in decision-making and resource allocation, and facilitating targeted stakeholder engagement. However, it also has limitations, such as oversimplifying stakeholder relationships and potentially overlooking the complexity of stakeholder interests and dynamics. Careful interpretation and complementing it with other analysis methods can help mitigate these disadvantages. The power-influence matrix for the parachute mortar system can be seen in Figure 4.7, and is further explained in Table 4.5.

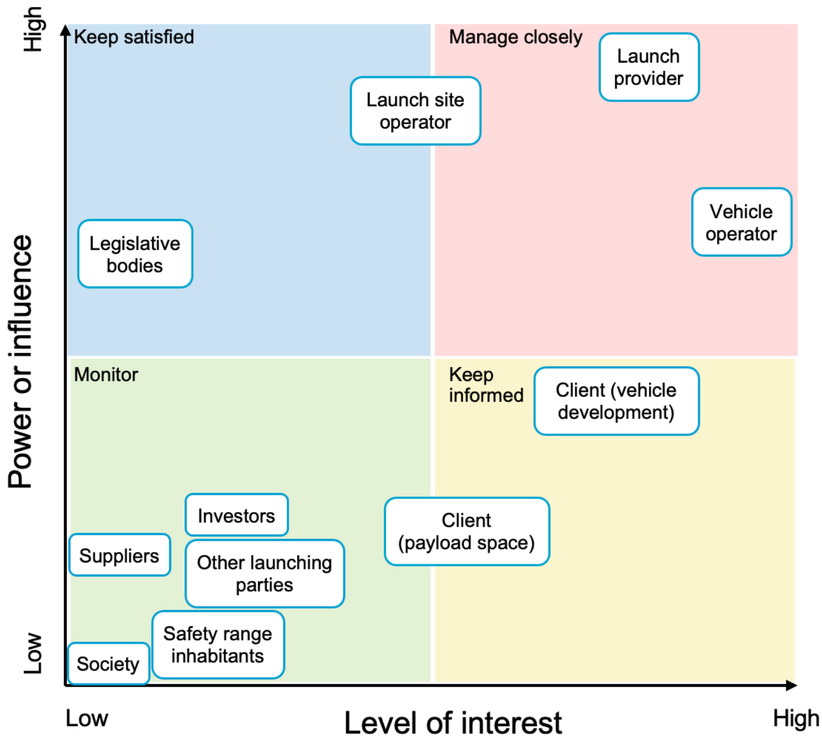

Figure 4.7: Power-interest matrix on stakeholders in the parachute mortar socio-technical system

Stakeholder	Interest, values	Power, influence
Launch provider	A successful launch, fulfilling contractual obligations to the client, at minimal cost. Preferably no damage/harm to infrastructure or people. Ability to reuse the sounding rocket hardware. Satisfy investors/shareholders and entice prospective new customers to launch.	Full design of the system, assembly procedures and tests performed.
Launch site operator	Maintaining safe operations and successfully launch sounding rockets.	Final go/no-go on all operations and/or launch of a system or sounding rocket.
Vehicle operator	Successful assembly and integration of the system without being harmed.	Performs the final assembly, may influence procedures during design/test phase.
Client	Recover their payload (customarily). Perform experiments with their payload or on the sounding rocket.	Influence varies depending on contract, from a client that buys a payload spot on existing sounding rocket (perhaps a shared launch) to a client that co-develops a new sounding rocket for their specific wishes and experiment purpose.
Legislative bodies	Safeguard values of countries, governmental bodies and other parties in the law.	Documenting laws that must be abided, which can be enforced.
Investors	High return on investment (ROI).	Provide funding to launch provider or launch site operator to grow/develop their company and products.
Government funding	Promote technical development, scientific or educational research.	Provide funding to launch provider, launch site operator or client to launch a mission.
Suppliers	Maintain steady output of product, reliable payment from customers.	Assortment, quality, price and delivery time of products.
Other launching parties	Launch their own vehicle/mission successfully. Receive sufficient resources from the launch site to do so.	Lobbying with the launch site to distribute resources (manpower, launch windows, work space).
Safety range inhabitants	Do not want damage or harm to property/people from descending rocket systems.	Can petition the launch site or legislative bodies.
Society	General advances in research and education. Concerns regarding sustainability.	General public interest influences funding, including available space funds.

Table 4.5: Description of the interest and power for stakeholders in the parachute mortar socio-technical system

4.2. Risk management methods

4.2.1. Conventional risk management methods

Risk management encompasses a wide range of methods and techniques that are available to organisations. There is a vast array of risk management methods that can be applied to identify, assess, mitigate, and monitor risks in different industries and contexts. These methods include but are not limited to qualitative and quantitative risk assessments, risk registers, risk matrices, fault tree analysis, event tree analysis, Monte Carlo simulations, and probabilistic risk assessment.

Various standards, such as ISO (International Organisation for Standardisation) and ECSS (European Cooperation for Space Standardisation), provide guidelines and frameworks that describe specific risk management methods, their advantages and disadvantages, and their intended purposes. These standards offer valuable insights into best practices, terminology, and systematic approaches to risk management, facilitating consistency, interoperability, and effective risk management implementation across industries and organisations. The following standards were reviewed for this research:

- ISO 31010: ISO 31010 is a risk management standard focusing on risk assessment techniques [33]. It provides a framework for identifying, analysing, and evaluating risks in diverse contexts. By employing the techniques outlined in ISO 31010, organisations can make informed decisions on risk treatment and mitigation.
- ECSS-M-ST-80C: ECSS offers a set of standards for risk management in space systems and spaceflight operations [20]. This standard addresses various aspects, including risk identification, analysis, and mitigation strategies specific to space project management.
- The ”Project Management Body of Knowledge” or PMBOK by the Project Management Institute (PMI) is another established standard on project management, including project risk. However, this standard focuses primarily on project management and discusses various communication models, change models, and team models. The PMBOK mainly touches upon project risk, which is not in the scope of this review. Therefore this standard is not further discussed.

The ISO 31010 standard provides a comprehensive overview of the available risk management methods by introducing and describing 42 different methods. The ECSS standard describes the process for implementing risk management, with a focus on risk matrices (probability/severity matrices) as the chosen risk assessment method. The literature review on risk management methods in subsection 2.2.1 identifies the most common methods used in engineering and specifically the spaceflight industry:

1. Risk identification methods: Brainstorming, interviews with key project personnel and independent experts. Analyses such as ETA, FTA, or FME(C)A can help in structuring the brainstorming.
2. Qualitative risk assessment methods: likelihood/severity matrices or risk matrices and Failure Mode Effect (& Criticality) Analysis (FME(C)A).
3. Quantitative risk assessment methods: Fault Tree Analysis (FTA) or other Probability Risk Assessment (PRA) methods.
4. Risk evaluation methods: rarely explicitly described.
5. Risk mitigation methods: risk prevention such as (re)design, risk control such as testing or analyses, and risk acceptance.
6. Risk monitoring and control: risk registers.

Al Witkowski from Katabasis Aerospace and Charles Lowry from Airborne Systems are highly experienced experts in the field of parachute mortars within the spaceflight industry. They were interviewed to gain additional insight into industry practices of risk management on parachute mortar systems. The interviews, which can be read in Appendix B, revealed several key points.

- Missions using parachute mortars that took place a few decades ago, had no clearly defined risk management process, resulting in the absence of applied risk management methods and undocumented identification and assessment of risks. Risk identification, assessment and evaluation were based on the judgement of the engineers.
- In more recent years, documentation has become obligatory to attain certain standards and certification. Currently FMEA is used as the main method to assess and document risk at Airborne Systems.

- Risk identification is primarily done through brainstorming/talking to key personnel.
- It is not feasible to perform quantitative risk management on parachute mortars, as there is insufficient input data available on failure probabilities to do so.
- The risk evaluation process, particularly the determination of an acceptable level of risk, is conducted entirely qualitatively and relies on expert opinion.
- The level of acceptable risk depends on the scale of the mission and the budget available. A student team may have higher risks due to limited resources, but their projects are also smaller in scale compared to major space exploration missions.
- Risk acceptance on the parachute mortar system does not often occur. As it is quite a critical system for many spaceflight missions, risks on a lowered performance (ejection velocity) or the structural integrity have to be mitigated.

4.2.2. Selection of risk identification, assessment and evaluation methods

As described in subsection 4.2.1, there are numerous methods available to conduct risk identification, assessment, and evaluation. In order to develop a risk management approach, select methods may be chosen based on their suitability to parachute mortar systems on sounding rockets. The full selection process can be seen in Appendix A and a top-level overview is graphically displayed in Figure 4.8. The figure outlines three paths that were undertaken to determine the most appropriate methods to construct the risk management framework: 1) a top-down selection from the full set of risk methods described in ISO 31010, 2) an evaluation of risk management methods used in the spaceflight engineering industry, 3) an evaluation of risk management methods or analyses that can be employed to implement a broader, socio-technical view. These different selection paths are described below, and each result in a collection of suitable risk management methods.

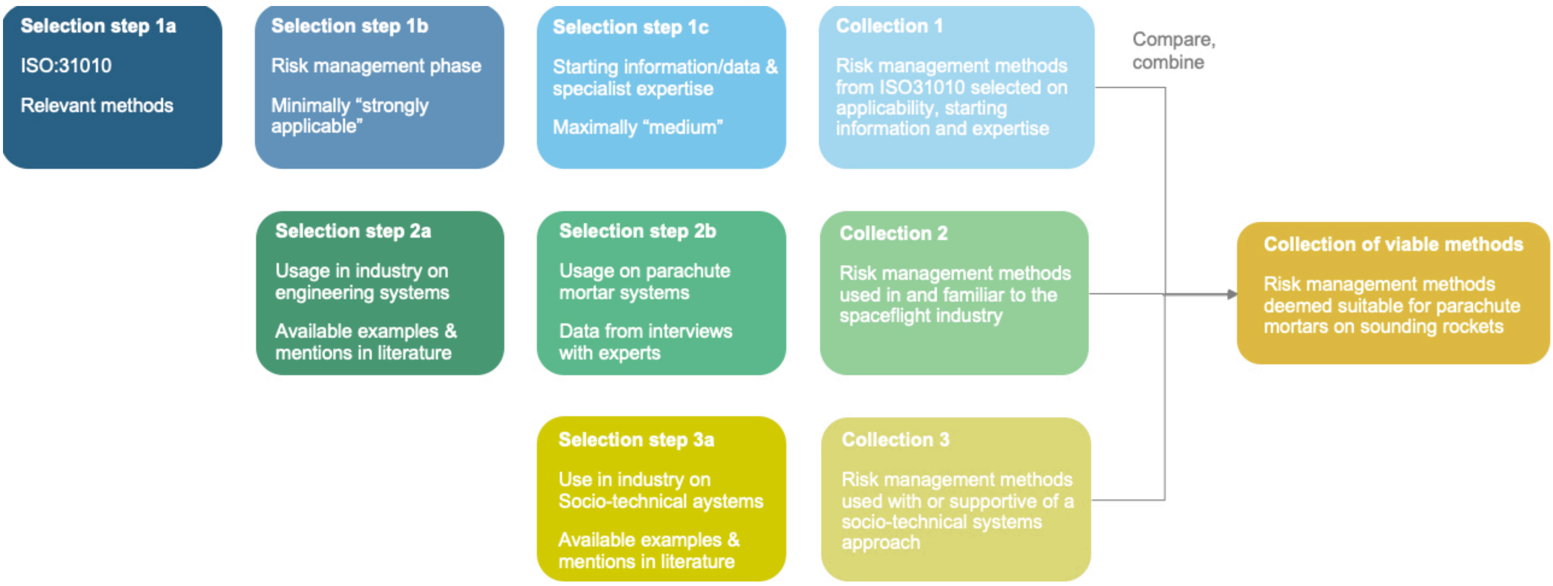

Figure 4.8: Selection process of risk management methods

Methods from ISO 31010

As the ISO 31010 standard encompasses a large collection of risk management methods that are widely implemented in engineering projects, this collection forms the starting point of selection path 1. This path reviews a wide scope of methods to ensure no suitable risk management methods for parachute mortars on sounding rockets are missed.

Firstly, methods irrelevant to the parachute mortar case are discarded, such as a Privacy Impact Analysis or Toxicological Risk Assessment. The subsequent selection of risk management methods was guided by the following considerations:

- Sounding rocket missions typically operate under shorter timescales and have limited resources compared to interplanetary or human spaceflight missions described in the literature. Consequently, the allocation of resources for risk management on the mortar system on sounding rockets is expected to be relatively constrained compared to those on other missions.

- The parachute mortar is not the most critical system on the sounding rocket, hence less resources will be dedicated to the risk management process for this particular subsystem in comparison to others.

These assumptions collectively form the basis for a scenario where risk management activities for the mortar system must be executed within strict timelines and with limited manpower and financial resources. Hence, the time required to perform the risk management process becomes a critical factor in the selection of risk management methods.
As a result, the second round of method selection focuses on the ”applicability” of each method to specific risk management phases. The selected methods must be deemed ”Strongly applicable” to their respective phases, as this minimises the need for employing multiple methods within a single phase, thereby saving valuable time and effort.
The third round of selection is based on the availability of ”starting information/data” and ”specialist expertise,” both of which are preferred to be at a ”low” or ”medium” level rather than ”high.” This ensures that the selected methods can be easily applied without extensive research into the methods themselves or the collection of data to support their application.
By following these selection criteria, the chosen risk management methods can be tailored to the specific needs and constraints of the parachute mortar on a sounding rocket, allowing for effective risk management within the given resources and timeline. This selection process results in the following risk management methods[1]:

- **Risk identification**:
  - Brainstorming/nominal group technique
  - Checklists, classifications, taxonomies
  - Cindynic approach
  - Delphi technique
  - Failure Modes and Effects Analysis (FMEA)
  - Hazard Analysis and Critical Control Point (HACCP)
  - Interviews
  - Ishikawa analysis (fishbone diagram)
  - Scenario analysis
  - Surveys
  - Structured what-if technique (SWIFT)
- **Risk assessment**:
  - Bow tie analysis
  - Consequence/likelihood matrix
  - Decision tree analysis
  - Event tree analysis (ETA)
  - Risk indices
  - Scenario analysis
  - Structured what-if technique (SWIFT)
- **Risk evaluation**:
  - HACCP
  - Multi-criteria analysis (MCA)
  - Pareto charts

This still results in a high number of suitable risk management methods, which cannot all be applied to a case study. One can narrow this selection down based on input requirements, for example, the cyndinic approach and Delphi technique require repeated contact with stakeholders and experts over time, which may not be available. To further reduce the selection, the next subsection evaluates which methods are frequently used in industry.

[1]A detailed description of these techniques can be found in ISO standard 31010 [33]

Methods used in industry

In the selection process of risk management methods, Path 2 considered the usage of these methods in industry as a guiding factor. A literature review was conducted to explore the risk management methods commonly employed in engineering, with a specific focus on spaceflight applications. This review indicated that the following methods are (frequently) applied in the spaceflight sector:

- **Risk identification**: interviews with experts, past incident reports, and Failure Modes and Effects Analysis (FMEA).
- **Risk assessment**: severity/likelihood matrices (risk matrices), FMEA, and Fault Tree Analysis (FTA).
- **Risk evaluation**: very few methods available or discussed, As Low As Reasonably Practicable (ALARP) is occasionally implemented in human spaceflight.

Additionally, two interviews were conducted with experts on parachute mortar systems to gather insights on their preferred risk management methods. Here FMEA surfaced as the main method implemented to identify, assess and document risk. Risk evaluation is done solely through expert opinion. Due to the limited number of interviews conducted, they provided valuable supplementary insights to the literature review, rather than serving as an additional stringent selection criterion.
Applying methods that are used in industry offers several advantages. Firstly, the use of established industry methods provides confidence in their implementability and feasibility. This reduces the risk of encountering unforeseen challenges or limitations during the application process. Secondly, industry-standard methods facilitate better communication and interpretation of results among professionals in the field. This promotes collaboration, peer review, and knowledge sharing, as industry experts are familiar with the methodologies employed. Additionally, utilising widely recognised methods enables easier engagement with external experts, fostering meaningful discussions and valuable insights. Lastly, industry methods often come with a wealth of real-world examples and available data, enhancing the robustness and contextual relevance of the analysis conducted. These resources contribute to a more comprehensive understanding of the risks involved.

Methods facilitating a socio-technical approach

Path 3 in the selection of risk management methods focuses on those that support the implementation of a socio-technical system view. This involves drawing from relevant literature that explores assessments of socio-technical systems in various domains. The aim is to identify methods that explicitly consider and evaluate the interactions between different stakeholders or elements within the socio-technical system. By incorporating such methods, the risk management process can capture the broader context and interdependencies that exist in complex systems. Two main methods of interest emerged. Firstly, the widely used Failure Modes and Effects Analysis (FMEA) method is generally applied in its standard product-oriented format, primarily focusing on the risks inherent to the design. To extend the scope and encompass the broader socio-technical aspects, it is proposed to complement the analysis with the process-oriented FMEA. This alternative version allows for a more comprehensive examination of the interactions between the designer, vehicle operator, and technical system, incorporating risks and considerations related to the five elements of a process: people, materials, equipment, methods, and environment [44]. By adopting both the product FMEA and the process FMEA, a more holistic and detailed overview of the risks can be achieved, capturing the full socio-technical dimensions encompassing both the social and technical aspects of the system.
The second method that surfaced was the Human Reliability Analysis (HRA). Human error plays a significant role in the occurrence of failures in aviation and spaceflight, especially in piloting situations, but also during maintenance activities. When reviewing inflight engine shutdowns or other quality lapses, missing or incorrect parts are the major contributors to these issues (56% caused by omissions) [68]. Early research and methodology of Human Reliability Analyses (HRA) stem from the nuclear power and aviation industries. However, HRA is now expanding its reach to various other industries, including spaceflight. By studying and understanding human factors and their impact on system reliability, HRA contributes to enhancing safety and performance in complex operational environments.
Contrary to the depiction of Human Reliability Analysis (HRA) in certain sources, it is not limited to a single method but rather encompasses a large array of techniques. HRA is a comprehensive term that describes a wide range of methods which aim to assess and understand human performance and its impact on system reliability. These approaches can be classified into different generations, as described

by Schiraldi [74]. The first generation of HRA methods (e.g., THERP, ASEP, HCR, HEART, OATS) primarily focus on establishing and quantifying the Human Error Probability (HEP). These methods treat performance shaping factors (PSFs), which represent the contextual influences on human behaviour, as a minor factor. The emphasis is placed on quantifying the likelihood of human errors, with less emphasis on understanding the underlying cognitive processes. The second generation of HRA methods (e.g., CREAM, SPAR-H, ATHENA) shift towards incorporating cognitive models to explain human behaviour. These methods consider a combination of cognitive activities and errors, actively taking into account the influence of context in the form of the Performance Shaping Factors (PSFs). However, a major challenge in these methods lies in the quantification of PSFs, as it often remains implicit. Additionally, the identification and assessment of PSFs heavily rely on expert input. Schiraldi also recognises a third generation of HRA methods, which is new and upcoming, and solely consisting of the NARA method which is an adaptation of the HEART method. A general shortcoming of the various existing methods that still exists is the lack of evaluating and modelling the interdependencies between PSFs, as various dependencies can exist between these factors and their influence on the HEP.

As there are so many methods, the differences between these methods must be evaluated and compared to the needs of a Human Reliability Analysis in this context. The HRA methods vary in terms of methodology, scope, level of detail, application to a specific domain, quantitative versus qualitative approach, input data required, complexity, and emphasis on human factors (such as organisational factors or Performance Shaping Factors) [28] [12] [7]. The selection of an appropriate method depends on the specific objectives, system characteristics, available data, and the desired level of detail and rigour required for this research. The objective of the HRA in this research is to perform a qualitative analysis to understand the main contributing factors to (decreased) performance of humans involved in the socio-technical system, specifically, the operator. It is of interest to select one qualitative method which focuses on, or can be implemented in, the risk management process. When reviewing this objective, a key point of interest is found in the performance shaping factors (PSFs), as they are feasible to observe over the time duration of this research and open to adaptation in DARE. Performance shaping factors are frequently found in different HRA methods, although slightly adapted or with different definitions, and are frequently evaluated in Human Reliability Analyses applied to spaceflight applications [23] [11]. While other factors like organisational and safety culture are important, they pose challenges in terms of adaptability within DARE. Additionally, elaborate data collection methods such as surveys or qualitative interviews would be required to evaluate these aspects in-depth [23]. Therefore, an assessment of the safety and organisational culture in this research would focus mainly on identifying factors which influence the performance of the operator the most.
When combining these objectives, the SoTeRiA (Socio-Technical Risk Analysis) framework provides a suitable solution, which aims to integrate the socio-technical perspective in risk management processes. One key objective of the framework is ”to identify the controllable characteristics of individuals and organisations in order to be able to prevent incidents and accidents” [52], which aligns well with the objectives for the human reliability analysis in this study. The framework is displayed in Figure 4.9. A strong advantage of using this method is that it provides an existing framework demonstrating how various social aspects and processes contribute to risk, allowing for an holistic view. This research will restrict itself to evaluate the following parts of the model: organisational and safety culture, organisational and safety practices, and (individual) performance shaping factors (PSFs). The SoTeRiA framework extends beyond a qualitative core to 1) building detailed causal models demonstrating the influences of various sections of the model, and 2) working towards quantification of (parts of) the model [51]. However, these parts are not deemed feasible in this research, and are excluded.

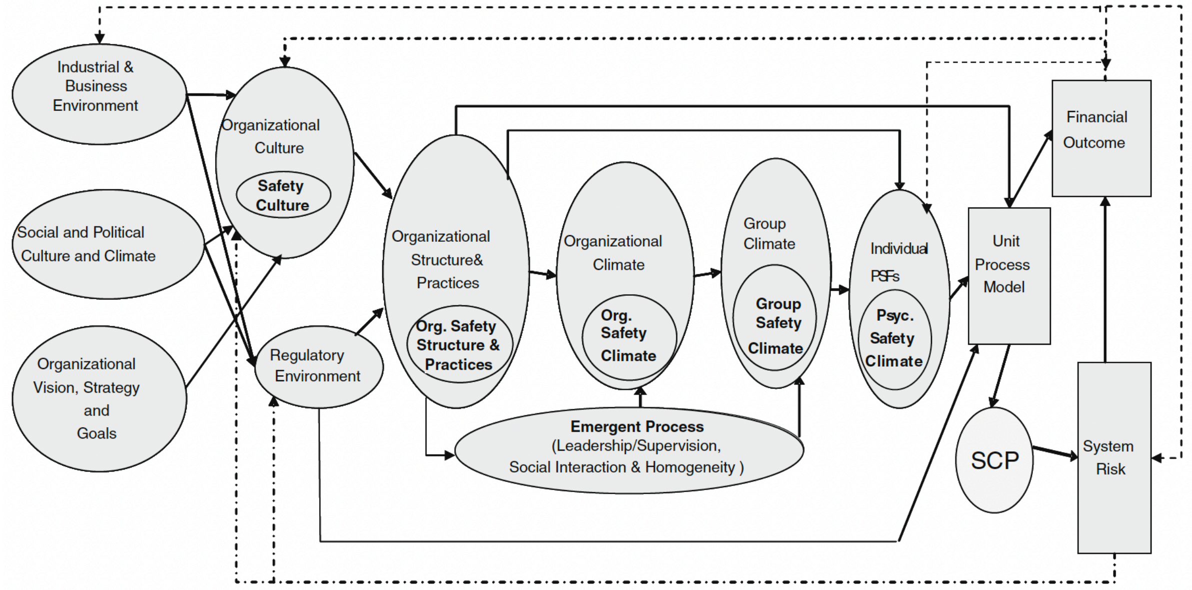

Figure 4.9: Socio-Technical Risk Analysis (SoTeRiA) framework [52]

To summarise, the methods that shape collection 3 are the process FMEA and Human Reliability Analysis (HRA), specifically utilising the SoTeRiA framework. Next to these methods, the evaluation of the socio-technical system provides context to the full risk management process, allowing for increased understanding of prioritisation of risks, selection of mitigation strategy based on available resources, and functioning of implemented controls.

Comparing and combining the collections

The three collections are reviewed, compared and combined to form the proposed risk management approach. Methods for risk identification, assessment and evaluation are reviewed subsequently.
Collection 1 contains of a diverse set of 11 potential risk identification methods. Collection 2 includes interviews with experts, past incident reports, and Failure Modes and Effects Analysis (FMEA) as practices widely used in the industry. There is a high overlap between the collections, where the latter methods are all found in collection 1 as well. The current approach implements the subset of methods found in both collections, however, the alternative identification methods from collection 1 are still available. These may offer flexibility to organisations utilising the approach who prefer different methods based on their specific needs and circumstances. The selection of appropriate methods is influenced by the availability of relevant input data, such as reports on previous tests, team discussions, or external interviews/surveys.

When reviewing risk assessment methods, the sole strong overlap between Collection 1 and 2 is in the consequence/likelihood matrix, which is often applied in space systems engineering (collection 2 [20]). Another method often applied in industry is FMEA, however, according to ISO31010 this is not deemed a Strongly Applicable method for the risk assessment phase when not considering a quantified criticality level (FME**C**A). Within industry, the Risk Priority Number (RPN) is computed using only the severity (S), occurrence (O) and detectability (D) which are all present in regular FMEA as well. This method is still included in the approach and extra care is taken to objectively assess the S/O/D levels.
In addition to the aforementioned methods for identifying and assessing system risks, it is pertinent to incorporate a safety-oriented perspective in this research by employing a risk management method that analyses potential hazards. Notably, the Hazard Analysis and Critical Control Points (HACCP) and Bow-tie methods were identified as recommended approaches to analyse controls in Collection 1. By employing these methods, researchers can gain comprehensive insights into potential risks, their causes, and the preventive measures required to mitigate them, ensuring a more proactive and targeted approach to system safety. The HACCP method is chosen for the parachute mortar system analysis due to its focused approach on specific hazards, whereas the bow-tie approach primarily aims to identify the causes and consequences surrounding an event.

In this stage of the selection process, the methods from collection 3, which emphasise the implementation of a socio-technical approach, were carefully reviewed. Two methods are proposed: the process FMEA and Human Reliability Analysis (HRA) utilising the SoTeRiA framework. As practical examples of the implementation of a socio-technical view in risk management are scarce, usage in industry is not used as a selection criteria. Both methods are added to the proposed risk management approach to expand on the standard, accepted methods implemented in the spaceflight industry. It must be noted that the HRA method will not be employed to assess the risks identified during the risk identification phase, but rather as a standalone method to evaluate the organisational and safety culture and procedures, as well as relevant Performance Shaping Factors (PSFs).
The selected risk assessment methods for the parachute mortar system are exclusively qualitative, as no quantitative methods are present in any of the three collections. This choice is primarily driven by the limitations in input data availability and the required level of expertise, which both range from low to medium. These constraints are deemed realistic for parachute mortars on sounding rockets. Furthermore, this approach aligns with industry perspectives, as confirmed by the two expert interviews conducted, indicating that risk management for parachute mortars predominantly relies on qualitative methods. One of the main factors contributing to this preference is the scarcity of mortar systems in operation, resulting in a lack of statistical data concerning their failure modes, unlike more widely and frequently used systems such as transportation systems or equipment failure rates in chemical processes.

To evaluate risks, the Multi Criteria Analysis (MCA), Pareto charts and the HACCP method are deemed ultimately suitable by ISO31010 [33] and form Collection 1. However, the reviewed sources on the risk evaluation process revealed a scarcity of objective methods, with most recommended approaches still relying on subjective identification of an acceptable level of risk. While these methods emphasise the implementation of risk acceptance criteria, they provide limited guidance on their establishment. When reviewing collection 2, methods favoured by industry, risk evaluation is primarily based on expert opinion, occasionally guided by the As Low As Reasonably Practicable (ALARP) principle. The process of determining risk acceptance criteria lacks clear recommendations or examples, posing a significant challenge within the overall risk management process. Although this research does not aim to create a new risk evaluation method, it underscores the significant challenge of establishing objective risk acceptance criteria. This challenge is prevalent in both academic research and industry practices, where risk acceptance and evaluation heavily rely on subjective expert judgement. Therefore, this study recognises the ongoing subjectivity involved in determining risk acceptance criteria, a limitation that persists throughout the research and industry contexts.

4.2.3. Risk treatment options

Risk treatment refers to the actions taken to accept, reduce or eliminate risks that were identified, assessed and evaluated in the previous risk management phases. These activities aim to minimise the likelihood or impact of potential risks. Several common risk treatment strategies and activities include:

1. **Risk acceptance**: In some cases, organisations may choose to accept certain risks when the associated costs or efforts of mitigation outweigh the potential impact. This decision should be based on a thorough evaluation of the risk and its potential consequences.
2. **Risk avoidance**: This involves avoiding activities or situations that pose a high level of risk. It can entail selecting different technologies or approaches that eliminate or reduce the identified risks.
3. **Risk mitigation**: This strategy focuses on implementing measures to reduce the likelihood or severity of risks. It can include implementing safety controls, improving design or manufacturing processes, or using redundant systems. By conducting tests, engineers can assess the performance, functionality, and safety of systems or components, identify potential issues or vulnerabilities, and make necessary improvements to reduce the likelihood or impact of risks. Testing plays a crucial role in validating designs, verifying system functionality, and ensuring that the implemented measures effectively mitigate risks.
4. **Training and education**: Providing comprehensive training and education to personnel involved in the project or process can help mitigate risks by enhancing their knowledge and skills, enabling

them to identify and respond to potential risks effectively.

5. **Continuous monitoring and improvement**: Regularly monitoring and evaluating the effectiveness of risk mitigation measures is essential. By conducting periodic reviews and assessments, organisations can identify new risks, adjust mitigation strategies, and implement necessary improvements.
6. **Risk transfer**: Risk transfer involves shifting the financial or operational consequences of a risk to another party. This can be done through insurance policies, contracts, or outsourcing certain activities to external entities.

The risk treatment strategy is case specific and tailored to address the specific risks identified in the system. It takes into account factors such as the severity and likelihood of the risks, the mission objectives, available resources, technological constraints, regulatory requirements, and lessons learned from previous missions. By considering these factors, the risk treatment strategy aims to implement targeted measures and controls to minimise or eliminate the identified risks and ensure mission success.

4.2.4. Proposed Risk Management Approach

The selected risk management methods from different phases are combined to form one proposed approach, which is visualised in Figure 4.10. Although the risk management phases should be conducted in series, occasionally there is some movement between and referencing to different sections. This approach will be validated by applying it to the case study during this research, which is described in chapter 5. Figure 4.10 also displays which parts of the risk management process can be found in which (sub)sections of chapter 5. The advantages/disadvantages of each method in the approach will be evaluated after each risk management phase is concluded, based on its utilisation in practice. Finally, the combination of selected methods and practical recommendations is proposed as guideline for future risk analyses on parachute mortars in section 5.7.
Risk documentation is done through the working templates from the various risk management methods, which can be seen in Appendix A, in combination with information provided in this thesis report. An online, editable version of the risk register is made available to DARE for continued research and development of the system.

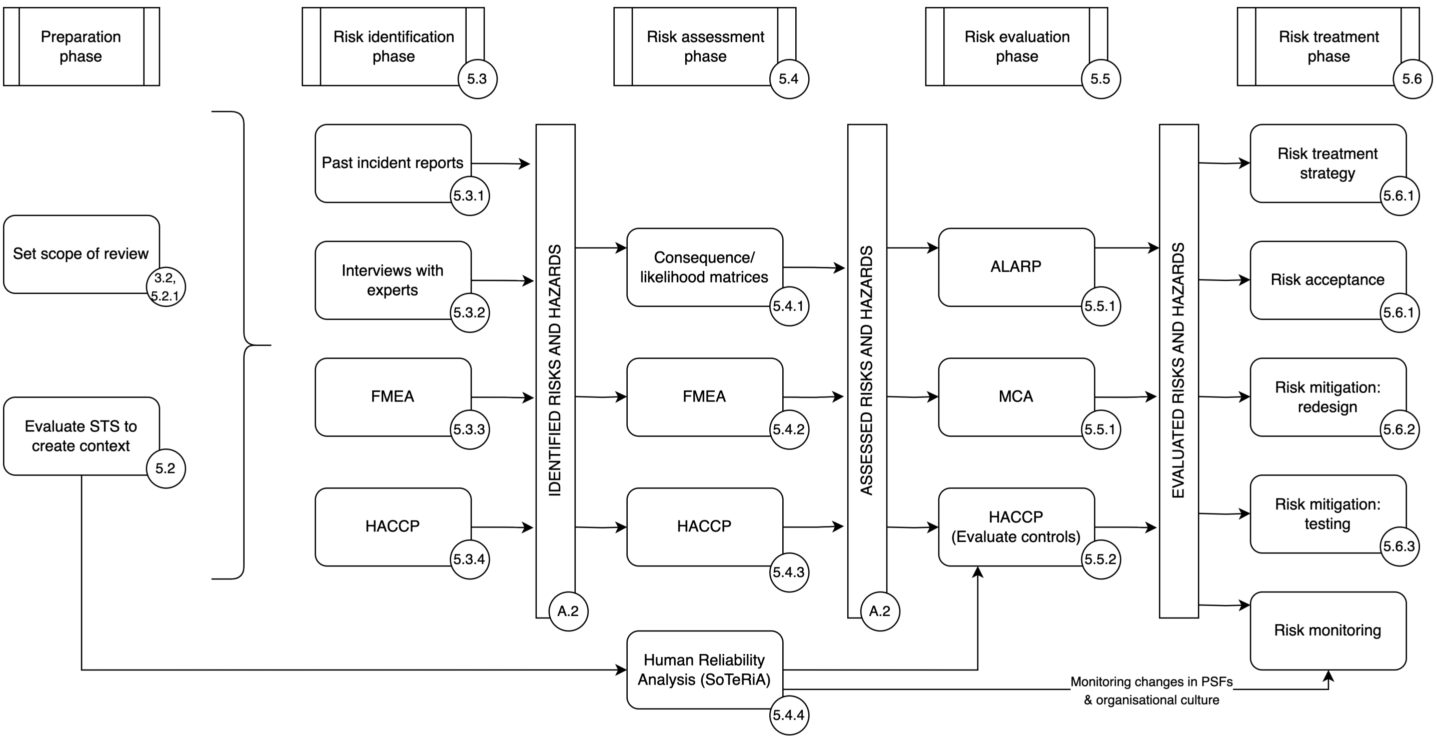

Figure 4.10: Proposed Risk Management Approach

5
Case Study

This chapter aims at evaluating the risk management approach as proposed in subsection 4.2.4 by applying it to to the case study of the parachute mortar developed in Delft Aerospace Rocket Engineering. The structure outlined in Figure 4.10 will be followed, addressing all risk management phases in chronological order.

5.1. Description of the case study

Delft Aerospace Rocket Engineering (DARE) is a student rocketry society in Delft, The Netherlands. The society aims to enable students to gain practical experience in a great variety of fields within experimental rocketry. The Stratos flagship missions aimed to reach high altitude goals, amongst which space at 100km altitude (Stratos IV). A Parachute Recovery Group (PRG) is active within the student society to research recovery systems and implement them on various rockets. Within this group, a parachute mortar system was developed for the Stratos III, Stratos IV, and SPEAR missions. The development of this system in DARE will be shortly described in subsection 5.1.1, and the technical overview of the final design as flown is presented in subsection 5.1.2. A more in-depth description of the society, its structure and relevant cultural aspects is presented in section 5.2.

5.1.1. Parachute mortars in DARE

The first mortar developed by DARE used a cold gas system and was flown on the Stratos III rocket in July 2018 [63]. Although the cold gas pressure system is not under review, the system did provide the canister and its internals which would be adapted to all future pyrotechnic parachute mortars within DARE. The switch to a pyrotechnic ('hot gas') system was primarily based on the lower volume and mass of a pyro charge with respect to the cold gas feed system, as can be seen in Figure 5.1 [61]. This reduced the volume and mass of the system by 77% and 34% respectively. The gas generator contains 0.5 grams of Nitrocellulose pellets (pyro charge), constrained by a steel mesh.

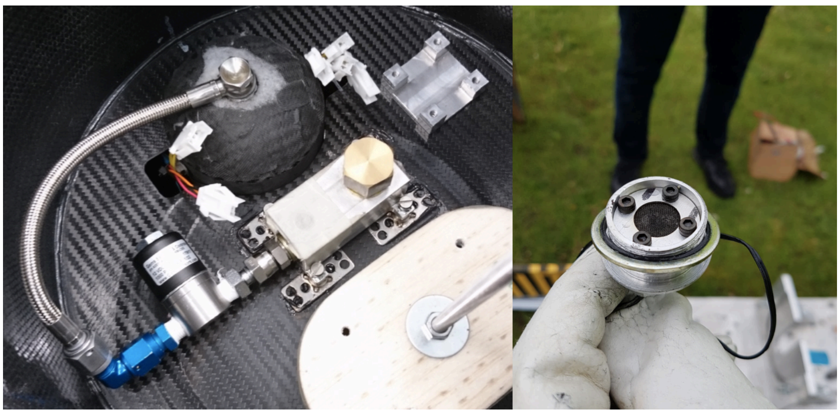

Figure 5.1: Feed system of a cold gas mortar (left) and pyrotechnic charge of a hot gas mortar (right) [46].

The NTC charge is ignited by two electric matches to implement redundancy [62]. The pyrotechnic mortar has been implemented in the Stratos IV and SPEAR missions, aiming to deploy a drogue parachute in supersonic conditions [46]. The mortar size is primarily driven by the drogue parachute, which has an area of 0.2 m^2. The mortar tube is 80mm in diameter and 278mm in length between the dome and lid for all of the aforementioned missions, and is manufactured from Carbon Fibre Reinforced Polymer (CFRP). The mortar has a relatively high L/D ratio of approximately 3.5, whilst most parachute mortars in industry have an L/D ratio of 1.2-2.5, as can be seen in Figure 2.1. From expert interview the 'typical' L/D ratio in mortars is deemed between 1.75-2.25. This higher L/D ratio of the DARE mortar results in a relatively high reaction load when compared to a system with the same performance in terms of ejected mass and ejection velocity, but a lower L/D.
The risk management activities on the SPEAR parachute mortar consisted of creating risk analyses, writing detailed operational procedures and performing various tests. In terms of functionality testing, at least twelve ejection tests and three low-pressure ignition tests were performed. Ejection tests of the flight version showed a minimum and average ejection velocity of 20.9 m/s and 24.5 m/s respectively, verifying the requirement of 20 m/s as the minimum ejection velocity [48]. Additionally, the integrated SPEAR vehicle, including mortar, underwent two vibration tests to demonstrate its structural integrity. Despite this elaborate testing scheme, various risks and/or issues were identified that could not be resolved throughout the SPEAR project due to time constraints. It is of interest to evaluate risk management activities and methodologies implemented in other missions using parachute mortars.

5.1.2. Technical details of the DARE parachute mortar

An overview of the SPEAR parachute mortar design can be seen in Table 5.1. A technical overview drawing can be found in Figure 5.2, which also includes the connecting subsystem of the deployable drag cone. Abbreviations that also refer to the parachute mortar system are: DPDD - Drogue Parachute Deployment System, and HGDD - Hot Gas Deployment System. These may appear in various design documents or images from the DARE society or SPEAR team.

Subsystem	Part	Material	Production method
Gas generator	Ignitor bolts M8x12	Stainless steel	COTS, turning
Gas generator	E-matches	Electric wire, pyrotechnic charge	COTS
Gas generator	Ignitor bolt glue	Bison Kombi epoxy lijm	COTS
Gas generator	Gas generator	Aluminium	Turning, milling
Gas generator	Teflon tape	Teflon	COTS
Gas generator	Flash paper	Paper, nitric acid	COTS
Gas generator	Vectan Ba10 powder	Nitrocellulose	COTS
Gas generator	Mesh 60	Stainless steel	Laser cutting
Gas generator	Retainer ring	Aluminium	Laser cutting
Gas generator	Retainer ring bolts (M3)	Stainless steel	COTS
Canister	Insert	Aluminium	Turning
Canister	Insert glue	Araldite AW4858	COTS
Canister	Endstop	PLA	3D printing
Canister	O-rings	Nitrile Butadine Rubber	COTS
Canister	Sabot	POM	Turning
Canister	Canister	CFRP	Prepreg layup
Canister	Parachute pack	Various fabrics	Sewing
Canister	Lid	Aluminium	Turning, milling
Canister	Shear bolts (M4)	Nylon	COTS
Attachment	Attachment ring	Aluminium	Water cutting, turning, milling
Attachment	Attachment bolts (M4)	Stainless steel	COTS
Attachment	Attachment ring glue	Araldite AW4858	COTS

Table 5.1: Parts and materials list of the parachute mortar

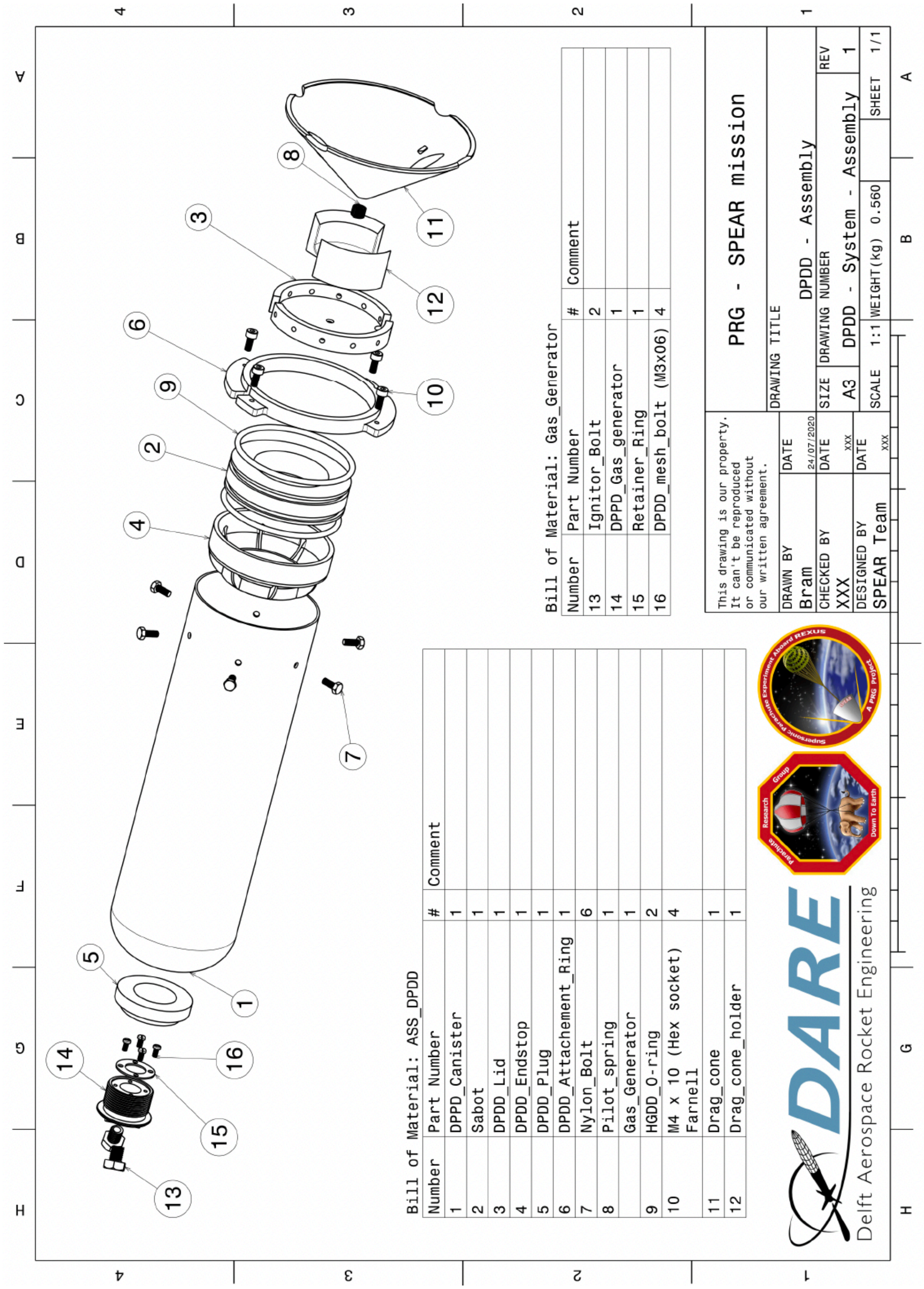

Figure 5.2: Technical overview drawing of SPEAR mortar

5.2. The socio-technical system of the case study

5.2.1. System boundary

This subsection reviews which elements (hardware, actors, social elements) are inside the socio-technical system or outside. Firstly, the parts described in Table 5.1 fall within the socio-technical system, which aligns well with the proposed general boundary from subsection 4.1.3. The society Delft Aerospace Rocket Engineering (DARE) is inside the socio-technical system as launch provider. DARE designs, builds, tests and launches their own rockets fully autonomously and has control over the design and validation of a subsystem. Although the sounding rockets may be developed by smaller subteams in DARE, the majority of the society is involved in the operations of preparing and launching them. Next to the society as a whole, members of DARE are included in the socio-technical system as vehicle operators. The society is fully student-run and all operators are students participating in secondary education in the Netherlands. A continued explanation on the society structure, culture and characteristics can be found in subsection 5.2.2.

Delft University of Technology is an element that hovers around the boundary of the socio-technical system. DARE used to be very autonomous, without any supervision or official engagement from the TU Delft besides design reviews and support from professors. In this case, the university would fall outside the system boundary. However, this relationship is becoming more and more integrated, where the Health, Safety and Environment (HSE) department of the Aerospace Engineering faculty is more involved in the tests that are executed on university grounds. This is a fairly new development that has accelerated in the months of March-June 2023 and the exact working relationship is still crystallising. Therefore, it is difficult to assess the place of the university (departments) inside or outside the socio-technical system. As throughout past missions the university was not in the socio-technical system, this point of view will be taken throughout this research. Still, this relationship must be evaluated in the future to ensure no important risks are missed in case the connection with the university strengthens.

DARE has launched sounding rockets from numerous launch sites. To evaluate the Launch site provider actor in the socio-technical system, each has to be reviewed independently:

- **The Dutch military** operate ASK 't Harde; a shooting terrain near Zwolle, in the Netherlands. DARE launches low-altitude rockets here until 3km. This forms a unique scenario, as DARE launches here as part of SARON; the Samenwerking Amateur Raket Organisaties Nederland, an organisation which consists of three amateur rocketry societies including DARE. The military entrusts SARON to provide their own safety assessment of each launch, and this is presented and discussed on each launch day. They also check the launch and test installations before any activity. However, they do not have specific influence on or interaction with any subsystems, such as the parachute mortar. Therefore, the Dutch military as launch site provider of ASK 't Harde falls outside of the socio-technical system.
- **The Spanish National Institute for Aerospace Technology (INTA)** operates El Arenosillo Test Centre (CEDEA), a launch site in the south of Spain. The maximum launch altitude depends on legislation and NOTAMs [1] that the launch site could/would request. For launches within DARE, the restrictions laid around 100km altitude. The primary focus of interactions with INTA were focused on launch safety; primarily to discuss trajectory simulations to ensure the launches would not exit the safety zone [2], and did not include in-depth discussion of the parachute mortar. The launch site operator was not involved in the assembly of or final operations on the mortar system. Therefore INTA falls outside of the socio-technical system.
- **The Swedish Space Corporation (SSC)** operates Esrange, Kiruna, a launch site located in the north of Sweden. The largest sounding rocket launched from this site is MAXUS, with an approximate apogee at 750km. DARE flew the SPEAR mission, an experimental payload, on the REXUS28 sounding rocket which reached an altitude of 95.7km. SSC as launch site operator had a far more direct involvement with DARE; the mortar design and procedures were reviewed, the type of electric matches were discussed and revised, and the assembly and operations including any pyrotechnic activity on the parachute mortar were supervised. This involvement fostered and required a strong relationships, adding social complexity to the socio-technical system. Therefore, SSC falls within the socio-technical system.

[1] Notice to Air Missions

[2] Designated area reserved for a rocket launch to ensure the safety of the general public, personnel and equipment

- **The Portuguese Space Agency** promote the European Rocketry Competition (EuRoC). The maximum altitude of this competition is 9km. Although the documentation of the teams is reviewed, there is no particular involvement in the design, risk management, assembly or operations of the parachute mortar system. As long as the documentation explains how the system meets the preset requirements of the competition, no further interaction is needed. Therefore the Portuguese Space Agency and EuRoC organisation fall outside of the socio-technical system.

To conclude, the socio-technical system of the DARE parachute mortar consists of: all hardware of the parachute mortar subsystem as listed in Table 5.1, the DARE society, the members of the DARE society functioning as vehicle operators, and the Swedish Space Corporation (SSC) as launch site provider, when launching a mission from the launch site Esrange.

5.2.2. Delft Aerospace Rocket Engineering (DARE)

Delft Aerospace Rocket Engineering (DARE) is a student rocketry society that consists of approximately 180-200 members. The first aim of DARE is to enable students to gain practical experience in the field of rocketry, as described in the statutes of the society. In the past, DARE had the additional objective of reaching space at an altitude of 100km. However, following the conclusion of the Stratos IV mission in 2021, the focus of projects shifted from high altitude launches to the development of complex technologies. The society also performs and organises various educational activities. These include the Dutch CanSat competition, where high-school teams launch small soda can sized satellites to 1km altitude, the Small Rocket Project (SRP) where first year students can develop and launch a small sounding rocket to launch and safely recover an egg to/from 1km altitude, and the Thermal Rocket Propulsion (TRP) practical, where DARE tests Ballistic Evaluation Motors (BEM) to provide a practical case study for a university course at the faculty of Aerospace Engineering.
This subsection describes select details of the DARE society to facilitate the analyses on the socio-technical system and the Human Reliability Analysis. The following information is deemed relevant; a general description of how DARE operates and is organised, available resources, description of projects, members and knowledge in DARE, and the safety culture and practices within DARE.

Organisation structure

A basic organigram of the DARE society can be seen in Figure 5.3, as presented by the DARE executive board at the General Members Assembly[3] (GMA) in February 2023.

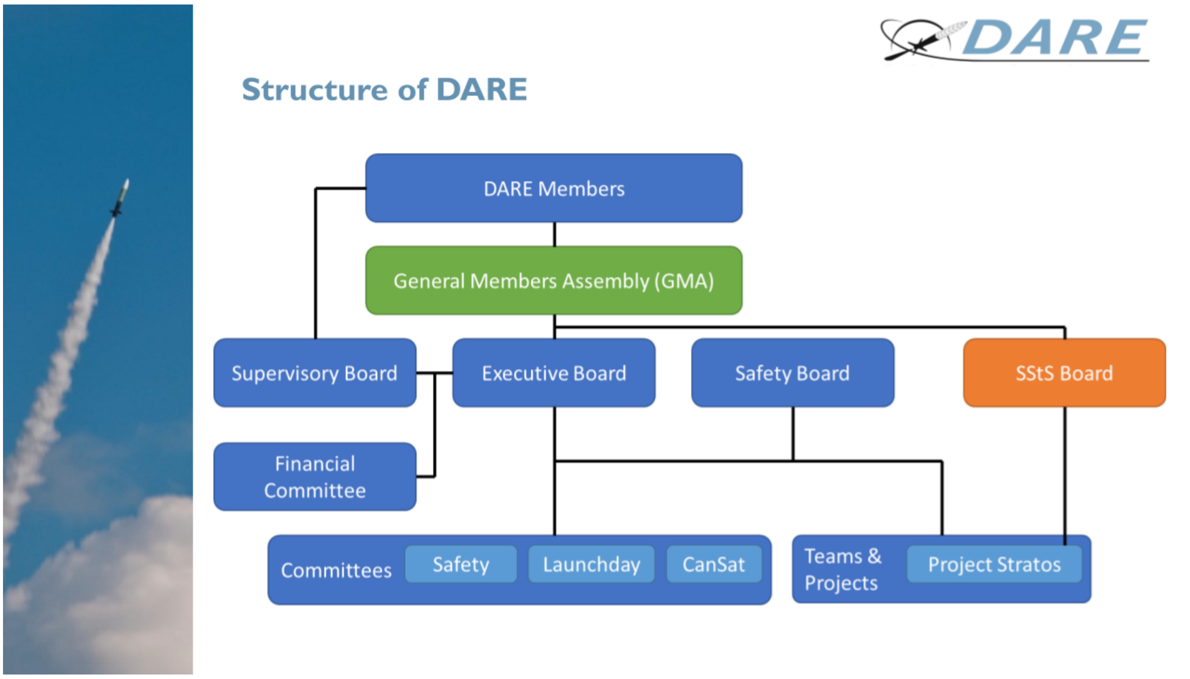

Figure 5.3: Organisational structure of DARE

[3]General members assembly: a society wide meeting that decides on budgets, new regulations, and plans for the next year.

The following groups are described in the organigram:

- **DARE members**: the full DARE organisation is run by its members. Any student registered with a Dutch educational institute can apply to DARE. The majority of members in DARE is a student at Delft University of Technology, predominantly at the Aerospace Engineering faculty.
- **General Members Assembly**: a society wide meeting that decides on budgets, new regulations, and plans for the next year. All important decisions in the society are voted upon at the GMA and all regular DARE members have voting rights.
- **Executive board**: a board that manages the day-to-day operations of the society. Generally consisting of 5-6 members, representing the functions: president, secretary, treasurer, commissioner of internal affairs, commissioner of external relations, and commissioner of operations. A new executive board is appointed at the start of each academic year.
- **Supervisory board and Financial Committee**: these advisory groups, consisting of ex-board members and ex-treasurers respectively, aid the executive board and the full society in dealing with meaningful issues and decisions.
- **Safety board**: the group of all active Safety Officers (SOs), responsible for supervising all safety critical operations within DARE and observing the safety standards and procedures.
- **Safety, Launchday and CanSat committees**: organisational committees to arrange the logistical aspects of all safety related activities, launch days, and CanSat competitions.
- **SStS board**: the Stichting Students to Space is a separate entity which contains all finances and legal responsibility of the flagship projects in DARE, including the Stratos projects, to lower financial risk to the DARE society.
- **Project Stratos**: a series of sounding rockets that holds a prominent position among the flagship projects of DARE, with the development of Stratos V currently ongoing.
- **Teams and Projects**: DARE contains various teams and projects, working on research and development (R&D), engine development, or a particular sounding rocket.

The DARE society has or can make use of various resources such as workshops, test locations, tools and funding. The primary sources of monetary income are: sponsorships from different faculties at Delft University of Technology, contribution from members in the form of membership fees, and income from organising the CanSat competition launch campaign. The flagship projects are largely sponsored by various companies from different sectors, both in the shape of financial or in-kind sponsorships of hardware or services [4]. The Aircraft Hall (ACH) within the Aerospace Faculty provides storage space and working space in various labs, enabling electronics and composite manufacturing as well as general metal bench working and assembly. DARE and the ACH also share a machining workshop for milling and turning which is funded by both parties. The Science Centre Delft (SCD) provides storage space and access to their Makerspace workshop, including a laser cutter and 3D printers. DARE is able to perform small tests of safety critical systems, such as engines, pyrotechnic systems or pressurised tests, at the Fellowship field in Delft. Larger tests can be performed at ASK 't Harde during a launch campaign, or at other military facilities with which DARE has good relationships. Recently DARE has performed its first test campaign at the Netherlands Aerospace Centre (NLR), which may enable more tests in the future.

Projects

DARE has a large variety of projects, ranging from smaller R&D projects to various sized engine development to sounding rocket launches. Some R&D teams also support various missions with their knowledge base, in these cases members often also become part of those projects. Engine development projects include various solid, hybrid and liquid rocket motors, which is quite unique for a student rocketry team. The sounding rockets and missions launched in DARE exhibit a large variety in scale, from small-scaled launches with an altitude below 3km (ASK 't Harde, approximately 15 per year), to medium-scaled launches between 3-9 km altitude (EuRoC, once to date), to large-scale launches above 10km altitude (INTA or Esrange, once every 1-3 years). The Stratos rockets and other flagship projects have a significantly larger project regarding manpower, where often a core team of 8-13 full-time members works on the project next to 40-50 part-time members, and in terms of budget, which is

[4] An overview of the sponsors can be seen via this hyperlink.

approximately one order of magnitude higher than that of other DARE teams. Images of the CanSat Launcher and Stratos III can be seen in Figure 5.4 as example of a small-scale and large-scale sounding rocket respectively.

Figure 5.4: CanSat Launcher (left) and Stratos III (right)

The general project phases of a DARE mission can be seen in Figure 5.5. This is the case for the majority of the projects, however very small projects (team budget $\leq$ €500,- or less than 3-5 members) often do not hold official design reviews. Teams with a budget exceeding €500,- must submit and adhere to milestones that should be met before the next section of the budget is released. Possible milestones include design reviews, hardware production and/or system tests. These milestones are observed and judged by the treasurer in the executive board.

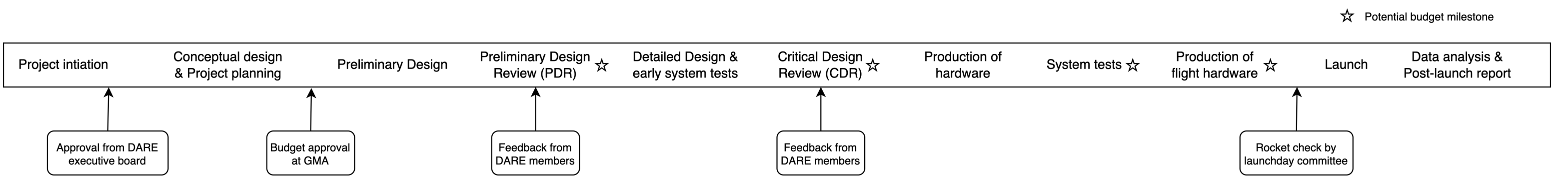

Figure 5.5: DARE project phases

A team has to apply to the DARE board to initiate a project. If budget is required, this is requested to and (dis)approved by the General Members Assembly (GMA). In some large-scale projects, an additional conceptual design review or requirements review is held to establish the goals, requirements and/or general lay-out of the vehicle and mission.
Most projects perform a Preliminary Design Review (PDR), describing which (sub)systems, materials, and general dimensions have been chosen and why. It often contains trade-offs between different design options. A Critical Design Review (CDR) is held after the team finalises the design and CAD

model, sometimes simulations are run on the system such as Finite Element Modelling (FEM) or Computational Fluid Dynamics (CFD), but this is quite rare for small-scale projects. For both these reviews, teams provide written documentation and/or an update presentation and receive feedback from other members in the society. It has been a persistent issue in DARE that attendance to these reviews by other members is low, limiting the feedback that is received.
The majority of production and tests on a system is performed after the CDR. During this phase, a lot of design changes are still made. Most often there is no official ”design freeze” after this phase anymore. This means meagre documentation on the final design as-built or as-flown is present. The quality and clarity of post-flight analyses vary significantly between projects, and in the case of small-scale projects, they are often not publicly disclosed or reviewed by the society. It also happens occasionally that a project or team has insufficient time before the scheduled launch campaign to fully test their systems, leading to potential failures of different subsystems. Teams within DARE are often constrained by their timeline, which in turn is constrained by a combination of available launch dates and member availability. To prevent unfinished or untested systems to fly, the launchday committee organises a rocket check three weeks in advance of a launch campaign.

Experience and knowledge transfer within DARE

DARE possesses a lot of knowledge about designing, building, testing, and launching sounding rockets. This acquired knowledge is the result of a large number of small-scale launches carried out frequently with an average of more than 10 launches per year. As a result, knowledge remains active and widespread within a substantial portion of the society. The risk of knowledge loss is greatest for large-scale launches, which take place less frequently. Given the rarity of these launches, it is essential to address efficient knowledge transfer methods to evaluate the preservation and distribution of valuable knowledge. Knowledge transfer within DARE occurs through a combination of documentation and interpersonal interaction. Detailed project documentation is primarily written throughout the design phases for the various reviews (PDR, CDR). However, it is often lacking or of lesser quality for system tests, design modifications throughout the testing phase, and the final design as launched. Consequently, reliance on documentation alone may prove insufficient for a comprehensive understanding of the entire development process. Design reports, presentations and information is stored on a server (hosted through Nextcloud[5]), where select folders are available to the relevant members. General information on designs, accessible to the whole society, is written on Notion[6] pages. But, various Notion pages are empty, and the quality and quantity of available information is strongly dependent on initiative from teams and individual members.
To supplement documentation, knowledge transfer heavily relies on the engagement of more senior members in DARE. Through working together, conversations and design reviews, new members can learn from more experienced members. This interpersonal exchange is vital to transfer tacit knowledge and practical insights that may not be captured in the written documentation. The effectiveness of knowledge transfer and the smooth handover between members within DARE depends on the overall experience present within separate teams and the duration of members' involvement. The greater the accumulated experience and the longer members remain in DARE, the more opportunities for knowledge transfer and seamless transitions between generations of projects and members.

A significant part of the knowledge and capabilities within DARE is rooted in practical experience, specifically in the areas of manufacturing and working with energetic materials. The following manufacturing methods are used often, ranked in order of frequency of use: turning, milling, soldering, sewing, and composites manufacturing. To use the lathe and mill, which are available in the shared machining garden of the ACH and DARE, members are required to undergo training and pass an exam before gaining autonomy to operate these machines. Those without direct access can still gain experience by practising under the supervision of experienced members with access, allowing them to build confidence in using the machines correctly and safely. Soldering and sewing tasks primarily fall under the responsibilities of the electronics and recovery teams respectively, and knowledge transfer and practical training take place within these teams. This works effectively as the production methods are used regularly and by many different team members. However, the domain of composites manufacturing presents a challenge as the knowledge and experience base within DARE in this area is decreasing. Acquiring the

[5]Nextcloud is an open source private cloud-based file hosting software
[6]Notion is a productivity and note-taking web application

necessary expertise to produce composite parts to the desired quality standard requires considerable experience and regular practice. Between 2019 and 2020, a few members actively engaged in composite manufacturing during the Stratos IV and SPEAR missions, but even this group was limited to approximately 5-6 individuals. In recent years, the production of composite parts, particularly complex ones beyond simple tubes, has significantly reduced, leading to a decline in the knowledge base within DARE. This is especially significant for the case study at hand, as the current design involves a carbon fibre reinforced polymer (CFRP) tube. It is questionable whether this part can be manufactured with the required quality.

Knowledge transfer concerning logistics and handling of energetic materials within DARE demonstrates a successful process. Individuals who express interest in engaging in safety-related tasks undergo an extensive training period usually lasting at least 1.5 years. Upon completion, they become Safety Officers (SOs) capable of autonomously supervising tests or activities involving energetic materials or other safety critical systems. Any activities on safety critical systems, including pressurised systems, handling energetic materials, or operating potentially hazardous mechanisms or installations, must be conducted under the supervision of a safety officer. This protocol enables DARE members from various teams, even those without specific training, to engage in these activities with adequate supervision. Further details regarding this aspect are elaborated in Figure 5.2.2. This approach has existed for nearly the full existence of the DARE society and ensures a decent level of oversight on the safety of operations whilst allowing for the involvement of all members.

Safety culture and practices

The safety of DARE is warranted by the DARE Safety Board, which is charged with the following responsibilities [DARE Charter, Article 14.1]:

- ”Overseeing the safety at all times during activities and work organised by the society which relate to rocketry;
- assessing activities or work organised by the society relating to rocketry which carry an increased safety risk;
- gathering knowledge concerning safety during experimental rocketry;
- informing and advising members of the society concerning safety during experimental rocketry.”

The Safety Board consists of all Safety Officers (SOs) active in DARE at that moment in time. Safety Officers are voted in and installed, or discharged, at a General Members Assembly of the DARE society. New SOs can be nominated by the existing Safety Board, the DARE executive board, or by ten or more DARE members. This happens after their period as Safety Trainee, where they develop their knowledge and experience by accompanying SOs during tests and launch campaigns. The Safety Board is logistically supported by the Safety Committee. This committee organises the practical aspect of the activities, such as test applications, propellant production and storage.

The general values of DARE regarding safety are not officially registered in society-wide documentation. However, each year a Safety Board Annual Report is published, from which a few points can be extracted that reflect the standpoint of the safety committee (chair) of that year:

- The key area that should receive much more attention in the safety board and our society are the daily operations and work that are not labelled as safety critical. DARE can pride itself on the way it organises itself around the dangerous systems that are rockets, in that we are exceptional in the D:Dreamhal. This should however not mean that safety can be taken for granted, especially when looking at work that is considered mundane or safe. [GMA September 2017]
- A lot of small incidents happen not at high profile tests or where large amounts of pyrotechnics are involved, they happen during the every day tasks that are not necessarily seen as unsafe but because of their low profile breed significantly more incidents. [GMA September 2019]
- Everybody in DARE is responsible for Safety during DARE activities [GMA September 2019 and 2020]
- We are still struggling with knowledge transfer, and as many of Safety’s activities are conducted on a personal knowledge basis, this knowledge is being lost ... This is also to be expected as the society continues to grow and evolve. However, Safety’s knowledge systems need to grow and evolve to match. [GMA September 2022]

When a team or project in DARE wants to perform a test, the application process as shown in Figure 5.6 is followed, created by DARE Safety.

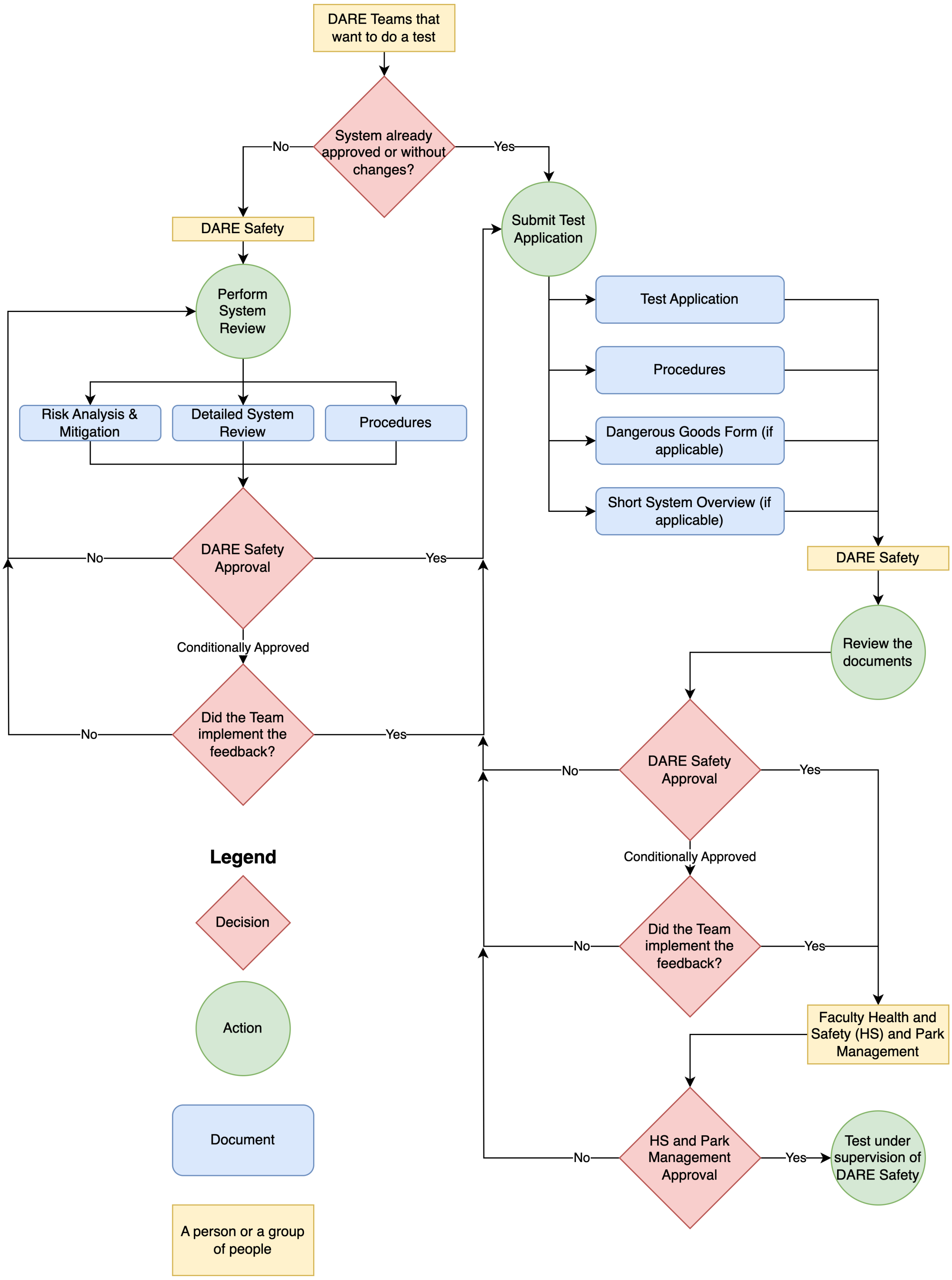

Figure 5.6: Test application process in DARE, created by DARE Safety

The various documents mentioned in the application flowchart must contain the following information:

- System overview: a document detailing the design of the system, failure modes and loads, a feed system diagram (if applicable), risk assessment of the test, and indication of any dangerous goods used.

- Test application: detailing the purpose and goals of the test, the test set-up (including supporting equipment), responsible persons, test location description, list of abort conditions, and any other relevant information.
- Test procedures: a step-by-step guide of the operations that must be performed during the test, detailing the relevant safety personnel, emergency information and warning labels.

A Safety Poster has been created by DARE safety to indicate which types of test require approval by an SO and what measures are obligatory, how to apply for a test, and which DARE members are presently installed as Safety Officers. The aim of the safety poster is to make the regulations and guidelines as clear as possible and widely distribute them amongst DARE members, by hanging the posters in prominent places in the workshops and offices. A section of the safety poster can be seen in Figure 5.7. Although the implemented processes have been in effect for a longer period of time, both the safety poster and test application flowchart are recent efforts of DARE safety to increase the clarity and familiarity of these processes within the DARE society.

SAFETY POSTER

Safety level	Type of operation	Example
Level 0	Standard lab work	Working with tools, machining and assembly
Level 1	Operation with individual danger	Leak testing <10 bar, or ~0.1L, wind tunnel tests
Level 2	Operation with risk to immediate area	High energy systems (e.g. electronic, mechanical, chemical)
Level 3	Operation with significant risk to surroundings	Gaseous leak testing >10 bar and small motor tests
Level 4	Operation with significant risk to wide area	Big engine tests and rocket launches

Safety measures	Level 0	Level 1	Level 2	Level 3	Level 4
Use appropriate personal protective equipment (PPE)	X	X	X	X	X
Safety officer must be informed of operations		X	X	X	X
Safety officer must approve		X	X	X	X
Safety board must validate procedures				X	X
Safety officer must attend operations			X*	X	X
Immediate surroundings have to be evacuated, only necessary personnel present		X	X	X	X
Larger area around must be evacuated, only necessary personnel present			X*	X	X
Blast radius/exclusion zone must be evacuated				X	X
First responders on standby					X

*this precaution can be exempted on a case by case basis after explicit permission of a safety officer

Figure 5.7: Safety Poster fragment, created by DARE Safety

To evaluate the safety culture and practices within DARE, the past accidents and incidents should be reviewed. For this purpose the Safety Board Annual Reports from 2012-2023 and available incident reports are reviewed. These documents and in-depth description of incidents are restricted to DARE internal use, but the following general remarks can be made on the accidents and incidents, specifically regarding the controls that were lacking during their occurrence:

- Two accidents occurred where DARE members burnt their skin during regular work, not whilst performing safety critical operations. The accidents are largely attributed to wearing insufficient Personal Protective Equipment (PPE).
- No accidents occurred whilst performing safety critical operations.
- In 2018 the Stratos III rocket experienced an anomaly and broke up in-flight. Parts of the sounding rocket drifted back to land and exited the predicted safety zone, whilst still landing on restricted military terrain. An in-depth root cause analysis on the anomaly was performed, resulting in the

conclusion that inertial coupling caused the vehicle breakup [90]. A key lesson learnt for the DARE society from the unexpected descent trajectory is that, even whilst working with professional institutions, their approval does not guarantee a sufficient level of safety.

- In March 2023 the Thermal Rocket Propulsion (TRP) practical, a collaboration between DARE and Delft University of Technology, saw an anomaly during one of the static engine tests. Resulting from this anomaly, parts exited the designated area for the test, but this did not lead to harm or property damage. Although the incident review is still ongoing, possible contributing factors to the incident include a lack of explicit task division and appointed operational safety officer (OSO), reduced attention to the written procedures, and influence from various performance shaping factors (PSFs) such as high fatigue and time pressure.

Various controls measures are standard in place during any operations with pyrotechnic materials or high energetic systems, such as the mortar. These are well ingrained in DARE and presented in subsection 5.5.2.

Members

Statistics on members in DARE, such as age, years of experience, study level, study direction, nationality, and distribution among commissions and teams, can be found in Appendix D. Two important pieces of information can be evaluated.
The age distribution of DARE members is predominantly concentrated within the range of 19-24 years old, accounting for 80% of the member base, with a median and mean age of 22 years old. The brain undergoes significant development and maturation until the mid-to-late 20s, with the prefrontal cortex, being one of the last areas to fully mature. This area is responsible for decision-making skills, planning and prioritising. Given the relatively young age of DARE members, there may be a diminished capacity for accurately assessing risk and making sound decisions regarding safety. Consequently, the presence of established standards that all members must adhere to becomes even more crucial, as these standards are developed and evaluated based on years of collective experience.
Furthermore, the length of time spent in DARE contributes to the accumulation of experience among its members. The mean duration of membership for current members is 2.0 years, with a median value of 1.5 years. This is influenced by a few outliers of members in DARE with over 6 years of experience, as well as the regular influx of new members in May who join as part of the Small Rocket Project (SRP). While all current SRP members are still active members, it is possible that not all will remain in DARE for an extended period. The duration of one's membership in DARE significantly influences their familiarity and experience with the safety culture, procedures, and implemented controls. However, it is important to be mindful that extensive experience can potentially breed a false sense of confidence, leading to undesirable behaviour such as deviating from established safety standards.
These factors highlight the diverse characteristics of DARE members and their impact on experience levels and attitudes towards risk-taking.

5.2.3. Analyses on the case study socio-technical system

Relationships between elements in the socio-technical system

A visual representation is created of the relationships between elements in the socio-technical system, similar to Figure 4.4. Two versions are made; one analysis of the SPEAR team and parachute mortar, launched from Esrange (launch site operator included) in Figure 5.8 and one analysis of DARE teams launching a parachute mortar on a small-scale sounding rocket at ASK 't Harde (launch site operator excluded) in Figure 5.9.

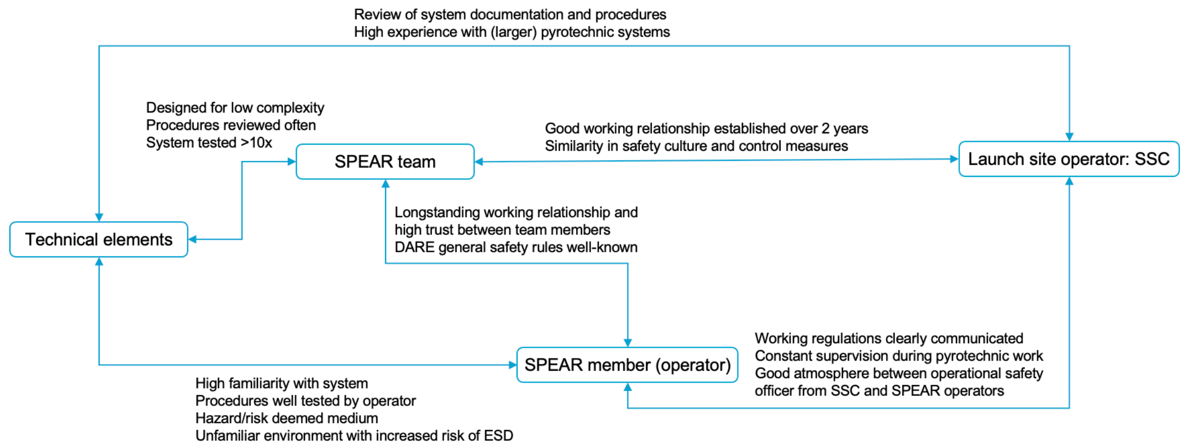

Figure 5.8: Relationships between elements in the socio-technical system of the SPEAR parachute mortar

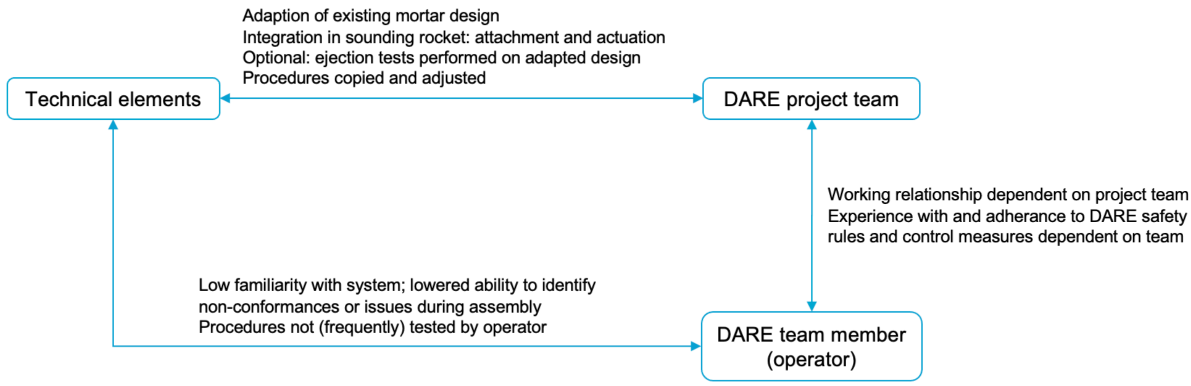

Figure 5.9: Relationships between elements in the socio-technical system of DARE parachute mortars

When performing the analysis, two challenges are apparent. Firstly, it is difficult to differentiate between relationships between the vehicle operator (member) and technical elements/launch site operator and relationships between the launch provider (team) and technical elements/launch site operator. This is partly due to the fact that the vehicle operator (member) is a part of the launch provider (team), meaning the relationship will be largely based on the same contact moments, however, the nature of the relationship may differ. Secondly, although this analysis can be performed in detail when considering 3-4 elements in the socio-technical system, the workload will significantly increase if it is performed on a socio-technical system with much more elements. Although this is done for other systems in literature, as can be seen in Figure 2.6, the level of depth per relationship decreases and the analysis becomes less clear.

When looking at relationships in the socio-technical system, the largest change occurs between the team using the parachute mortar system. The parachute mortar in the SPEAR mission is currently under evaluation and past development activities from this team form a large part of the risk identification and assessment phases in this research. For future implementations of the parachute mortar, other DARE teams and members will use the system. A considerable decrease in the familiarity of these teams and operators with the system itself and the assembly procedures can be expected. Because the risk management performed in this research is on the SPEAR parachute mortar, and the future usage of mortars in DARE is not exactly known, it is not feasible to accurately assess the risks induced by this reduced familiarity. Inexperience of members is taken into account as cause of errors or failures in the process FMEA, however the assessment of occurrence will vary per operator depending on their level of experience and must be re-evaluated by new teams using the parachute mortar system. It is strongly recommended for any new team implementing a parachute mortar, to:

- Perform an ejection test of the parachute mortar configuration as it will be used in the select

sounding rocket, to practice assembly and become more familiar with the system and operations.
- Perform a dress rehearsal of the parachute mortar and integration in the sounding rocket, including order of assembly and final arming procedures, without using pyrotechnics.

When reviewing internal and external items or actors that are influencing elements in the socio-technical system, as shown in Figure 5.10, it is interesting to see that a number of Performance Shaping Factors (PSFs) are reflected in the influences present on the operator.

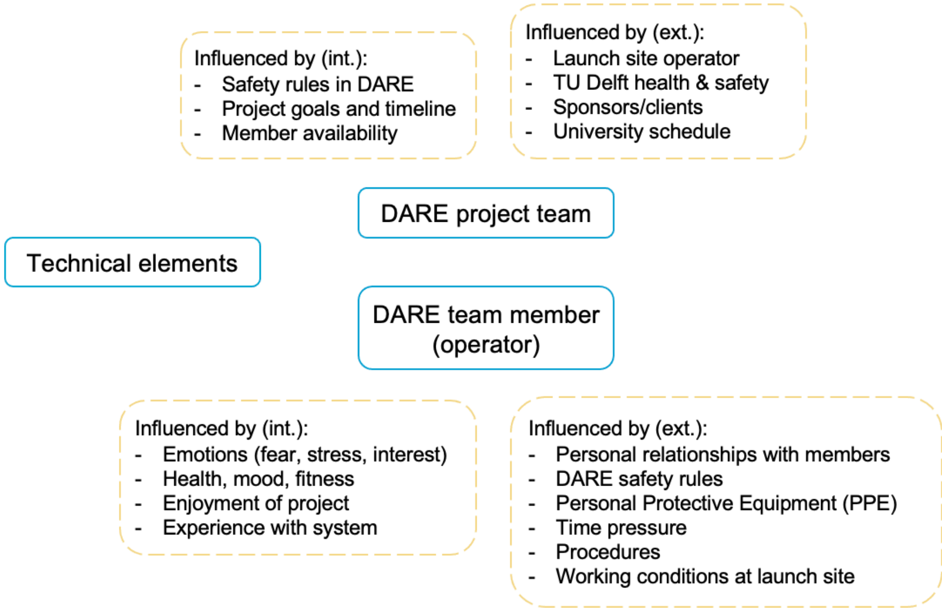

Figure 5.10: Influences on elements in the socio-technical system of DARE parachute mortars

Value chain analysis

A value chain analysis is performed on small-scale DARE launches at ASK 't Harde using the parachute mortar. The analysis can be seen in Figure 5.11. Monetary streams can be quantified through financial overviews which are accessible only internally in DARE and published at each General Members Assembly (GMA).

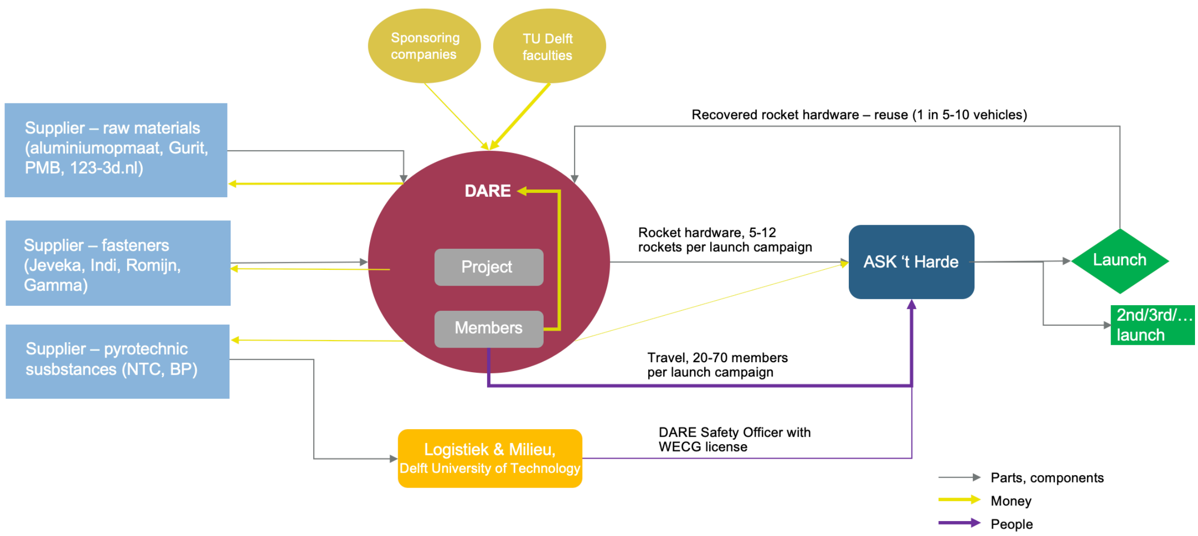

Figure 5.11: Value chain analysis of DARE parachute mortars

From the analysis, one of the key interesting results is the low recovery and therefore reusability rate. Reuse of hardware is excluded from the scope of this research, however it is a recommended topic for future exploration. Currently in DARE the recovery rate of sounding rockets lies between 10-20%, and it differs strongly per type of vehicle that is launched. Select launchers, such as the CanSat Launcher V7 (CSL V7), have a very high recovery and reusability rate and it is therefore possible that the same hardware is flown more than 5 times. Future research into the refurbishment and reusability of the parachute mortar should include investigation into DARE rocket recovery rates to establish requirements on the number of repeated use that is desired.

Integration of socio-technical analyses and risk management methods

Within this case study, the process-based Failure Modes and Effects Analysis (FMEA) and the Human Reliability Analysis (HRA) will be included in the risk management process. These bridge the socio-technical view with present risk management methods.
Additionally, the information described above provides extra context for the choices made throughout the risk management phase, such as trade-offs and selection of risk treatment methods, as well as risk evaluation. For example, it explains why DARE adopts a much higher level of accepted and tolerable risk than other organisations, and provides background information on the relevant Performance Shaping Factors (PSFs) and implemented controls.

Stakeholder analysis

A stakeholder analysis is performed on the DARE parachute mortar system. This enables a broad view of all actors and organisations inside and outside the socio-technical system. As described in subsection 4.1.4 this is done through a power-interest matrix and table, which can be seen in Figure 5.12 and Table 5.2. Generally, DARE has no client as stakeholder for a launch. The only exception is for the CanSat launches, where NEMO buys payload space from DARE.

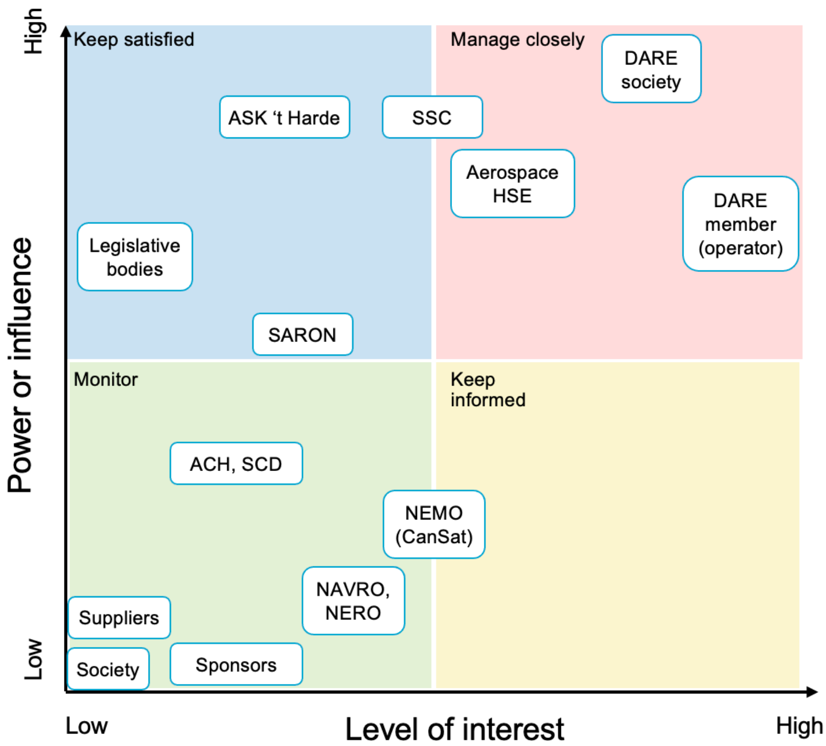

Figure 5.12: Power-interest matrix on stakeholders in the DARE parachute mortar system

What makes the DARE case study so unique, is that the normal prime motivator of a financial/commercial perspective disappears for nearly all stakeholders. There is no monetary compensation for the sponsors, members, launch site or workshops. Their main interests lie with facilitating this extraordinary form of education, and relationships must be fostered with care to maintain willingness from stakeholders to keep supporting DARE.

Stakeholder	Interest, values	Power, influence
DARE society	A successful launch and completion of mission goals. No damage/harm to infrastructure or people. Ability to reuse the sounding rocket hardware.	Full design of the system, assembly procedures and tests performed.
DARE member (operator)	Successful assembly and integration of the system without being harmed.	Performs the final assembly, may influence procedures during design/test phase.
ASK ‘t Harde	Maintaining safe operations and successfully launch sounding rockets.	Final go/no-go on all operations and/or launch of a system or sounding rocket.
SARON	Maintain good relationship with ASK ‘t Harde to keep facilitating rocket launches.	Review of technical systems that are being launched/tested, go/no-go below military.
Swedish Space Corporation (SSC)	Maintaining safe operations and successfully launch sounding rockets.	Final go/no-go on all operations and/or launch of a system or sounding rocket.
Legislative bodies	Safeguard values of countries, governmental bodies and other parties in the law.	Documenting laws that must be abided, which can be enforced.
Aerospace HSE	Ensure that all activities organised from/at Delft University of Technology occur safely.	Can require reviews on various tests/launches. Have a final say on tests on university or campus grounds. Can influence sponsorship of Aerospace faculty.
Sponsors	Support education amongst students. Recruitment of capable students. Gain promotional material.	Provide funding to DARE, enabling student development.
Faculties	Support education amongst students. Promotion of university towards prospective students.	Provide funding to DARE, enabling student development.
Aircraft Hall, SCD	Support education amongst students.	Provide workshop, equipment and storage locations.
Suppliers	Maintain steady output of product, reliable payment from customers.	Assortment, quality, price and delivery time of products.
Other SARON parties (NAVRO, NERO)	Launch their own vehicle/mission successfully. Have sufficient preparation time and launch slot(s) during a launch campaign to do so.	Discussing with all SARON parties to distribute resources (launch windows, work space).
Society	General advances in research and education. Concerns regarding sustainability.	General public interest influences funding, including available space funds.

Table 5.2: Description of the interest and power for stakeholders in the DARE parachute mortar socio-technical system

5.2.4. Reflection on the socio-technical system

The purpose of performing this evaluation of and analysis on the socio-technical system is twofold. Firstly, It is important to document and understand the status quo and assumptions present when performing a risk analysis, which enables all future readers to interpret it more accurately. Non-technical aspects of the situation and environment, such as organisational aspects, contribute significantly to the risk (level) present. This context also helps to understand how the goals and constraints of the risk management process are shaped. Secondly, the safety culture, safety procedures and characteristics of operators are all important contributing factors and input to the human reliability analysis (HRA). These must be explored to enable performing an HRA.

The various analyses performed on the socio-technical system can also be reviewed. It is deemed important to map the current relationships and elements in the socio-technical system, to also understand changes in the situation when they arise and how they impact the risk management. A prominent example is shown where the experience of the team and operator with the system and procedures will decrease between the SPEAR mission and future teams that will use the parachute mortar. Within this research, the value chain analysis did not add significant value, possibly because the goal is not to evaluate or optimise the process itself. It was useful in analysing and specifying the scope during earlier phases of research, resulting in the exclusion of reusability of rocket subsystems from this study.

5.3. Risk Identification

This section describes the application of the risk identification methods selected in subsection 4.2.2 to the DARE case study. The following methods are employed: review of past incident reports, interviews with experts, the product and process versions of Failure Modes and Effects Analysis (FMEA), and the Hazard Analysis and Critical Control Points (HACCP). Lastly, the applicability of these methods is reviewed.

5.3.1. Review of past incident reports

In the risk identification process, the first method employed was the review of past incident reports. A comprehensive collection of information on the full development cycle of the SPEAR (Supersonic Parachute Experiment Aboard REXUS) mortar system was conducted, encompassing parts production, integration, and system tests. This extensive review was undertaken as part of the Space Project course (AE4499), and the main content of the report can be found in Appendix E.
The evaluation of past incident reports yielded several key findings:

1. **Leakage in the plenum volume**: the gas generator in the parachute mortar system is located within the plenum volume[7]. Pyrotechnics can exhibit decreased performance or even failure to ignite in low atmospheric pressures. When the parachute mortar is implemented on a mid- to high-altitude sounding rocket, the external pressure surrounding the vehicle significantly decreases during the flight [8]. This poses a potential risk where, in the event of leakage and subsequent reduction in pressure within the plenum volume, the gas generator may underperform or fail to ignite, resulting in a failure to deploy the parachute. This behaviour was examined during low-pressure ignition tests conducted in the early stages of the mortar system's development.
2. **Difference between test and flight conditions**: ideally tests would be conducted in environmental conditions identical to those experienced during flight, such as ignition/deployment in low external pressures, cold temperatures, and after undergoing vibrations during ascent. However, these tests were scarce to nonexistent in the development phase of the DARE mortar. As a result, there remains uncertainty regarding the system's performance under these specific conditions.
3. **Uncertain ejection velocity**: the ejection tests performed on the parachute mortar yielded inconsistent results in terms of ejection velocity, between 20-30m/s, indicating potential variability in the system's performance. This may be partially explained through changes in the configuration, but is not proven.
4. **Failure of attachment ring joint or CFRP canister**: during ejection tests, the glue joint between the attachment ring and canister failed, resulting in a disconnected canister. This poses a significant concern since it is difficult or even impossible to detect whether the glue joint will fail. Additionally, damage to the CFRP (Carbon Fibre Reinforced Polymer) canister was visible after repeated testing, raising concerns on the structural integrity of the canister.
5. **Insufficient quality of CFRP canister**: the production process of the CFRP canister presented challenges, particularly concerning tolerances and ensuring the correct quality. Low experience with the production processes lead to low repeatability and uncertainty regarding the burst pressure of the canister.
6. **Inadequate documentation**: documentation related to production and testing was found to be lacking and highly dispersed. Insufficient documentation increases the likelihood of repeating past mistakes in the future.

Figure 5.13: Observed failure modes of and damages to the SPEAR mortar

[7]Sealed volume between the bottom of the canister and the sabot.
[8]Pressure at; Sea level = 1.013 bar, 5km altitude = 0.540 bar, 10km altitude = 0.264 bar.

The failure modes and damages observed during development and testing on the SPEAR mortar can be seen in Figure 5.13. From left to right: shear out of the steel mesh, failure of the attachment ring glue joint, damages to the CFRP canister and gas generator thread. As final result of the development process, the launch of the SPEAR mission was successful, and the parachute mortar performed a drogue parachute deployment in supersonic conditions. However, the assessment of the mortar's nominal performance in terms of ejection velocity remains uncertain due to the absence of specific data and limited fidelity of available video footage.

The advantage of utilising past incident reports is their specificity to the case at hand, ensuring the identification of relevant risks. However, a potential drawback is the tendency to focus excessively on known or previously identified risks and incidents, potentially overlooking new and unidentified risks. Additionally, the availability of reports on production, design, and performed tests was often either missing or of low quality. Therefore, the effectiveness of this risk identification method heavily relies on the quality of documentation within the organisation.

5.3.2. Interviews with experts

Two interviews were conducted with experts specialising in parachute mortar systems in the context of spaceflight. These interviews aimed to gather insights into the most significant risks associated with parachute mortar systems. During the interviews, the experts were specifically asked about the prominent risks they have encountered or identified in their experience. The interviews conducted with the experts were time-limited, and the main focus was on discussing their practical implementation of risk management methods rather than conducting an in-depth exploration of specific risks. Therefore, the questions regarding the identified risks were not extensively probed. The complete transcripts of the interviews can be found in Appendix B, providing a comprehensive record of the conversations. The following risks were highlighted as noteworthy considerations in the context of parachute mortar systems and are categorised into performance risks and safety risks:

The critical performance risks that were identified:

- The gas generator has a different performance in the relevant deployment environment (atmosphere, pressure, temperature)
- The gas generator cannot withstand the pressure created upon ignition of the pyrotechnic charge
- The gas generator is insufficiently sealed
- The mortar canister does not retain structural integrity under launch loads
- The mortar canister does not retain structural integrity during parachute ejection
- No actuation signal is received from the electronics subsystem

The critical safety risks and/or hazards that were identified:

- Undesired ignition of initiators due to electrostatic discharge (ESD)
- High velocity projectiles during ejection tests
- Loud sounds, hot gases released during ejection tests
- Undesired ignition of charge/mortar due to voltage on firing lines

The risks identified through interviews with experts hold significant importance due to their direct relevance to real-life parachute mortar cases. The expertise of these professionals, who possess extensive experience with various mortar systems and diverse designs, ensures that the identified risks encompass a broad spectrum of potential functional risks and safety hazards. The weight carried by these expert-identified risks is further reinforced by their deep understanding of the field, providing valuable insights and knowledge that contribute to comprehensive risk management.

5.3.3. Failure Modes and Effects Analysis (FMEA)

As described in subsection 4.2.2, both the product FMEA and process FMEA will be conducted. The steps taken to conduct the FMEA are described in Table 5.3, as written by McDermott [44], as well as their corresponding risk management phase.

Number	Step	Risk management phase
1	Review the process or product.	Risk identification
2	Brainstorm potential failure modes.	Risk identification
3	List potential effects of each failure mode.	Risk assessment
4	Assign a severity ranking for each effect.	Risk assessment
5	Assign an occurrence ranking for each failure mode.	Risk assessment
6	Assign a detection ranking for each failure mode and/or effect.	Risk assessment
7	Calculate the risk priority number for each effect.	Risk assessment
8	Prioritise the failure modes for action.	Risk evaluation
9	Take action to eliminate or reduce the high-risk failure modes.	Risk mitigation
10	Calculate the resulting RPN as the failure modes are reduced or eliminated.	Risk mitigation

Table 5.3: 10 Steps for an FMEA [44]

To perform the analyses, the FMEA worksheet is used [44]. This sheet provides a full overview of the risk identification, assessment and mitigation phases and immediately forms the basis of the risk documentation. The full worksheets and thus analyses can be found in Appendix A. The risk identification phase only includes step 1: reviewing the process or product, and step 2: brainstorming potential failure modes. Step 1 consists of making a blueprint (product FMEA) or flowchart (process FMEA), enabling the same understanding amongst all members performing or reading the FMEA. For the product FMEA, the technical drawing and parts list as presented in subsection 5.1.2 are used to establish the scope of the analysis. When reviewing the Design FMEA Scope Worksheet by McDermott et al. [44], part 5 and 6 decide on the inclusion of raw material failures and packaging, storage and transport, which are both excluded from this analysis. Part 7, "the operational process requirements and constraints" is extremely important for this case, as this may vary heavily between different launches. Operational requirements can be seen as: launch loads (acceleration, vibration), time until parachute deployment, external environment upon deployment (temperature, pressure, atmospheric composition). For the DARE sounding rockets, the main distinction must be made between the external environment which differs among low altitude launches (max. altitude of 5km) and medium- to high-altitude launches (5-120 km), as well as consider the parachute deployment altitude.
For the process FMEA, the value chain analysis is taken as the starting point. As this FMEA form focuses on the process of creating the product, the analysis boundary is placed until right before the launch itself. It is visually represented by a flowchart in Figure 5.14.

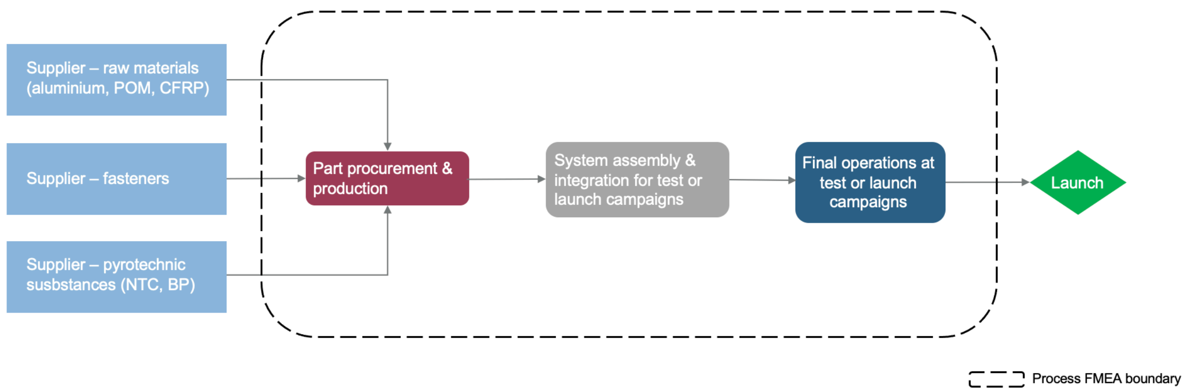

Figure 5.14: Process FMEA boundary

Over 100 risks were identified through the process and product FMEAs. Some overlap between the risks identified in the process and product FMEA is visible, which is reasonable, as most risks in the design are a result of the design/production/operations by the launch provider or vehicle operator. It can therefore occasionally be seen that "failure modes" in the process FMEA form "potential cause(s) of failure" in the product FMEA.

A number of risks surface in both analyses, such as the variable parachute packing density: SAI-15, SAI-16 and SAI-17 in the process FMEA as well as INT-03 and INT-04 in the product FMEA. When comparing the risks covered in the process FMEA, the major addition with respect to the product FMEA lies in two aspects; 1. safety risks during assembly, 2. risks focusing on incorrect performance of assembly steps.

As the worksheet already includes all fields for the risk assessment and mitigation phases as well, it is difficult to focus solely on the identification phase. This presents a drawback as valuable inputs may be overlooked when transitioning too quickly to the subsequent phases. The assessment of risks identified through the product and process FMEA methods is presented in subsection 5.4.2.

5.3.4. Hazard Analysis and Critical Control Points (HACCP)

The full HACCP analysis can be found in Appendix A. The risk identification phase of HACCP orders the risks by process step or raw material, and allocates the relevant hazard and source. A hazard is defined as ”any factor that may be present in the product, which can cause harm to the consumer either through injury or illness.” [53]. Risk identification on the parachute mortar therefore focuses on the used materials, such as CFRP, resins, and Nitrocellulose, and processes, such as use of liquid nitrogen for canister demoulding and use of powertools and machinery. The HACCP method starts by clearly describing the production process, which is described in previous documentation, located in Appendix E.

Similar to the FMEA method, the HACCP worksheet also encourages direct completion of the risk assessment and mitigation stages. This approach can present a potential issue because it may result in a lack of focused attention on the specific identification phase of the risk management process. By immediately shifting focus to the assessment and mitigation stages, valuable inputs and insights related to risk identification might be overlooked or not given adequate consideration. The assessment of hazards identified through the HACCP method is presented in subsection 5.4.3.

5.3.5. Reflection on risk identification methods

The review of past incident reports, as described in subsection 5.3.1, provides a large amount of detailed information on the challenges and risks present in the system. However, this identification method only uncovers or collects risks that have been encountered in the past. Additionally, it relies strongly on the quality of documentation that is present. Interviews with experts are valuable to observe whether the identified risks align with the general industry views. Both the FMEA and HACCP methods structure the brainstorming process to identify risks within a team. Because the worksheets of these methods already include fields for risk assessment, evaluation and mitigation, they do not promote the exhaustive completion of the risk identification phase.

5.4. Risk Assessment

This section describes the application of the risk assessment methods selected in subsection 4.2.2 to the DARE case study. The following methods are employed: severity/likelihood matrices, the product and process versions of Failure Modes and Effects Analysis (FMEA), Human Reliability Analysis (HRA) following the SoTeRiA (Socio-Technical Risk Analysis) framework and the Hazard Analysis and Critical Control Points (HACCP). Lastly, the applicability of these methods is reviewed.

5.4.1. Severity/likelihood matrix

All risks identified through FMEA, past incident reports, and interviews with experts are assessed based on their severity and likelihood. This combines into a risk matrix which provides a simple and direct assessment of the risks. It is often used in the space industry, and selected as risk management method in the ECSS standard [20]. An important goal in this method is to ensure the assessment of severity and likelihood is as objective as possible, which is why detailed rating scales are used. These can be found below in Table 5.4 and Table 5.5. Note that a different scale is applied to functional performance risks and safety risks.

Rating	Scale - Likelihood	Scale applied to DARE case
5	Almost certain	Has occurred regularly in DARE and/or during mortar tests
4	Likely	Has happened on occasion during mortar tests
3	Moderate	Exact or similar incident has happened sometimes in DARE
2	Unlikely	Has not yet happened in DARE, but similar incidents happened in other DreamTeams, at TU Delft, or other student rocketry teams
1	Rare	No known occurrence

Table 5.4: Ratings used to evaluate likelihood of risks in risk matrices

Scale - safety risks	Rating	Scale - functional performance risks
Significant harm/damage to people/property	5	Complete system failure, loss of vehicle system(s) before re-entry
Medium harm/damage to people/property	4	Complete system failure, no parachute ejection
	3	Successful ejection but underperformance or risk of unsuccessful parachute inflation (damage/debris/entanglement)
Minimal harm to people (cut, scrape, etc.)	2	Slight underperformance or overperformance
No harm/damage to people/property	1	Nominal system performance

Table 5.5: Ratings used to evaluate severity of risks in risk matrices

The full analysis can be found in Appendix A. The main results can be seen in the final risk matrix in Figure 5.15. The most critical risks, located in the red area of the table ($L \cdot S \geq 15$) are listed in Table 5.6.

L	S	1 Insignificant	2 Minor	3 Significant	4 Major	5 Severe
5	Almost certain	GG-06	PPP-11 SAI-01, 02		SAI-15	
4	Likely	PPP-05 SAI-31	PPP-04, SAI-03, 04, 13 GG-10	SAI-05, 16, 17, 30 OPS-02 CS-07 GG-03 SB-05 INT-03	OPS-05 CS-04 IG-01 INT-04, 05	
3	Moderate		SAI-11 GG-08 SB-03, 04	PPP-02, 09 SAI-19, 20, 21, 24, 25, 26 OPS-08, 09, 10, 11, 12, 13 INT-06	PPP-03, 06, 07, 10, 12 SAI-07, 10, 18, 22, 23, SAI-27, 28, 29 OPS-01, 03, 04, 06 GG-02 SB-02	CS-02, 03
2	Unlikely		PPP-13 SAI-08 GG-12	PPP-08 SAI-14 IG-03, 04 GG-05, 07, 11 SB-01, 06 LD-01	PPP-01 SAI-06 IG-02 GG-01, 04, 09	OPS-07 CS-01, 05, 06 INT-01, 02
1	Rare		EC-01	LD-04	SAI-09 GG-13 LD-02, 03	

Figure 5.15: Risk assessment: severity/likelihood matrix

Risk ID	Risk description
SAI-15	A different parachute is used than during (qualification) tests, leading to a significant over- or underperformance due to changed compressibility, possibly resulting in no ejection.
OPS-05	Critical assembly mistakes in arming procedure due to rush and time constraints, resulting in no ejection.
CS-02	Structural failure (radial burst) of canister due to the true burst pressure being lower than the designed pressure.
CS-03	Structural failure (radial burst) of canister because the canister cannot withstand repeated application of design pressure (cyclic loading).
CS-04	Failure of glue joint between CFRP canister and attachment ring due to insufficient (and inconsistent) strength of glue joint.
IG-01	Ignition signal is not received from electronics subsystem, due to damaged cabling or no ignition signal is sent (causes described in INT-05).
INT-04	Packing density of the parachute subsystem is lower than during ejection testing, leading to underperformance of the system, possibly no ejection.
INT-05	No ignition signal is given from the electronics subsystem, due to bad connections causing momentary power loss or system reset, faulty or damaged electronics components, general software bugs, sensor triggers for deployment set incorrectly (pressure, acceleration, timers, etc.), battery or power supply unable to provide sufficient power (brownout).

Table 5.6: Most critical risks resulting from severity/likelihood matrix assessment

The severity/likelihood risk matrix method offers a straightforward visual representation of risks by combining severity and likelihood assessments. Its advantages include simplicity, ease of communication, and the ability to prioritise risks based on their position in the matrix. However, it may oversimplify the complexity of risks, rely on subjective judgements, and fail to account for interdependencies or uncertainties that can influence risk outcomes.

5.4.2. FMEA

All risks identified through FMEA, past incident reports, and interviews with experts are rated and assessed based on their Severity (S), Occurance (O) and Detection (D). These ratings, ranging from 1-10, are multiplied to form the Risk Priority Number (RPN). The severity/likelihood risk matrix method and the FMEA risk management method share similarity where both methods involve evaluating the severity and likelihood of potential failures. However, the severity/likelihood risk matrix method typically provides a limited qualitative assessment, while FMEA offers a more detailed analysis by considering failure modes, their causes, effects, and mitigation strategies. The FMEA therefore covers more risk management phases, and is a more structured and comprehensive approach that allows for a deeper understanding of risks and their potential impact on a system or process. Similarly to the risk matrix, the objective grading of these scales is crucial to ensure repeatability of the method, and therefore detailed rating scales are used. These can be found below in Table 5.7, Table 5.8 and Table 5.9. Per scale, remarks on its implementation are shared.

When comparing the scales of severity and likelihood in the risk matrices and the scales of severity and occurrence in the FMEA, they exhibit similarities. However, a notable difference is that the risk matrix typically employs a rating scale from 1-5, while the FMEA utilises a broader scale ranging from 1-10. This expanded scale offers more granularity and allows for nuanced assessments. In the case of the parachute mortar, which involves a ”pass/fail” scenario, the need for such nuance may be debatable as failure modes can either have minimal impact or lead to complete system failure. Consequently, the 1-10 rating scale is currently not fully utilised. Nevertheless, it permits more precise placement and weighting of criteria, enabling better differentiation between consequences.
When looking at the severity rating scale, a different scale is applied to functional performance risks and safety risks, as was done in the risk matrix rating scales. An important aspect to consider in the implementation of the severity grading scale is the uncertainty surrounding the thresholds for certain consequences. The specific levels of overperformance of the gas generator leading to structural failure or levels of underperformance causing a complete lack of ejection are currently unknown. Therefore, decisions on the severity grading between rating 6-7 (slight underperformance vs. underperformance) and 5-7 (overperformance vs. structural failure of casing upon ejection) cannot be seen as objective. Further ejection tests with varying masses of NTC could provide valuable insights to better understand these critical consequences.

Scale - severity of safety risks	Rating	Scale - severity functional performance risks
Significant harm/damage to people/property	10	Complete system failure, loss of vehicle system(s) before re-entry
	9	Complete system failure, no parachute ejection
Medium harm/damage to people/property	8	
	7	Successful ejection but underperformance or risk of unsuccessful parachute inflation (due to damage, debris or entanglement)
	6	Slight underperformance
Minimal harm to people (cut, scrape, etc.) or damage to property	5	Successful ejection but overperformance
	4	
	3	Successful ejection but loss of parts
	2	
No harm/damage to people/property	1	Nominal system performance

Table 5.7: Ratings used to evaluate severity of risks in FMEA

The implementation of the occurrence scale aims to be objective by considering the frequency of similar events in mortar tests, launches, and experiences within DARE, Delft University of Technology, and other student rocketry teams. However, it should be noted that the occurrence rating is somewhat influenced by the detection rating, as items that are easily detected through, for example, rigorous procedures within DARE tend to have a lower occurrence rating.

It should be noted that there is uncertainty in the ratings of the severity (S) and occurrence (O) for the following scenarios:

- When does overperformance (e.g. due to overfilling) lead to structural failure of the casing? Currently it is presumed that overperformance does not lead to structural failure, as there is a high safety factor on the designed burst pressure of the casing.
- When does underperformance (e.g. due to underfilling or increased friction) lead to no ejection? It is currently presumed that underfilling can lead to no ejection, as observed during early mortar system tests where a lower mass of NTC, in combination with a higher amount of shear bolts, did

not lead to parachute ejection.

- What is the occurrence of leaks in the plenum volume under vibration loading? It is currently presumed that there is a significant chance on leaks during ascent (O=5-7). During low-pressure ignition tests, various leaks in the system were observed, and new leaks arose after transporting or adjusting the system.
- What is the occurrence of decreased mortar performance due to temperature drop in the vehicle during launch? It is currently presumed that the temperature drop does not have a significant input on performance, as the mortar was stored inside the SPEAR vehicle and temperature sensors in the electronics compartments did not register low temperatures inside the vehicle during flight.

These effects cannot be assessed properly based on the current knowledge and experience. Tests can be performed to enable better assessment of these failure modes, specifically on the underperformance limit and leaks in the plenum volume, as these are deemed most likely to occur.

Rating	Scale - Occurrence	Scale applied to DARE case
10	1 in 5	
9	1 in 10	Failure modes that occurred during previous mortar tests or sounding rockets with mortar systems
8	1 in 20	
7	1 in 50	Anything that has happened multiple times in DARE (other teams)
6	1 in 100	
5	1 in 500	Anything that has happened in DARE (other teams)
4	1 in 1000	Anything that has happened in the DreamHall, Delft University of Technology, or other student rocketry teams
3	1 in 2000	
2	1 in 5000	
1	Failure eliminated	

Table 5.8: Ratings used to evaluate occurrence of risks in FMEA

The implementation of the detection scale in this case study presented challenges due to the absence of a distinct design freeze moment in DARE, as described in subsection 5.2.2. As the FMEA handbook suggests a division between pre-design freeze and post-design freeze detection [44], it was not fitting to apply this detection rating scale. There are alternative detection scales available in literature, however they mostly rank the scale in the form of: absolute uncertainty - low - moderate - high - almost certain. This makes objectivity difficult, and a more practical scale is sought which more clearly defines the ranking. Some sources quantify the probability of detection, but this is not feasible for the mortar system. A compromise is made by using the qualitative, top-level detection scale, and adding a description on how this level of detection (e.g. 'moderate') is interpreted for the mortar parachute case. This involved reviewing the detection methods, potential scenarios, and ranking them based on the likelihood of detection. Although there might be a slight bias favouring risks that are already identified and addressed, the detection rating serves its purpose by assessing the ease of detecting risks based on the current controls in place. Notably, the detection rating includes and regards the implementation of the current controls in place to prevent the failure mode. For example, detection ratings on assembly mistakes regards the situation where one product assurance engineer (PA) reads through the procedures and checks for correctness of the assembly steps.

Scale - Detection (top level)	Rating	Scale - Detection (mortar case)
No design control or no chance of detection	10	Even if the risk is known, it is not possible at all to establish whether it will occur
Very remote chance of detection	9	Very difficult to detect whether the risk will occur, for example, the failure may occur even if detection activities were performed
Remote chance of detection	8	The required effort/resources to detect the risk/issue is very high (e.g. extra test campaigns or expensive equipment are needed), generally not done
Very low chance of detection	7	The required effort/resources to detect the risk/issue is high (e.g. an extra test is needed), occasionally done for important missions
Low chance of detection	6	Detection is possible, but detection methods are not (standard) implemented in the procedures and/or test campaigns, and are only known/performed by experienced operators.
Moderate chance of detection	5	Detection is possible, but detection methods are not (standard) implemented in the procedures and/or test campaigns. Detection methods are naturally done during operations and/or are known and performed by most operators.
Moderately high chance of detection	4	Detection is possible, currently implemented in procedures and test/launch campaigns, and requires a medium level of effort or they are occasionally skipped during the procedures.
High chance of detection	3	Detection is possible, currently implemented in procedures and test/launch campaigns, and requires little to no effort.
Very high chance of detection	2	Detection is almost automatic, direct through observation or it is not possible to continue assembly, is recognisable by operators with little to no experience.
Cannot occur, or almost certain detection	1	Very low chance of failure mode to occur due to prevention in design

Table 5.9: Ratings used to evaluate detection of risks in FMEA

The Risk Priority Number (RPN) is computed using the formula $RPN = S{\cdot}O{\cdot}D$. This formula calculates the RPN by multiplying the severity (S), occurrence (O), and detection (D) ratings. Instead of a full priority ranking of all risks based on the RPN, four levels are made which group the RPN in a range; 4. ≤ 150, 3. $150 - 249$, 2. $250 - 349$, and 1.≥ 350. Risks categorised as priority level one, with an RPN (Risk Priority Number) exceeding 350, are presented in Table 5.10.

Risk ID	Risk description
PPP-07	Casing has production errors resulting in a lowered maximum burst pressure, leading to structural failure of the casing.
SAI-15	A different parachute is used than during (qualification) tests resulting in significant system underperformance due to large change in compressibility and therefore no ejection.
CS-02	Structural failure (radial burst) of canister due to the true burst pressure being lower than the designed pressure.
CS-03	Structural failure (radial burst) of canister because canister cannot withstand repeated application of design pressure (cyclic loading).
CS-04	Failure of glue joint between CFRP canister and attachment ring due to insufficient (and inconsistent) strength of glue joint.
GG-02	Charge does not (fully) ignite or underperforms due to leaks in plenum volume during ascent, (pressure in plenum volume 35mbar-0,5bar).
IG-01	Ignition signal is not received from electronics subsystem, due to damaged cabling or no ignition signal is sent (causes described in INT-05).
SB-05	Sabot collides with parachute (pack) after deployment as it is ejected from the mortar in the same direction as the parachute assembly.
LD-02	Lid has insufficient momentum to pull the parachute from its bag (extraction), leading to no parachute deployment.
INT-05	No ignition signal is given from the electronics subsystem, due to bad connections causing momentary power loss or system reset, faulty or damaged electronics components, general software bugs, sensor triggers for deployment set incorrectly (pressure, acceleration, timers, etc.), battery or power supply unable to provide sufficient power (brownout).
INT-07	Parachute entanglement during ejection due to complex interaction between parachute pack movement due to the mortar ejection and aerodynamics during descent.

Table 5.10: Most critical risks resulting from FMEA assessment

A comparison between the risk assessment conducted using the risk matrix and FMEA methods reveals the following differences:

- PPP-07 is included in the FMEA but not the risk matrix, due to a high detection rating. Establishing the quality of the CFRP product and the real maximum burst pressure requires hydrostatic testing. This risk aligns with risks CS-02 and CS-03.
- OPS-05, included in the risk matrix, is not listed in the FMEA due to its good detection possibilities.
- GG-02, not present in the risk matrix, is included in the FMEA because of its high detection rating, as it requires additional leak testing measures.
- SB-05, not accounted for in the risk matrix, but is included in the FMEA due to its high detection rating. Although it has never occurred in DARE before (low occurrence/likelihood), it is recognised as a significant risk based on industry standards and expert interviews, where the sabot capture net is identified as a critical functionality. The high detection rating reflects the inability to determine in advance whether this failure mode will occur without capture net present, as the movement of the sabot and parachute, and therefore collision probability, is random.
- LD-02 and INT-07 are included in the FMEA but not the risk matrix, due to a high detection rating. Establishing the successful parachute extraction and inflation requires flight testing.
- INT-04, originally included in the risk matrix, is omitted from the FMEA. However, it still carries a relatively high RPN (343) and falls near the threshold of being listed in Table 5.10.

Another noteworthy observation is that most safety risks receive relatively low RPN scores, primarily due to their low detection ratings resulting from the effective controls implemented in the assembly procedures and operations. This aligns with the insights shared by experts during interviews, where the safety controls mentioned closely mirror those implemented in this particular case study. Although the risks of undesired ignition of pyro charge shave a higher detection rating due to the challenging nature of anticipating electrostatic discharge (ESD) and spontaneous combustion, its overall Risk Priority Number (RPN) remains relatively low. This is primarily attributed to the significantly lower probability of such events occurring. When reviewing all safety risks, SAI-08 has an RPN of 240, whilst all other

RPN values of safety risks fall below 200. SAI-08 describes the risk of squib firing unintentionally due to ESD.

5.4.3. HACCP

The HACCP method also uses a basic assessment of likelihood and severity (low (L), medium (M), high (H)) to determine the significance of a hazard. The grading scale used to rate the likelihood and severity of each hazard is presented in Table 5.11 [53]. Risks resulting in burns (hot and cold) are assessed with a high severity, as they may be lifelong. Selection of the risk likelihood is based on history in DARE as history in 'sector'. The overview of the HACCP assessment can be seen in Figure 5.16. Implementation of control measures is further discussed in subsection 5.3.4.

S/L	Rating	Description of severity and likelihood
Severity	L	Minor effect. Short duration.
Severity	M	Injury or intolerance. Not usually life threatening.
Severity	H	Life threatening or long-term chronic illness (e.g., infection, intoxication, or anaphylaxis), chronic effects or death.
Likelihood	L	Unlikely to occur. No known examples.
Likelihood	M	Could occur. Minimal history within the sector but has happened.
Likelihood	H	Highly probable. Known history in the sector.

Table 5.11: Rating scales for HACCP assessment [53]

HACCP (Source of template: HACCP a practical approach)

Process step / raw material	Hazard and source	Likelihood L/M/H	Severity L/M/H	Significant hazard Y	Significant hazard N	Control measures
CFRP	Loose carbon fibres, from processing / handling CFRP parts.	H	M	Y		Personal protective equipment: full face piece respirator, full body cover, gloves.
	Exposure to resins may cause irritation of eyes, nose, throat and skin, allergies and asthma.	H	M	Y		Personal protective equipment: safety glasses, gloves, long sleeves, mouth respirator (depending on resin).
Epoxy / resins	Flammable. Some resins may (when combined) have an exothermic reaction.	M	H	Y		Dispose of resins in appropriate manner (organised by university). Adhere to maximum amount of resin disposal in 1 batch.
Liquid nitrogen	Extremely low temperatures; cold burns, frostbite.	M	H	Y		Personal protective equipment: safety glasses, liquid nitrogen gloves.
	Loose flying dust or particles.	H	L		N	Personal protective equipment: safety glasses, mouth respirator (depending on material)
Production using power tools	Collision with power tool.	M	L		N	Safety culture in organisation: Operate machining equipment with care. Do not rush manufacturing.
Production using machining	Loose flying metal chips / particles.	H	L		N	Personal protective equipment: safety glasses, labcoat, working shoes.
Carrying heavy equipment	Potential energy of mass	H	M	Y		Personal protective equipment: working shoes.
Acetone / IPA	Highly flammable. Can irritate nose, lungs, hands.	H	L		N	Drip trays for large jugs. Keep working amounts of acetone or IPA dispensers. Wear nitrile gloves whilst using acetone/IPA.
Nitrocellulose	High energetic material, explosive hazard - may release high amount of energy (heat and flames) upon combustion	L	H		N	Use high energetic materials that display deflagration instead of detonation. Wear personal protective equipment when handling explosives (safety glasses). Measure and handle working quantities of NTC, not the full jar.
Flashpaper	Low energetic material	L	L		N	No control measure needed
E-matches	Low-hazard explosive - may release medium amount of energy (heat and sparks) upon ignition	M	M		N	Wear personal protective equipment when handling explosives (safety glasses). Discharge any static energy before handling e-matches. No phones on.

Figure 5.16: Risk assessment: HACCP analysis

5.4.4. Human reliability analysis

The chapter on human reliability analysis encompasses two main aspects of the SoTeRiA (Socio-Technical Risk Analysis) framework: organisational and safety culture and practices, and Performance Shaping Factors (PSFs). Their influence on the functioning of (operators in) the socio-technical system will be reviewed.

The organisational and safety culture and practices of DARE are described in subsection 5.2.2. Certain aspects support correct functioning by the operator, whilst some inhibit this. An overview of these aspects is given in Table 5.12.

Influence	Safety culture and practices	Organisational culture and practices
Support	Safety culture has a long history in DARE and is deeply ingrained in the society. A thorough framework exists on how to prepare for and perform safety critical operations. Elaborate training required before a member is nominated as safety officer. Safety critical operations are performed at allocated locations with reserved areas for tests/launches.	High intrinsic motivation for participation in rocketry activities. High commitment of management (board) to safety practices. Society supports safety practices from a logistical perspective. Launch day committee rocket check promotes readiness of hardware on time.
Inhibit	No general values on safety established. Subjectivity of SOs may lead to difference in standard operations or assessment of system. Workload on safety officers occasionally too high. Work and decisions of SOs not supervised or checked.	Level of knowledge transfer falls significantly below the desired standard. Diverse quality of documentation, insufficient information on development after design reviews. Young members may not assess risk properly. Low (financial) resources available for system development. High turnover of members.

Table 5.12: Supporting and inhibiting factors on nominal operations from organisational and safety culture and practices

In general the safety culture and practices are well established, which is a great base to use for development of safety critical systems. However, knowledge transfer is deemed one of the essential factors that ought to be evaluated and improved to promote positive organisational effects in the socio-technical system. This may also induce various risks relating to project timeline and budget, which are currently excluded from the research scope but are incredibly relevant in DARE.

As described in subsection 4.2.2 various Performance Shaping Factors (PSFs) influence the ability of an operator to successfully perform the required activities. Various PSFs are described in different methodologies and sources, although they have a high overlap. The starting point of PSFs used in this research is based on the work of Blackman et al. [8] and can be seen in Table 5.13. This work focused on quantifying PSFs by allocating a multiplier, which is used to adjust the Human Error Probability (HEP). The range of multipliers is displayed here as well, not to support quantitative analysis, but because it indirectly displays the weights given to various PSFs. In some cases, the multiplier is replaced by ”Probability of Failure = 1” (PF1), directly replacing the original HEP value. It can be seen immediately that ”Procedures” and ”Ergonomics and HMI” can very strongly influence the HEP according to this model, and whilst decreased time or fitness has a lower impact (M=10, M=5), insufficient time or fitness leads to immediate failure.
To evaluate the Performance Shaping Factors as presented in Table 5.13, the operations on the parachute mortar for the PIP-III launch were observed on the 30th of March. Background information is also available on the tests performed for the SPEAR mission, which are described in Appendix E. The primary difference between these cases is that up until 2021, all pyrotechnic preparation happened inside the DreamHall workspace at Delft University of Technology. In the academic year of 2020/2021, the DARE society was required to leave the DreamHall and continued its activities in other locations. This meant that pyrotechnic preparation, including assembly of the ignitor bolts and gas generators, has to be done at launch campaigns. All required facilities and items are present, as the preparation of other pyrotechnic systems (such as the rocket motors and ignitors) also occur on the launch campaign. For each launch at ASK 't Harde, these activities are performed on a ”prep day”, generally on a Thursday, before the actual ”launch day” on Friday. DARE is currently working on arranging different locations for pyrotechnic preparation activities, as this positively influences various PSFs during safety critical operations.

Performance Shaping Factor (PSF)	Description	Range of multiplier
Available time	The amount of time that an operator or a crew has to diagnose and act upon an abnormal event	PF1-M=0.01
Stress and stressors	Negative & positive motivating forces of human performance, such as mental stress, excessive workload, or physical stress from environmental factors	M=5-1
Complexity	How difficult the task is to perform in given context	M=5-0.1
Experience and training	Years of experience of the individual or crew, and whether or not the operator/crew has been trained on the type of activities	M=10-0.1
Procedures	Existence and use of formal operating procedures for the tasks under consideration	M=50-0.5
Ergonomics and Human Machine Interaction (HMI)	The equipment and the interaction of the operator/crew with the equipment to carry out tasks	M=50-0.5
Fitness for duty	Whether or not the individual performing the task is physically and mentally fit to perform the task at the required time	PF1-M=0.5
Work process	Aspects of doing work, including inter-organisational, safety culture, work planning, communication, and management support	M=2-0.8

Table 5.13: Performance Shaping Factors and multipliers by Blackman et al. [8]

For each PSF, an assessment of the multiplier can be made, not to calculate the Human Error Probability (HEP), but to compare the level of influence of different PSFs on the parachute mortar operations. Additionally, it can be reviewed how much we can alter the situation per existing PSF.

- **Available time**: pyrotechnic preparation and system assembly are performed on the ”prep day” of a launch day, providing the operator with copious amounts of time to perform all activities. The final window of operations during a rocket launch is lower, however, additional time can be requested in case of complex assembly procedures. Generally speaking, there is sufficient available time to perform the operations, resulting in a nominal Multiplier of 1. It must be noted that this is dependent on both the number of other activities (tests, launches) during a launch campaign, as well as the availability of Safety Officers. The team launching and operating the mortar system cannot influence these factors. On launch campaigns with a relatively high number of launches (≥ 6), especially the available time for final operations during the launch window itself is lowered.
- **Stress and stressors**: the activities of pyrotechnic preparation and final operations on the system are performed at the launch site, in a tent. This means the operator is subjected to various weather conditions, such as low temperatures and high winds. Specifically during the operations on PIP-III in March, this was a prominent factor in the stress on and performance of the operators, resulting in a High level of stress, providing a Multiplier of 2. These conditions can mainly be improved when an alternative location for pyrotechnic preparation is found.
- **Complexity**: mortar system only has a few parts and is relatively simple. Any abnormalities are easy to identify. This results in a nominal Multiplier of 1. This factor cannot be easily adjusted, however, it is dependent on the integration of the mortar within the sounding rocket. This may add complexity to the system or operations.
- **Experience and training**: the experience of the operator with the mortar system, pyrotechnic preparation, or general tools and parts that are used, depends fully on which operator is preparing the system. The Multiplier will range between 0.1-10 depending on the operator. Members with all levels of experience are expected to be able to work on the system.
- **Procedures**: the procedures are available, but their quality lies between ’enhancing performance’ (M=1) and ’difficult to use due to ambiguity’ (M=5). The procedures support the operations successfully, however, there is ambiguity noticeable especially for members with lesser experience on identifying the parts and steps mentioned in the procedures. There is room for improvement in the procedures and this is deemed feasible to adjust.

- **Ergonomics and HMI**: the description of this PSF, specifically Human Machine Interaction, is not highly relatable to the case of a mortar system as it focuses on computer interfaces and instrumentation. When reviewing PSFs mentioned or used in other methods, the main relatable item that comes close is the use of tooling during the operations. In principle all tools needed for preparing and assembling the mortar system are present in DARE, however, they need to be transported to the launch campaign. To ensure this happens a tool list could be included in the procedures. Ergonomically the assembly is not comfortable, as it is performed whilst standing over a regular height table. These conditions can mainly be improved when an alternative location for pyrotechnic preparation is found. A nominal Multiplier of 1 is selected, however, the rating scale of [8] does appoint high multipliers to this PSF, so monitoring these conditions should receive a high priority. The absence of a required tool during assembly will result in a significantly increased multiplier, as other unsuitable tools need to be used to continue with the operations.
- **Fitness for duty**: the general fitness of DARE members at a launch campaign is degraded, due to the low quantity and quality of sleep between the prep day (Thursday) and launch day (Friday), as limited funds are available for accommodation and the launch day starts early. This affects all members differently, but it can certainly reduce the fitness, leading to a Multiplier of 5. These conditions are however not easily adjusted.
- **Work process**: crew performance is deemed nominal, resulting in a Multiplier of 1, however this may vary dependent on the operator and team preparing the mortar system. In general the work processes, coordination and communication during a DARE launch day are good and do not significantly influence the performance. A longstanding working relationship between the operator and Safety Officer or other members present may increase the work process grading to ”Good”, with a Multiplier of 0.8.

When reviewing the PSFs, it is apparent that an alternative location for pyrotechnic preparation before a launch campaign would bring great benefits to the operator's performance. This will also indirectly increase the available time, as less activities must be performed during the campaign. The procedures can still be improved further to ensure they solely support the operations and are unambiguous. An important factor is the availability of correct tools, as unavailability of (correct) tools would strongly impact the ergonomics and HMI multiplier.
As there is no comparison possible to a desired standard, except to reduce all Multipliers of PSFs to nominal (M=1), and there are no specific risks identified or assessed in the current application of HRA, the evaluation of risks from the Human Reliability Analysis is not feasible. Risk treatment of the parachute mortar will address improvements in the PSFs.

5.4.5. Consequences on the socio-technical system

The impact on stakeholders following a failed launch varies depending on the mission design and the criticality of recovery. The higher the criticality of the recovery system, the stronger negative impact on various stakeholders. Here are the scenarios that can occur:

1. Mission-critical recovery: In this scenario, the successful parachute recovery is crucial, and the deployment of the drogue parachute is necessary for the deployment of the main parachute.
2. Mission-critical recovery with alternative options: In this case, successful parachute recovery is still mission-critical, but there is a chance that the main parachute can survive without the deployment of the drogue parachute or with a sub-optimal inflation due to mortar underperformance.
3. Recovery for additional data and subsystems: In scenarios where parachute recovery is not mission-critical, it is still desired for the retrieval of additional experiment data and/or sounding rocket subsystems. The recovery contributes to gathering valuable information and enhancing the overall mission outcome.
4. Non-critical recovery: Some missions do not require successful parachute recovery as it is not essential to the mission objectives. These missions typically exclude a recovery system to avoid adding unnecessary mass and complexity, which is undesirable in such cases.

The potential impact of a failed parachute mortar during flight on stakeholders is described below:

- **DARE member (operator)**: If an assembly mistake is identified as the cause of the failure, the vehicle operator, who assembled the system, may face judgement or blame from colleagues.

They may also experience self-blame or guilt. Frequent failures due to assembly mistakes could potentially affect the vehicle operator's position within the organisation. However, in the case of DARE, where the objective is student education, negative reactions are kept minimal as failure is considered an inherent part of the learning process.

- **DARE team (Launch provider)**: the student organisation of DARE, specifically the team launching the sounding rocket, will be disappointed in the failure. They had invested time and effort into the mission and were anticipating a successful outcome.
- **Launch site operator**: A failure of the recovery system is generally not a significant issue for a launch site, as a ballistic descent would typically impact well within the safety zone. Launch sites that enable students to launch often do so for educational and public relations purposes, so they also feel disappointed when a student mission fails. Generally the reactions from different launch sites to DARE when a launch fails are very supportive.
- **People in the landing area**: For launch sites like ASK 't Harde, seeing a high number of ballistic trajectories is undesirable. Successful parachute deployment is desired to ensure safety and minimise the impact area. However, the assessment of successful deployment is not based on individual launches or recovery systems but on the overall recovery rate of rockets launched by DARE on a given launch day.
- **Sponsors and Delft University of Technology**: Sponsors providing financial support to student teams, as well as the university (TU Delft), understand the experimental and high-risk nature of student rocketry. In the case of a failed launch, they often continue their support to DARE, recognising the valuable learning experience and the educational benefit for the students.
- **Society**: The main societal benefit of launches by DARE is the educational value they offer. While an unsuccessful launch is disappointing, it can provide significant educational benefits through the lessons learned. However, the extent of these benefits relies on the team's ability to gather sufficient data for analysis, such as in-flight measurements or recovery of the rocket debris. In some cases, DARE rockets carry scientific experiments, and the loss of the recovery system could mean the scientific value for society is compromised unless alternative data retrieval methods are available.

5.4.6. Reflection on risk assessment methods

The implementation of various risk assessment methods, including FMEA, risk matrices, and HACCP, relies on the objectivity of rating scales and their interpretation. FMEA and risk matrices share many similarities, but FMEA introduces the detection rate as an intriguing aspect that shifts focus to less visible or apparent risks. It is essential to acknowledge that the detection rating is heavily influenced by the preventive and detection controls in place, necessitating regular monitoring and updates to ensure the accuracy of the assessment over time. Although the detection rating is deemed valuable in assessing performance risks, it was less straightforward for safety risks. One of the key advantages experienced in the FMEA was the increased nuance possible with the larger rating scale (1-10), whilst the risk matrices provided better visual presentation of the risk assessment, giving a direct first overview of the status quo. Overall risk matrices and FMEA are two similar methods, both deemed viable to implement on the mortar system, and which generated a nearly identical set of critical risks throughout the case study. On the other hand, while HACCP provided valuable insights during the identification phase, its assessment felt somewhat limited due to the narrow rating criteria. The original HACCP method primarily emphasises biological hazards, and the evaluation of control measures (as described in subsection 5.5.2) is primarily presented in table format. It may be worth considering a reevaluation of the bow-tie method to more effectively depict the implemented controls. Additionally, the probability of a safety risk is weighed equally with its severity, whilst subjective evaluation addresses safety risks based on order of severity. Results from the HACCP analysis evaluate the pyrotechnic substances as non-significant hazards, whilst within DARE they are deemed important to monitor and contain. Human Reliability Analysis is implemented to assess the influence of various aspects of the DARE organisational and safety culture and practices on the mortar system. Although this provides useful context, it is difficult to implement this information in the continued risk assessment or evaluation. The evaluation of Performance Shaping Factors (PSFs) provides more concrete steps to undertake to improve the operator's performance. The SoTeRiA framework determined which items were reviewed, but without quantification, does not lead to further conclusions on or next steps of implementing these findings.

5.5. Risk Evaluation

The process of risk evaluation poses challenges, as existing risk management methods do not provide an objective approach to establishing risk acceptance criteria. In industry, acceptance criteria are typically determined qualitatively through engineering judgement. Consequently, defining risk acceptance criteria in an objective manner becomes difficult within the scope of this research, as no examples or guidelines are available. This represents one of the major challenges faced in this thesis, which cannot be fully addressed in the current study. Further research is necessary to develop a method that objectively determines risk acceptance criteria. This chapter will address the factors which influence risk acceptance criteria, the establishment of risk acceptance criteria utilised in this research according to the ALARP (As Low As Reasonably Practicable) principle, an overview of the intolerable risks identified in this case study, and applying MCA (Multi-Criteria Analysis) to the tolerable risks for system optimisation.

5.5.1. As Low As Reasonably Practicable (ALARP)

Risk evaluation according to the ALARP principle (As Low As Reasonably Practicable) involves categorising risks into three distinct categories: acceptable risk, tolerable risk, and intolerable risk. These categories serve as indicators for the ALARP region, as depicted in Figure 5.17. They help differentiate between risks that require mitigation, risks that can be optimised through mitigation efforts, and risks that should not be mitigated. Hereby ALARP aims to create a balance between risk reduction and resource allocation, including time, effort and cost [31].

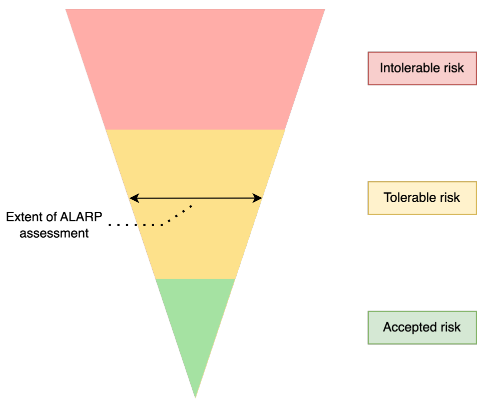

Figure 5.17: ALARP regions [31]

Establishing criteria for acceptable and tolerable risk

This thesis research examines two distinct types of risks: safety risks and functional performance risks, each requiring a unique approach to risk evaluation and risk acceptance criteria. This subsection will first address the evaluation of safety risks and subsequently focus on the functional performance risks.

The acceptance criteria for safety risks do not vary between different projects or teams within DARE, as all members must adhere to the same safety standard. A number of safety risks were identified in the FMEA. Criteria to evaluate these risks are established and described below:

- Any risk with severity = no harm (1) or probability $\leq$ 1 in 2000 (not occurred at university or other teams) is accepted.
- For risks with a severity of minimal harm (S=5), the risk is accepted with a maximum probability of 4 (O=4) and a maximum detection rating of 5 (D=5). This results in a maximum RPN value of $S \cdot O \cdot D = 5 \cdot 4 \cdot 5 = 100$.
- For risks with a severity of minimal harm (S=5), the risk is tolerated with a maximum probability of 10 (O=10) and a maximum detection rating of 10 (D=10). This results in a maximum RPN value of $S \cdot O \cdot D = 5 \cdot 10 \cdot 10 = 500$.
- For risks with a severity of medium harm (S=8), the risk is accepted with a maximum probability of 2 (O=2) and a maximum detection rating of 2 (D=2). This results in a maximum RPN value of $S \cdot O \cdot D = 8 \cdot 2 \cdot 2 = 32$.

- For risks with a severity of medium harm (S=8), the risk is tolerated with a maximum probability of 5 (O=5) and a maximum detection rating of 6 (D=6). This results in a maximum RPN value of $S \cdot O \cdot D = 8 \cdot 5 \cdot 6 = 240$.
- Any risk with severity = significant harm/damage (10) is not accepted.
- For risks with a severity of significant harm/damage (S=10), the risk is tolerated with a maximum probability of 3 (O=3) and a maximum detection rating of 6 (D=6). This results in a maximum RPN value of $S \cdot O \cdot D = 10 \cdot 3 \cdot 6 = 180$.

This leads to the categorisation of all identified safety risks in the tolerable region. It is important to note that, although all safety risks fall in the tolerable region of the categorisation, this is primarily because sufficiently strong controls are in place, influencing the occurrence and detection ratings. These controls are further evaluated in subsection 5.5.2 and must be monitored in the future. The safety risks and hazards identified in the HACCP analysis will be evaluated in subsection 5.5.2.

Subsequently, we can proceed with the evaluation of functional performance risks. Several factors influence the acceptance criteria for performance risk, determining the thresholds and conditions under which risks are deemed acceptable. These factors include:

- Type of launch and mission objectives: Different types of launches, such as crewed missions or scientific experiments, may have varying levels of criticality and require different risk acceptance criteria.
- Monetary effort: The amount of financial investment in the mission can impact the level of acceptable risk. Higher investment may necessitate stricter criteria to mitigate potential losses.
- Altitude: High altitudes introduce risks associated with lower pressure in the plenum volume, which may affect the performance and reliability of the system.
- Deployment conditions: The conditions in which the parachute is deployed, including the velocity of the vehicle (supersonic or subsonic), determine whether a lower parachute deployment velocity is acceptable.
- Dependencies within the recovery system: The recovery system may have dependencies, such as the ability of the main parachute to deploy even if the drogue parachute fails. These dependencies influence the risk acceptance criteria.
- Experiment data collection: If the primary purpose of the recovery system is to collect specific experiment data, the criteria for acceptance may be tailored to ensure successful retrieval of the hardware. The presence and reliability of telemetry also play a role in determining the level of acceptable risk.

These factors, among others, inform the establishment of performance acceptance criteria, as they consider the specific objectives, constraints, and risks associated with each mission. Within DARE, two example launches will be used for which the risk evaluation can be applied. Firstly, a low-altitude rocket launched from ASK 't Harde with an apogee between 1-3 km. The monetary value of the rocket is below €1000,- and the time put in the production of the rocket is lower than 400 man-hours. The recovery system is the primary method of data collection and the parachute mortar is critical in its success, however, recovery of the vehicle is not mission critical. For this launch, under- or overperformance of the system is acceptable (S=1-7), as well as risks regarding parachute inflation failure that have a low-medium probability (O=1-6), and any detection that is feasible through detection activities (D=1-8). This leads to an RPN value of 336 as barrier between acceptable and tolerable risk. No performance risks are intolerable, unless the project has specific mission objectives related to the recovery subsystem.
The second launch is of a high-altitude rocket launched from INTA, Spain, with an apogee between 50-120 km. The monetary value of the rocket, including in-kind sponsored equipment, lies between €200.000 and €500.000. The total amount of time spent on the design, development and production of the rocket exceeds 30.000 hours ($10 \cdot 1$ FTE and $40 \cdot 0.2$ FTE). The recovery system is the primary method of data collection, but a telemetry link is present to stream the most critical flight data. For this launch, slight underperformance is acceptable (S=1-6) in combination with non-frequent occurrence throughout system tests (O=1-7) and detection by experienced operators is possible (D=1-6). Therefore, risks with an RPN below 252 are accepted. Risks regarding underperformance or parachute

inflation (S=7) are tolerable when the risks do not occur during system tests (O=1-7), and with detection methods that require additional testing (D=1-7). Therefore, risks with an RPN between 252 and 343 are tolerable. Risks on underperformance or parachute inflation (S=7) with a combined higher probability and detection rating are intolerable, as well as any risks on no ejection or structural failure (S=9-10) which occurred in DARE (O $\geq$ 6) and have a very low chance of detection (D $\geq$ 7). An overview of the performance risk acceptance criteria can be seen in Table 5.14.

Risk evaluation region	RPN (Low-altitude launch)	RPN (High altitude launch)
Acceptable risk	0 - 366	0 - 252
Tolerable risk	$\geq$ 367	253 - 343
Intolerable risk	N.A.	$\geq$ 344

Table 5.14: Evaluation criteria for performance risks based on RPN

A few combinations of severity, occurrence and detection are now used to establish regions of RPN values that result in acceptable, tolerable, or intolerable risks. However, there are of course still combinations possible where a risk with a high severity (S=7-10) has such low occurrence and/or detection ratings that its RPN falls within the acceptable range. This method of establishing RPN ranges based on example scenarios is not foolproof, but should rather shape a guideline by which the RPN range can be established. It should be checked whether no risks that are deemed intolerable fall in the tolerable region, and vice versa.

Based on the criteria for intolerable risks ($RPN > 343$), the functional risks that are intolerable are listed as ”most critical risks resulting from FMEA assessment” in Table 5.10. In the risk evaluation process, multiple methods were employed, including risk matrix, FMEA, HACCP, and HRA. These methods provide valuable input for the assessment, although they may yield slightly different results. Given the comprehensive nature of FMEA, which considers detection as well, it has served as the primary basis for the risk evaluation. Any disparities with the likelihood matrix are carefully examined (see subsection 5.4.2), and adjustments are made based on individual judgement. In this particular case, OPS-05 and INT-04 were included in the critical region of the risk matrix ($L \cdot S \geq 15$) but not in the FMEA ($RPN > 343$). For OPS-05 this is due to a low detection rating, meaning the assembly mistake will likely be identified and corrected. Therefore this risk is not included in the critical risks. INT-04 does have a relatively high RPN (343) and is just on the border of the intolerable risk region, and will therefore still be included. The establishment of risk acceptance criteria relies on engineering judgement, introducing subjectivity into the decision-making process. As a result, the risk evaluation phase in this research is not reproducible, as the criteria are influenced by individual interpretation and subjective assessments.

Multi-criteria analysis

In the risk management process, it is essential to determine which risks should be mitigated and the means by which they can be addressed, taking into consideration the ALARP (As Low As Reasonably Practicable) principle. The ALARP level is considered to be reached when the additional risk reduction obtained from further reduction measures becomes unreasonably disproportionate to the associated time, effort, and cost. To assist in decision-making regarding risk mitigation, a Multi Criteria Analysis (MCA) approach can be employed. MCA allows for the ranking of risk reduction measures based on factors such as cost (both in terms of time and money). However, it is important to note that MCA alone cannot establish the precise ”ALARP level”, which is difficult to establish without detailed knowledge on the regulations and laws governing risk in the context of the parachute mortar system.

In the evaluation process, MCA will be applied to the range of tolerable risks as presented in Table 5.14 for a high-altitude launch. Tolerable risks that will be automatically mitigated through risk mitigation activities focused on addressing the intolerable risks will be excluded from further consideration. The full Multi Criteria Analysis can be found in Appendix A.

The MCA approach utilises the evaluation of risk reduction measures, associated costs in terms of time (man-hours) and monetary expenses (euros). For each tolerable risk identified, a risk treatment strategy is designed, and the costs of implementation are evaluated, along with the resulting updated (lowered) Risk Priority Number (RPN). The MCA rating incorporates the assessment of risk reduction

over cost, calculated using the formula:
$MCA_{rating} = RPN_{reduction} \cdot RPN_{multiplier} + \frac{Time_{multiplier}}{Cost_{time}} + \frac{Cost_{€multiplier}}{Cost_{€}}$.
The multipliers are used to scale the ratings to the average, meaning the following weights are used:
$RPN_{multiplier} = \frac{1}{RPN_{Average}}, Time_{multiplier} = Time_{Average}, Cost_{multiplier} = Cost_{Average}$.

The results of the analysis can be broadly categorised into three groups:

- Editing procedures rank at the top in terms of prioritisation, as they require minimal effort to implement.
- Quality control measures for parts fall in the middle range, indicating a moderate investment level.
- Tests to be conducted are positioned at the bottom of the ranking due to their higher associated costs and resource requirements.

By employing the MCA approach, informed decisions can be made regarding the allocation of resources and the selection of risk treatment strategies, taking into account the trade-offs between risk reduction, time, and financial considerations. This approach also immediately devises a preliminary risk treatment strategy for all tolerable risks of the system.
The RPN of multiple accepted risks can also be reduced further by simple edits in the procedures. Even though these risks are accepted, it is still worthwhile to review the procedures fully and ensure they are correct and complete, promoting a low Multiplier for the Performance Shaping Factor of ”Procedures”.

5.5.2. Evaluation of implemented controls on safety risks

Through a comprehensive approach involving expert interviews, incident reviews, FMEA, and HACCP analysis, a range of safety risks and hazards were identified. While the HACCP method typically utilises a ”HACCP control chart” (HACCP guideline [53]) in table format to review hazards and controls, it may not fully meet the needs of this particular case study. The critical limits in this study do not follow the typical select value or range approach but rather involve ”yes/no” judgements on adhering to specific safety precautions. In order to visualise and analyse the current implemented controls, the bow-tie method is considered more suitable, and it will be employed to depict the existing events, threats and barriers (controls) [14].
Additionally, the controls for working with pyrotechnic materials are being reviewed, despite not being initially considered a significant hazard in the HACCP assessment. The controls needed to mitigate hazards during the production process of the CFRP canister, which was the most hazardous as demonstrated by the HACCP assessment (see subsection 5.4.3), are not discussed as the redesign presented in subsection 5.6.2 includes a design change to an aluminium canister. When evaluating the new hazards of this system, one has been identified: an 80mm diameter snap ring, which contains a high amount of elastic potential energy when compressed. If the snap ring becomes dislodged, it can release this stored energy resulting in its sudden projection. According to the HACCP rating criteria as described in Table 5.11, the likelihood of the snap ring flying away and hitting someone is Medium, and the severity of the failure is also Medium, resulting in the status of a non-significant hazard.
This leads to the controls being evaluated for the following hazards or events:

- Lab accident (workshop incident)
- Undesired ignition of pyrotechnics (ignitors, gas generator)
- Person gets hit by projectile during test or unintended firing of parachute mortar
- Person gets hit by snap ring

The inclusion of ”Lab accident” and ”Person gets hit by snap ring” as undesired events ties directly into the evaluation of the safety culture in DARE, as described in Figure 5.2.2. Safety Officers repeatedly make remarks in the Safety Board Annual Report on how the predominant source of incidents in DARE lies not in complex safety critical operations, but the day-to-day activities in the workshops.
Figure 5.18 illustrates bow-tie analyses for the controls that are currently implemented in DARE to mitigate these hazards or events.

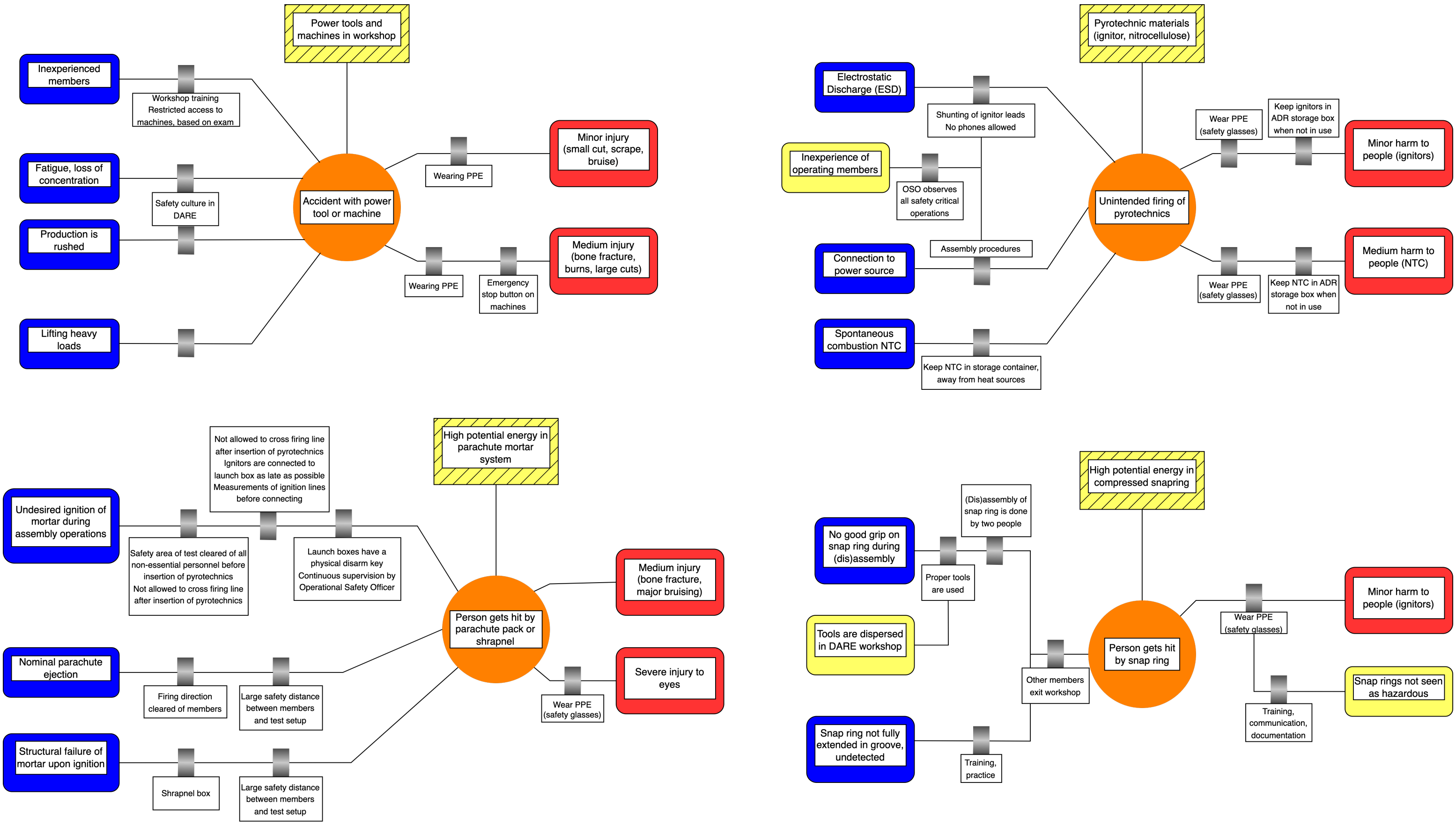

Figure 5.18: Bow-tie analysis of hazard controls in DARE

The current controls that are implemented can be reviewed on their appropriateness and effectiveness. First, a comparison can be made to controls used in industry. The main mitigating activities or controls mentioned by experts in interviews are as follows (see Appendix B):

- Safe distance from mortar tests
- Wearing Personal protective equipment (PPE)
- Grounding of equipment and personnel
- Anti-static garments and wristbands
- Zero voltage check on firing lines
- Lockout procedure on firing lines
- Weather checks (lightning)
- No cellphones

The controls implemented in the DARE case study and the controls implemented in industry are nearly identical. This provides great confidence in the appropriateness of the implemented controls. However, besides this, the effectiveness of the controls in DARE should also be evaluated. No accidents or incidents have occurred during mortar preparation or tests. All past accidents and incidents in DARE can be evaluated to observe how, why or when the implemented controls failed. When evaluating past incidents in DARE (see subsection 5.2.2), the two controls which predominantly failed, causing these incidents were:

- Not wearing the correct PPE, leading to burns. Accident 1 (2010): burn from hot water on feet whilst wearing open sandals. Accident 2 (2018): burn from hot propellant during casting on hand due to not wearing gloves.
- There is no clear task division, including that no safety officer has the sole responsibility of supervising the safety of the test. Safety officers are still present, but also performing operations during

the test. This leads to general fails in checking the safety of the setup and contributed to the TRP accident (2023) where debris from a non-nominal engine test violated the safety area allocated to test. Fatigue and sickness, important performance shaping factors (PSFs), also contributed to the accident.

The absence of these controls lead to other consequences than would be the case for the mortar system, but in principle the core of the control is the same. Therefore, in the future, DARE members must be aware to strictly adhere to recommended PPE usage and ensure the Operational Safety Officer only supervises the test and is not involved in any other test aspects or activities.

5.5.3. Reflection on risk evaluation methods

When conducting risk evaluation, the categorization of risks into intolerable, tolerable, and acceptable levels, as prescribed by the ALARP (As Low As Reasonably Practicable) principle, is a common approach. However, it is noteworthy that most existing risk evaluation methods predominantly focus on the prioritisation of tolerable risks. Concrete and objective guidelines for establishing the boundaries between intolerable, tolerable, and acceptable risks are generally lacking. The Pareto principle, which suggests that addressing the top 20% of assessed risks mitigates 80% of the total risk, is mentioned but cannot be considered entirely reliable since it is strongly influenced by the total number of risks identified and assessed.
As indicated by experts, establishing acceptable risk levels is primarily subjective and relies heavily on expert judgement. Furthermore, the evaluation of performance risks is strongly influenced by mission objectives and available resources, making it subject to variation for each launch scenario. This necessitates the ongoing re-evaluation of risk levels in different contexts. While this research adheres to these standards, it strives to provide explanations for the chosen risk levels, even though they may lack substantiation.

In the evaluation of tolerable risks, the ALARP principle and Multi Criteria Analysis (MCA) are available methodologies. Both approaches assess the trade-off between resources required and achievable risk reduction. The ALARP principle establishes a minimum threshold based on legal regulations and health and safety guidelines, while MCA serves as a ranking method that optimises risk reduction over cost. However, it should be noted that the ALARP evaluation is primarily rooted in a legal framework and necessitates a significant amount of input data and expertise, as indicated by ISO31010. In retrospect, it may not be the most suitable method for risk evaluation.

Furthermore, the evaluation of controls implemented to address safety hazards is typically better visualised through a bow-tie analysis rather than the Hazard Analysis and Critical Control Points (HACCP) method. However, there is currently no standardised method for evaluating controls, including their correct implementation, consistency, and effectiveness. In this research, comparison with industry practices and the examination of past accidents and incidents are employed to assess the efficacy of controls.

To ensure a more objective evaluation of risks, future research needs to focus on developing methods that provide a reliable and standardised approach. This entails addressing the limitations of current methods and exploring avenues for improved risk evaluation methodologies. By striving for more objective risk evaluation, the overall effectiveness and reliability of risk management practices can be significantly enhanced.

5.6. Risk Treatment

5.6.1. Design of a risk treatment strategy

This subsection describes the risk treatment strategy that will be applied to the identified risks, sorted by acceptable, tolerable, and intolerable risks resulting from the analysis in subsection 5.5.1.

Acceptable risks

Even though nearly all risks in this category will be accepted as risk treatment, some may benefit from minor mitigation activities. As described in Table 5.5.1, adjustments in the assembly procedures require minimal effort and can significantly reduce the RPN. The selection of acceptable risks shall also be reviewed to identify these opportunities. Remaining acceptable risks are accepted.

Tolerable risks

Within the selection of tolerable risks, nine out of twenty-one risks will be automatically treated through risk mitigation activities focused on the intolerable, critical risks. For the remaining risks, a risk treatment strategy is devised, which can be seen in Appendix A, and consists of the following key elements:

- Improving the procedures to lower detection rates.
- Implementing quality control on parts as well as dress rehearsals before launches.
- Performing (integrated) ejection testing.

These activities may be performed depending on available resources. If they are not performed, the risks must be monitored over time. Additionally, changes in the safety and organisational culture and practices as well as Performance Shaping Factors should be monitored over time subsection 5.4.4. Besides this, the implemented controls must be monitored and re-evaluated frequently as well subsection 5.5.2. It is recommended to re-evaluate the risks at least yearly within DARE, or when the system undergoes a change in the design or implementation.

Intolerable risks

The proposed mitigation strategies for each critical risk are displayed in Table 5.15. Below the table, further elaboration is given on the selection of the mitigation strategy when multiple options are possible. The research aims to execute the majority of these risk mitigation methods, to reduce the intolerable functional performance risks that are currently present.

Risk ID	Risk description	Mitigation strategy
PPP-07	Casing has production errors.	Redesign of casing Source casing commercially
SAI-15	Increased/decreased compressibility when a different parachute is used than during (qualification) tests.	Redesign: parachute container, ~~Additional ejection tests~~
CS-02	Structural failure (radial burst) of canister because the true burst pressure is lower than the designed pressure.	Redesign of casing, ~~Destructive hydrostatic testing~~
CS-03	Structural failure (radial burst) of canister due to cyclic loading.	Redesign of casing, ~~Nondestructive hydrostatic testing to nominal operating pressure~~
CS-04	Failure of glue joint between CFRP canister and attachment ring.	Redesign of casing
GG-02	Charge does not (fully) ignite or underperforms due to leaks in plenum volume during ascent.	Vibration and leak testing
IG-01	Ignition signal is not received from electronics subsystem.	N.A. in case study
SB-05	Sabot collides with parachute (pack) after deployment.	Design of sabot capture net (preliminary)
LD-02	Lid has insufficient momentum to pull the parachute from its bag (extraction).	Flight testing, development of low-cost low-altitude demonstrator vehicle
INT-05	No ignition signal is given from the electronics subsystem.	N.A. in case study
INT-07	Parachute entanglement during ejection.	Flight testing

Table 5.15: Mitigation strategies for intolerable risks

The CFRP canister is a part with many critical functional performance risks and safety hazards associated to it. Specifically, the unknown burst pressure of the in-house student built product brings about a great concern on structural failure. The current design can be kept, but this would require hydrostatic tests to confirm the performance of the casing. Alternatively, the part can be redesigned, aiming to resolve the majority of these risks. The latter is selected, as hydrostatically testing each canister would require enormous resources in terms of manpower. This redesign can also directly address the weakness in the attachment point of the canister.
The variability in parachute pack compression can be tackled through redesign of the configuration or additional ejection testing per parachute assembly. To promote easy and quick adoption of the mortar system throughout various missions in DARE, redesign is selected, to prevent the necessity of additional ejection tests for each parachute configuration.
The risk of not receiving an ignition signal from the electronics subsystem is not tackled in this case study because it covers the risk management of the mortar system for usage in various missions in DARE. No specific electronics system is selected in the case study. This risk must be mitigated through design and testing when a mission decides to implement the mortar system, or any recovery system using pyrotechnic actuation for that matter.
The risk of leakage in the plenum volume must be assessed through testing of the volume under overpressure and vibration loading. The risk of sabot collision with the parachute pack warrants the inclusion of a sabot capture net, which needs to be designed.
The risks on parachute bag extraction based on mortar lid momentum and the in-flight interaction between aerodynamics and deployment motion can only be tested in-flight. The movement of the parachute pack and inflation behaviour are too random to simulate, and the parachute mortar cannot be fired into an open wind tunnel due to safety constraints. As this is a risk that may vary depending on the final mortar design and configuration (primarily rigging of the parachute), it is of interest to develop a reusable, low-cost low-altitude sounding rocket to allow for repeated flight testing of mortar systems to assess these risks.
The quality of assembly and operational procedures must be assessed on its clarity and completeness, and improved where possible, to increase the operator reliability as much as possible as described in subsection 5.4.4.

5.6.2. Execution of risk mitigation: redesign

The redesign of three subsystems is desired based on Table 5.15, to achieve the following goals:

- Redesign of the (CFRP) mortar casing. Main goal: to achieve reliable structural integrity under loading.
- Redesign of parachute assembly. Main goal: to increase consistency in the compressibility of the parachute pack inside the mortar, even between different parachutes.
- Design of sabot capture net. Main goal: design of a part which constrains the sabot inside or close to the canister upon ejection.

For all designs, it is desired to achieve the new design with limited resources (financial, manpower). Albeit with a lower priority, mass and volume are also relevant design criteria to take into account. This study focused on the first two redesigns, for which Design Option Trees (DOTs) are presented in Figure 5.19 and Figure 5.20. The design and development of a sabot capture net is strongly recommended as a subsequent step following this research.

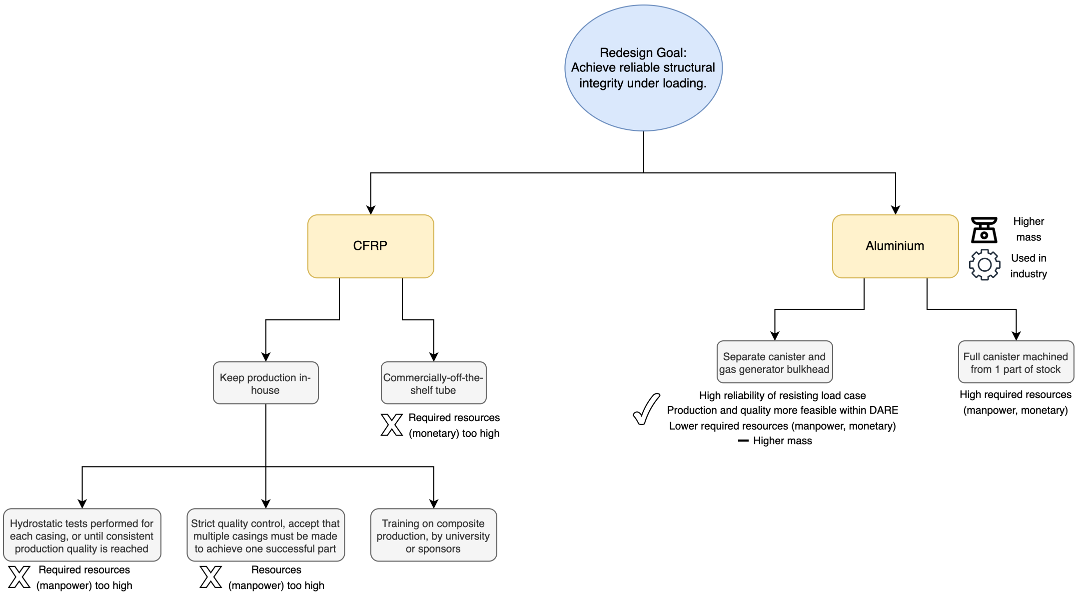

Figure 5.19: Design Option Tree for redesign of CFRP canister

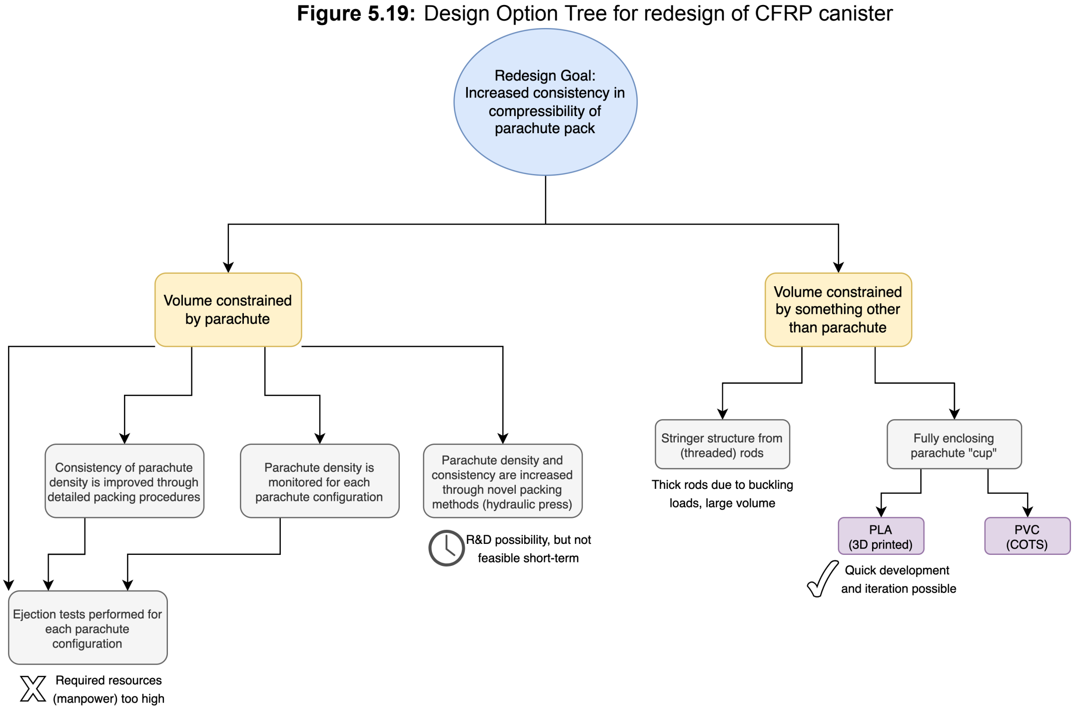

Figure 5.20: Design Option Tree for redesign of parachute pack

From the design option tree of the mortar canister, an aluminium canister has been selected. The primary disadvantage of this design is a higher mass, but it provides a more reliable assessment of the load case when produced by students, and it is used for all parachute mortars in industry. The current model selected is the canister used for battleship ejection tests in SPEAR, with a thickness of 5mm. This thickness can still be reduced if mass optimisation is important to a team, and is constraint by limitations in the production process rather than the experienced burst pressure.
To ensure consistency in parachute pack compressibility, a 3D printed parachute cup from PLA is developed. The parachute assembly is placed inside the cup, which in turn is placed inside the mortar canister. The cup consists of three parts such that they easily fall away during the ejection, enabling parachute extraction and inflation.
In addition to these design changes, a new design for the parachute lid is suggested to decrease required resources in terms of manpower. Manufacturing the metal lid takes up 1-1,5 day of turning

and milling, whilst it is a single use part on most rocket launches. An alternative design consisting of a 3D printed lid with heat set inserts for the shear bolts is proposed. The new parts can be seen in Figure 5.21. The redesign was tested through two ejection tests to demonstrate functionality of the new system, as described in subsection 5.6.3.

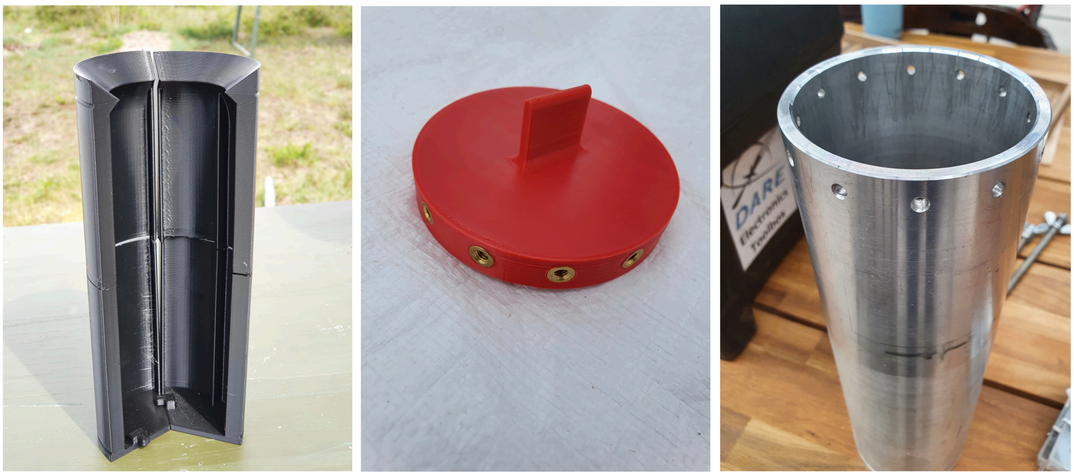

Figure 5.21: Redesigned parts: 2/3 of parachute cup (left), PLA lid (middle), aluminium canister (right)

5.6.3. Execution of risk mitigation: testing

Ejection tests

To confirm functionality of the redesign, two ejection tests were performed. The test goals are displayed in Table 5.16. All test goals were met. Due to safety considerations the set setup aims at an earth wall, and during the first test the parachute assembly impacted the wall before cup removal. During the second test, the setup was angled slightly higher to increase the flight path, and the parachute cup opened nominally (see Figure 5.23). The cameras currently used for data acquisition recorded video at a rate of 120 frames per second (fps). It can be seen that the parachute pack travels ~0.9 meters in the first test and $\geq$ 1 meters in the second test within 4 frames, which would indicate an ejection velocity between 27-30 m/s. This test campaign aimed at validating the design, but in the future it is of interest to assess whether a (more) consistent ejection velocity can be reached when using the parachute cup. For these tests, camera equipment is needed with a higher fps. Additionally, there should be a correction applied to the angle of the camera, which was not done to the current data. It must also be noted, that in Figure 5.23 it is clearly visible that the sabot follows the parachute pack movement, strengthening the need for a sabot capture net in the future.

ID	Test objective	Met Y/N	Comments
01	Successful ejection of parachute sub-assembly	Y	
02	Demonstrate survivability of redesigned parts during ejection	Y	
03	Successful release of parachute cup from sub-assembly	Y	During second test
04	Collect video data on the ejection tests	Y	

Table 5.16: Test objectives and evaluation for ejection tests

The ejection test setup, and still shot of the ejection can be seen in Figure 5.22. Numerous stills of the ejection, displaying the parachute cup opening, can be seen in Figure 5.23.

Figure 5.22: Ejection test: test setup front (left), test setup back (middle), parachute ejection (right)

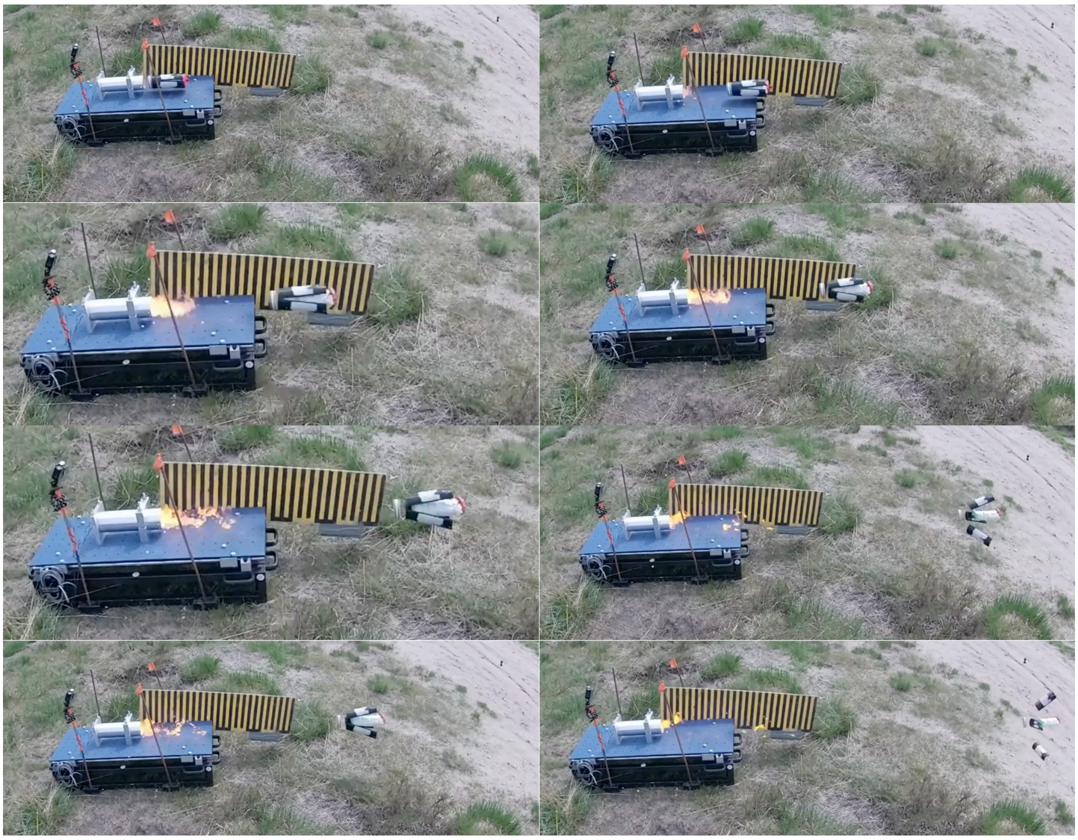

Figure 5.23: Ejection test: opening of the parachute cup

Evaluation and adjustment of launch procedures

During the launch of the PIP-III rocket on March 31st, 2023, the assembly and integration procedures of the parachute mortar were reviewed. The procedures used by the PIP team can be found in Appendix E. The assembly operations were performed by a member that had attended parachute mortar tests before, but never assembled the system himself. The following points of feedback on the assembly (procedures) were gathered:

1. Required preparation:
    - A dress rehearsal should be held before launchday/test day to collect and fit all parts and tools

   - A parts and tool list should be included at the start of the procedures
   - The first step should be parts preparation (cleaning, visual inspection, test-fitting), this was not performed.

2. Guideline on how to execute operations:
   - There should be one operator performing the assembly steps, and one product assurance (PA) engineer who reads the procedures and checks if all steps are performed correctly.
   - After the completion of each assembly step, the PA ticks off that step with a pen. Any comments on the system status or anomalies are also noted down.
   - Time is registered throughout the procedures to collect data on duration of the assembly. This was not noted down.
3. Unclarities in the procedures on ignitor bolt preparation:
   - Cap should be removed from squib
   - Orientation of how to lead squib through bolt
   - If there is a tight fit between the squib cable and bolt, check if the cable is not stripped
   - Push squib up and apply epoxy on the squib cable
   - Check with nut if ignitor bolt threads are free of epoxy
4. Unclarities in the procedures on gas generator preparation:
   - Mesh and retainer ring should be taken off GG before (NTC) filling
   - It helps to screw in bolt in mesh instead of pressing down
   - How to apply teflon tape

Additionally, it was not always clear which part is meant by which name, or what the required parts/tools look like. A visual parts and tools list should be added.
These changes were implemented in a new version of the procedures. This new version was tested during the launch of PyRocket, where a member fully inexperienced with the mortar system performed the assembly. This was successful, and the visual procedures were deemed helpful, albeit primarily for a first-time user of the system. These procedures can be found in Appendix E. Images of the parachute mortar assembly for PIP-III and PyRocket can be seen in Figure 5.24.

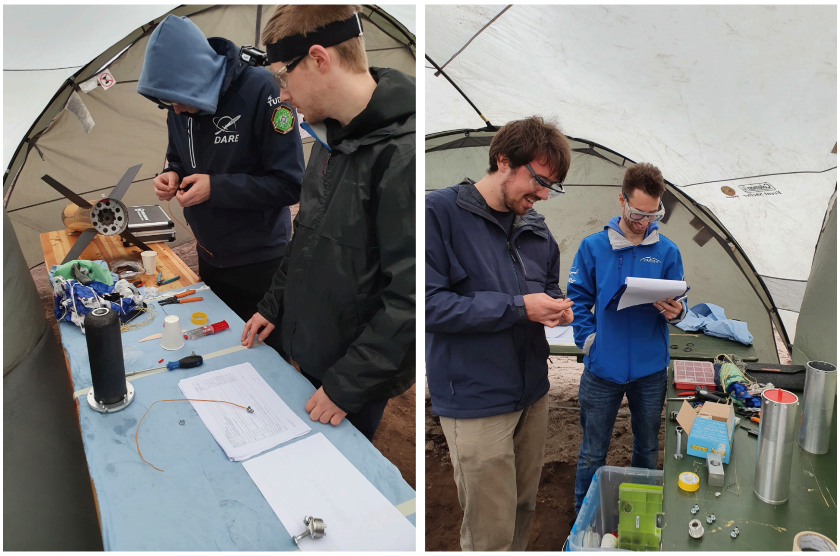

Figure 5.24: Images of the parachute mortar assembly for PIP-III (left) and PyRocket (right)

An important observation that was made during the PyRocket launch is that a lot of the procedures were dispersed. There was a different assembly procedure for the (pyrotechnic) reefing mechanism on the ringsail, one for the parachute mortar, and one for the full vehicle operations and arming. Ideally this should be combined into one set of procedures per sounding rocket, however, this will increase the likelihood of conflicting sets of procedures and the effort needed to make changes to the parachute mortar procedures as it has to cascade through all other sounding rocket procedures.

Flight testing and developing a low-cost low-altitude demonstrator

To enable flight testing of the mortar system at low required resources, a low-cost low-altitude sounding rocket has been developed called PyRocket. The design of the vehicle was aimed at simplicity, leading to the mortar casing forming part of the rocket structure and being equal to the outer rocket diameter (90mm). The rocket is approximately 0.9 meters long and utilises the Intermediate Rocket Motor (IRM) developed by the solid propulsion team in DARE. General characteristics of the rocket can be found in the Rocket Check Form (RCF) of PyRocket in Appendix E. Images of the rocket during assembly and launch can be seen in Figure 5.25. The rocket consists primarily of subsystems that are readily available in DARE, such as the IRM, the Kolibri electronics stack, RunCam 2 and parachute mortar hardware. The cost of the launch vehicle (excluding the aforementioned systems) was $\leq$ €40,- and was spent on aluminium sheetmetal, fasteners and PLA for 3D printing. The test goals are displayed in Table 5.17. In addition to these objectives, the PyRocket was used to test an experimental reefing system on a ringsail parachute for general parachute R&D within DARE.

Figure 5.25: PyRocket: vehicle and launch

ID	Test objective	Met Y/N	Comments
01	Successful ejection of parachute in-flight	Y	
02	Demonstrate survivability of aluminium canister during ejection in-flight	Y	
03	Demonstrate attachment point of aluminium canister in-flight	Y	
04	Collect video data on the in-flight ejection	-	Partial: riser blockage until ejection
05	Collect accelerometer data on the mortar ejection	Y	Data collected, still needs post-processing
06	Enable reuse of the rocket	Y	Minor damage to fins and engine section
07	Assessment of failed parachute extraction risk	Y	Extraction successful
07	Assessment of parachute entanglement risk	-	Partial: parachute entangled, uncertain if due to ejection or poor packing of ringsail

Table 5.17: Test objectives and evaluation for ejection tests

Figure 5.26 shows numerous stills from the camera onboard the PyRocket rocket during its launch. It clearly shows the riser blockage in the top middle image, however, it is resolved nearly immediately after actuation of the mortar. More test flights will be necessary to establish whether the entanglement of the parachute is induced by its deployment from the mortar, of if it is caused by the folding and packing method.

Figure 5.26: PyRocket: onboard camera footage

Vibration test campaign at the European Space Agency (ESA)

In order to evaluate and mitigate the risks of leakage of the plenum volume during a mid- to high-altitude rocket launch, a vibration test campaign of the mortar system was organised through the Test Opportunities Program (TOPs) at the European Space Agency (ESA). The test campaign included two Devices Under Test (DUTs), with the following test objectives:

1. **DUT1**: a setup using a small canister that mimics the plenum volume of the mortar system was used, intended to observe leakage in the plenum volume under vibration loading. The setup is made leak-tight through the same seals and interfaces used in the regular mortar system. A compressor is used to apply an overpressure of 1 bar inside the plenum volume, with respect to the external pressure, to simulate the maximum pressure difference throughout flight, where $p_{plenum} = 1bar$ and $p_{atmospheric} = 0bar$. A pressure sensor is connected to allow for measuring the pressure inside the volume before and after each vibration test run. Accelerometers are placed across the test set-up to regulate the vibration test (control sensors) and to observe the behaviour of the test set-up (measurement sensors). The test setup of DUT1 can be seen in Figure 5.27.
2. **DUT2**: the redesign of the parachute mortar, including an aluminium casing. The main objective of this additional test is to evaluate the survivability of the parachute mortar under vibration loading in all axes. The secondary objective is to evaluate one configuration with parachute cup and one without, to observe the influence of the parachute cup on the harmonic spectrum of the parachute mortar system. The test setup of DUT2 can be seen in Figure 5.28.

More detailed information on the test setup, vibration test spectrum and functional tests performed during the campaign can be found in the Test Specification and Test Procedures (TSTP) document in Appendix C. Additionally, minutes of two Test Readiness Reviews (TRRs) and one Post Test Review (PTR) are added here as well.

The key result of interest during the tests of DUT1 is the pressure before and after select tests. This data is presented in Table 5.18. Note; the overpressure indicates the pressure differential between the inside and outside of the canister. The total pressure inside the canister can be approximated through $p_{total} = p_{overpressure} + 1$ [bar].

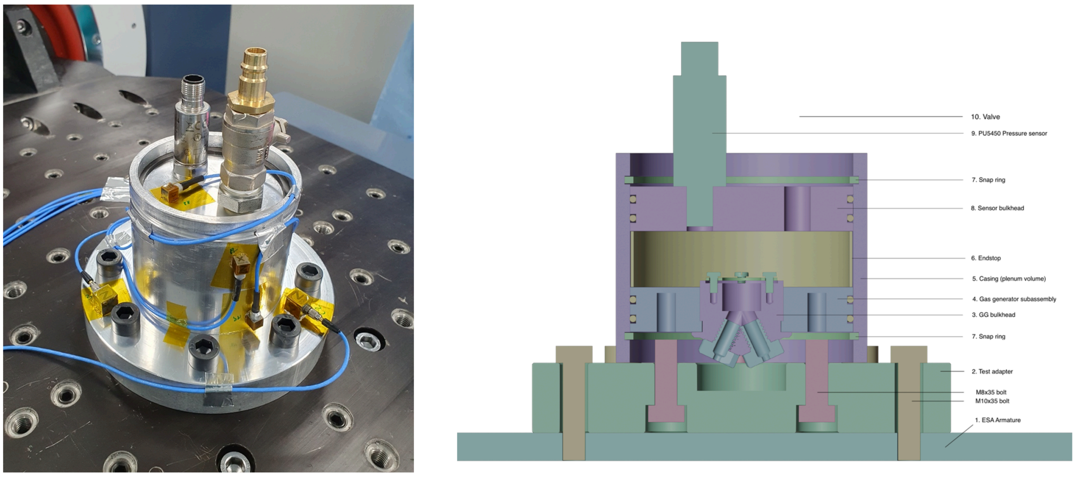

Figure 5.27: Test setup of DUT1

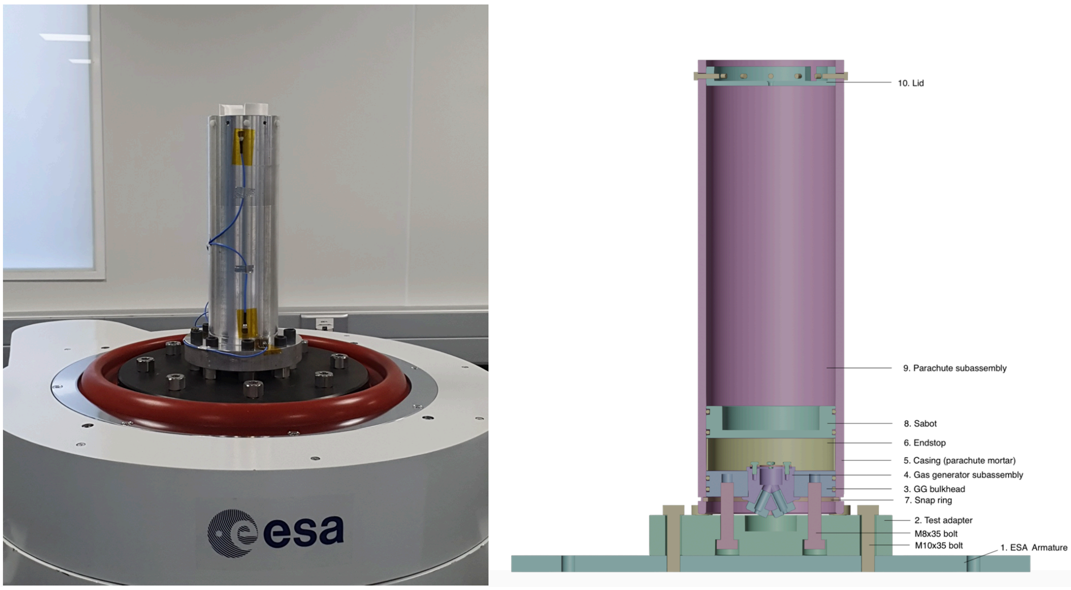

Figure 5.28: Test setup of DUT2

An intriguing observation in the data is that, contrary to expectations, the pressure increases during vibration testing instead of decreasing or remaining stable. This unexpected phenomenon led to the hypothesis that the temperature rise of the DUT1 setup, primarily due to conduction from the slip table through the adapter plate, plays a significant role in this behaviour. It was evident that the slip table, which is exclusively used for tests in the X and Y axes, experiences substantial heating during the tests. To investigate further, attempts were made to assess the temperature of various components using a laser thermometer. However, the obtained data proved to be highly inaccurate, with frequent jumps of several degrees and readings consistently exceeding 30 °C. Therefore, this data was deemed unreliable for presentation or discussion. Nevertheless, certain patterns emerge from the observations. The pressure increase appears to be less pronounced in the z-direction, aligning with the hypothesis. Additionally, there is evidence of a pressure drop following cool-down periods, further supporting the notion of temperature playing a role in the observed pressure behaviour.

These findings shed light on an intriguing aspect of the testing process, highlighting the complex interplay between temperature, vibration, and pressure dynamics. The observed increase in pressure during vibration testing rejects the risk of a significant pressure drop. However, in order to quantify the pressure increase and/or drop accurately, a more comprehensive understanding of the thermal effects on the system during testing is needed. For now it can be concluded that, by applying these methods of sealing, the probability of leaks in the plenum volume have significantly decreased.

ID	Time since pressurising	Overpressure [bar]	Notes
01	0 minutes	0.97-0.98	
02	5 minutes	0.96-0.97	
03	10 minutes	0.96-0.97	
04	55 minutes	0.956	Moved set-up to clean room
05	1hr 45 minutes	0.958	
06	3 hrs 25 minutes	0.952	
07	3 hrs 56 minutes	0.948	
08	4 hrs 17 minutes	0.954	
09	4 hrs 50 minutes	0.985-0.986	Post resonance search 1 (X-axis)
10	5 hrs 10 minutes	1.014	Post Random vibration test (X-axis)
11	5 hrs 14 minutes	1.015	
12	5 hrs 42 minutes	1.025	Post resonance search 2 (X-axis)
13	6 hrs 27 minutes	0.985	After cool-down break
14	6 hrs 50 minutes	1.005	Post resonance search 1 (Y-axis)
15	7 hrs 1 minute	1.019	Post random vibration test (Y-axis)
16	7 hrs 09 minutes	1.031	Post resonance search 2 (Y-axis)
17	22 hrs 54 minutes	0.944	After cool-down overnight
18	23 hrs 38 minutes	0.946	After rotating to Z-axis
19	23 hrs 53 minutes	0.950	Post resonance search 1 (Z-axis)
20	24 hrs 13 minutes	0.958	Post high level sine test (Z-axis)
21	24 hrs 21 minutes	0.962	Post resonance search 2 (Z-axis)
22	24 hrs 30 minutes	0.965	Post random vibration test (Z-axis)
23	24 hrs 37 minutes	0.965	Post resonance search 3 (Z-axis)
24	24 hrs 39 minutes	0.001	After releasing pressure

Table 5.18: Data of pressure measurements on DUT1

Additionally, tests on DUT2 confirmed the survivability of the parachute mortar design under vibration loading in all axes. The data analysis and comparison between DUT2 (with parachute cup) and DUT2+ (without parachute cup) is still ongoing. Figure 5.29 shows a fragment of the full data set, indicating a resonance frequency at ~650 Hz in DUT2 which is absent from DUT2+.

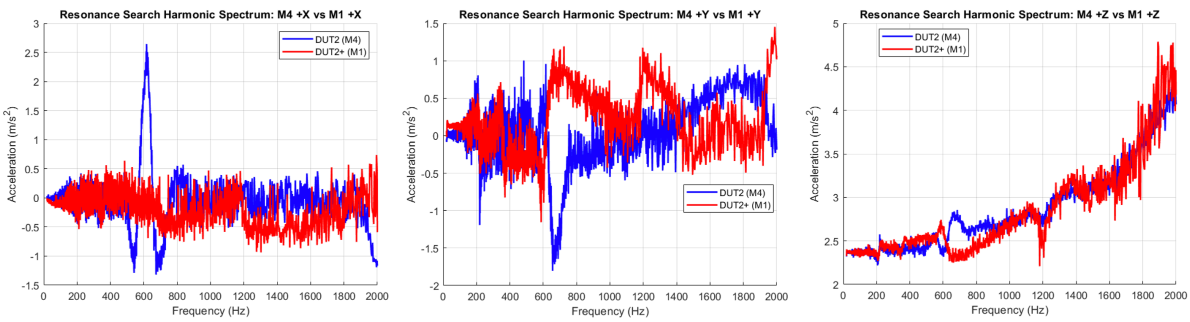

Figure 5.29: Harmonic spectrum of resonance search of DUT2 and DUT2+ (accelerometer at the top of the canister)

Through the redesign presented in subsection 5.6.2 and the tests described in subsection 5.6.3, six out of eleven intolerable risks have been mitigated. Two intolerable risks are dependent on the electronics system of the sounding rocket, which is currently excluded from the socio-technical system. Risks LD-02 regarding bag extraction through the mortar lid and INT-07 on parachute deployment and inflation can be continuously evaluated through more flights of the low-cost PyRocket demonstrator. Risk SB-05 of the sabot colliding with the parachute pack requires additional (re)design, which should shape the primary focus of risk reduction in the near future.

5.7. Risk Management Guideline

Following from the synthesised approach and lessons learnt during the implementation in the case study, the final risk management guideline can now be proposed, answering the main research question: ”*What are the design characteristics of a risk management guideline that enables the reduction of safety and performance risks of parachute mortar systems in sounding rockets?*”. The guideline is visually presented in Figure 5.30. Methods in italic font with dotted line arrows were not applied to the case study, and/or still require further selection of the risk management method.

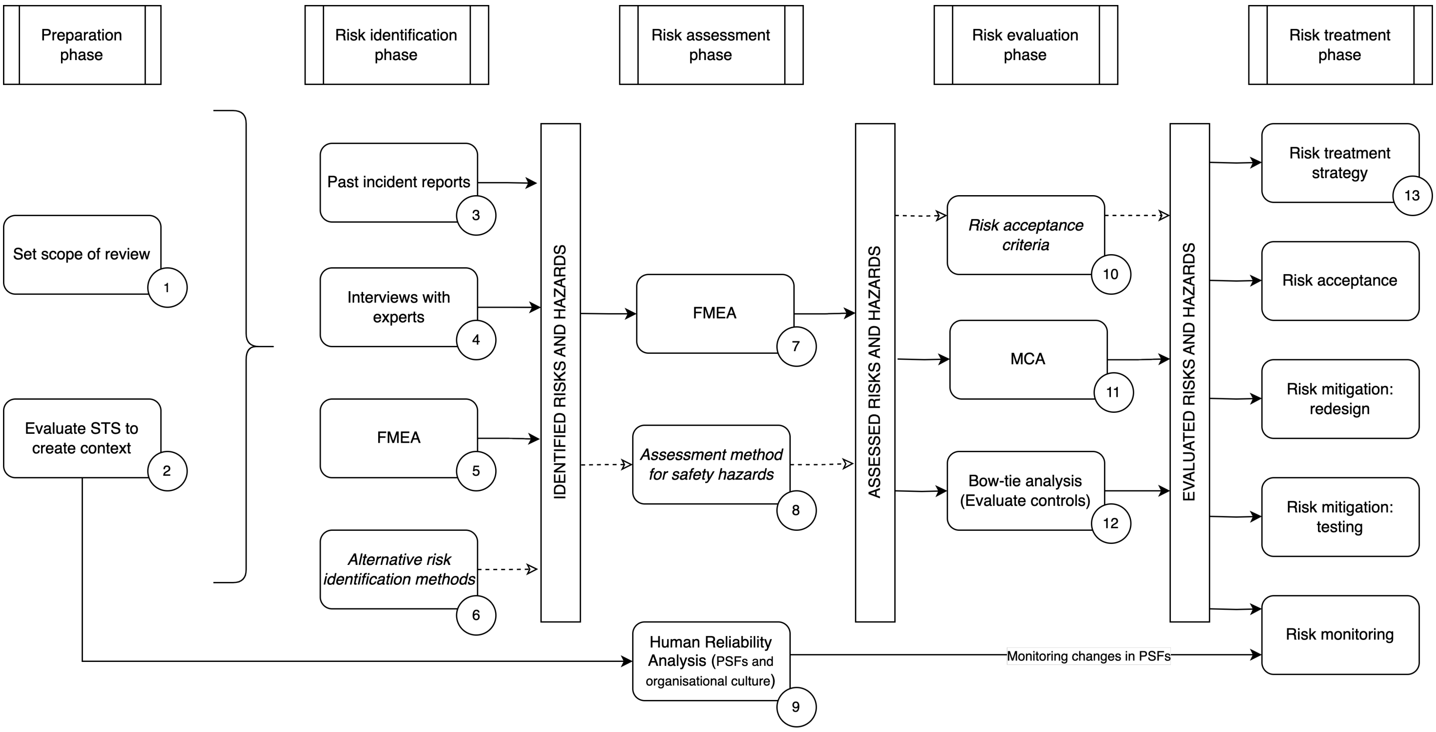

Figure 5.30: Risk Management Guideline

For each of the steps in the guideline, an explanation is given on the selection and/or practical recommendations on how to implement the method. These can be found below.

1. **Scope of review**: the type of risks analysed, a general description of the context and the case, and a selection of the evaluated hardware, processes and actors that are included in the analysis must be provided. Establishing a boundary of the socio-technical system can help with setting this scope, as well as a value chain analysis on which parts of the lifecycle are included/excluded.
2. **Analysis of socio-technical system**: the analyses performed provide the contextual input required in all phases of risk management. The mission objectives, restrictions in terms of project timeline and resources, and various important stakeholders and relationships shape the goals and content of the risk analysis. It is acceptable if there is some uncertainty or unclarity in the analyses that are performed, as it is deemed infeasible to present an objective and accurate overview of such complex concepts. The main objective should be to document the main relevant items in detail, including the thought processes leading to design choices or decisions in the analyses.
3. **Past incident report**: when the system under review or a similar design has been used beforehand, information on failure modes and non-conformance during production and testing provides incredibly valuable input for risk identification and assessment. All available sources should be used: communication channels, members or employees that worked on the system, existing procedures, used hardware, etc. Depending on documentation levels in the organisation, this may be a very time intensive phase of the risk management process.
4. **Interviews with experts**: similar to the past incident reports, information from experts on identical or similar systems is of immense value to the risk management process and can contribute significantly to the risk identification and assessment phases. Specifically with parachute mortar systems in

spaceflight, which is a niche area of research, this is one of the few methods to validate results from other risk identification methods. Based on the experience in this study, it is recommended to prepare semi-structured interview questions and run a practice interview on the researcher to assess researcher bias, clarity, and completeness of the interview. Additionally, it is suggested to share details on the parachute mortar design under review such that experts can provide more specific feedback. This could be done in advance as well by providing a very concise information package (1-2 pages) on the system design and development.

5. **FMEA** (risk identification): here, FMEA is used to structure brainstorming to identify risks. Before starting the identification using the FMEA, prepare according to the method [44], by defining the process steps or parts that are evaluated in detail. This method should be applied last, and the other sections of the FMEA worksheet (S/O/D) should not be reviewed or filled until the full identification method is completed. Risks identified through other identification methods must also be added to the FMEA worksheet. This sheet forms the core of documenting the risk process, and should ideally be accessible to all members working on the risk analysis.
6. **Alternative identification methods**: as described in subsection 4.2.2, there are numerous risk identification methods from the ISO31010 standard that are viable to apply to the parachute mortar system. The selection of risk identification method(s) will depend on the available input for a specific case or organisation, therefore it is acceptable to change the current proposed methods if needed.
7. **FMEA** (risk assessment): as discussed in subsection 5.4.6, the methods of risk matrices and FMEA to assess risk are quite similar. Both of these methods can be implemented, although a preference is given to FMEA as a higher nuance in ratings is available (1-10) and the detection rating provides an additional layer of differentiation between risks. An essential part of this assessment is to take time and draft clear objective grading scales for the S/O/D ratings. Secondly, the product and process FMEA identification and assessment will overlap, which is acceptable. Duplicate risks can be evaluated and removed after the assessment is complete.
8. **Alternative method for the assessment of safety hazards**: the HACCP method, applied to identify and evaluate hazards, was deemed insufficient. The assessment of the significance of hazards was based equally on severity and probability, whilst this results in undervaluing the hazard of pyrotechnic substances when compared to the general stance towards these materials within the DARE society. An increased focus on severity is desired. An alternative method should be selected to (identify and) assess safety hazards in the system.
9. **HRA**: evaluating the Performance Shaping Factors and (safety) culture within an organisation allows for the identification of short-term and long-term improvements that will enable increased operator performance and better processes in place to facilitate development of the system. As the integration of the HRA with the risk management process is complicated, additional attention should be paid that the results from the HRA are still incorporated in the final risk treatment strategy.
10. **Risk acceptance criteria**: although the ALARP principle describes three regions of intolerable, tolerable and acceptable risk, no objective method is provided to establish the boundaries of these regions. Further research is required to introduce objectivity in this process, which thus far is primarily based on expert judgement.
11. **MCA**: the region of tolerable risk is open to optimisation. A rudimentary MCA is applied to establish a ranking of risk reduction versus required resources, to enable efficient treatment of tolerable risks.
12. **Bow-tie analysis**: this method provides a great visualisation of the implemented controls, but supplementary methods are needed to evaluate whether the controls are adequate (appropriateness and effectiveness). In this case study it was feasible to compare the implemented controls with industry standards and evaluate past accidents and incidents, but if this information is not available, other methods have to be found.
13. **Risk treatment strategy**: this strategy will vary strongly between specific cases. An organisation may have a strong preference for risk acceptance, system redesign or testing. Establish all possible risk treatment options before making a selection. Monitor the PSFs, organisational (safety) culture and implemented controls to identify any changes that influence the risk level.

Additionally, the case study in this study supplements the guideline by providing a step-by-step description and example on how the specific risk management methods were implemented. The combination of the risk management guideline and case study encourages and facilitates future risk management on parachute mortars in sounding rockets.

6 Discussion

The general aim of this research is to enable performing comprehensive risk management on the parachute mortar subsystem used in sounding rockets. Through an extensive review of the existing literature, three knowledge gaps were identified concerning this objective: 1. the specific application of parachute mortars on sounding rockets, 2. application of risk identification, assessment, and evaluation phases in real-world cases of risk management on parachute mortars, and 3. the implementation of a socio-technical systems approach to the analysis of rocket subsystems. To address these gaps, this thesis research aims to develop a risk management approach suitable to the parachute mortars in sounding rockets, whilst also integrating a socio-technical perspective. The feasibility of implementing this approach is examined through a comprehensive case study focused on the DARE mortar system. This case study serves as a bridge between the theoretical frameworks and practical applications, facilitating the effective implementation of the synthesised approach for future applications.
This discussion chapter is separated in different sections, each focusing on a specific topic in the research. These sections will provide a reflection on the results obtained throughout the research process as well as the research sub-questions posed earlier, evaluating the extent to which they have been addressed and the insights gained from their exploration. Moreover, the limitations in the research are acknowledged and discussed, recognising areas where further investigation and refinement are warranted. Lastly, the work is contextualised within the broader landscape of existing research, highlighting its contributions and potential implications for future studies in the field.

6.1. Composing a socio-technical systems approach

The incorporation of the socio-technical system approach into this research required addressing two main points. These are formulated in sub-research questions SRQ1 and SRQ2: ”What technical elements, actors and social elements build up the parachute mortar socio-technical system?” and ”How does the scope of risk management change between an engineering or socio-technical system view?”. Firstly, it was necessary to explore the conditions under which a technical system can be considered a socio-technical system. Sources present widely differing views on socio-technical systems, their definitions, and their boundaries. A key limitation found during the literature review is that this diverse collection of views has little to no consensus. This means that the interpretation of whether a parachute mortar can be viewed as a socio-technical system or not, and how to analyse it, are dependent on which perspective of a socio-technical system is taken. In certain sources, such as Bauer and Herder, socio-technical systems are described as systems where ”technological components and social arrangements are so intertwined that their design requires the joint optimisation of technological and social variables” [5]. According to this criteria, the parachute mortar can certainly be viewed as socio-technical system. However, other sources, such as Kroes et al., deem the high complexity and large size of the system to be important characteristics of a socio-technical system [37]. There is a certain bias in literature where the socio-technical systems approach is predominantly applied to large, complex systems, with a high number of elements and relationships. Whereas these are not the only systems that require joint optimisation of technological and social variables. It can be argued that the socio-technical system approach should be applied to smaller technical systems as well, to facilitate

the broader review of risks present in a system. Especially because this is a crucial but often-omitted part of risk management.
An approach is suggested to select which technical artefacts, actors, and social elements fall inside or outside of the socio-technical system. However, it is noted that this system boundary must be treated as a design choice. An important objective for any research would be to explain in detail which elements are included or excluded, and provide the reasoning for this choice. The system boundary can also change over time, and it can be updated according to new results or insights, so it must be monitored and adapted over time. When applying this approach to parachute mortar systems on sounding rockets, the technical elements inside the socio-technical system are limited to parachute mortar hardware. Three key interfaces with other subsystems; the parachute, bulkhead and ignition signal, are reviewed, but currently excluded from the socio-technical system. Additionally, the vehicle operator, launch provider and launch site operator are included in the socio-technical system. The selection of elements within the boundary of the socio-technical system is fairly subjective, and therefore all considerations must be clearly presented.

Secondly, the research addressed the analyses that should be conducted on the socio-technical system in relation to risk management. Again, the available literature contains highly divergent views, and there are hardly any standard analyses implemented on socio-technical systems. Various sources present a form of mapping the socio-technical system, but they lack consistency and an explanation on the applied methodology. The analyses selected are based on occurrence in literature, specifically in case studies which include a clear application of the analysis. These include mapping of the socio-technical system, a value chain analysis, incorporating a socio-technical context in the risk management analyses and trade-offs, and a Human Reliability Analysis (HRA) focusing on performance factors. The execution and incorporation of these analyses in the risk management process represents the scope change that occurs when implementing a socio-technical system approach.
There are, up to now, limited sources available to support the selection of these analyses. The majority of Human Reliability Analyses are currently quantitative, which is not feasible within this research or on parachute mortar systems. Additional research is necessary to investigate how qualitative human reliability analyses can be effectively combined with or integrated into qualitative risk management methods. Additionally, the methods available focus on the reliability of operators or personnel working with the system. No analysis methods were discovered that specifically address the relationships between other elements within the socio-technical system. However, some elements in the socio-technical system, for example safety culture in an organisation or evaluation of complexity of the system, are reflected in the Performance Shaping Factors (PSFs).

6.2. Selection of risk management methods

As an immense range of risk management methods exists, it is of interest to review which ones are most suitable to evaluate a parachute mortar on sounding rockets. This query is formulated sub-research question SQR3: ”What combination or adaptation of conventional risk management methodologies is suited for identifying, assessing, and mitigating safety and performance risks of parachute mortar systems in sounding rockets?”. The discussion on selecting viable methods for risk identification, assessment, and evaluation involved the exploration of three distinct paths. Path 1 focused on the methods mentioned in the ISO standard, which generated a multitude of potential methods, particularly in the realm of risk identification. This suggests that the selection had not gone far enough, leaving too many options on the table. Further refinement and tailoring of the methods were necessary, requiring a case-specific approach.
Path 2 involved evaluating industry-used methods, revealing a limited number of commonly employed approaches such as the risk matrix and FMEA. Resulting in a selection of risk assessment methods on parachute mortars limited to qualitative methods. Although there are limitations to relying solely on qualitative methods, such as increased subjectivity and limited comparability, they have explicit advantages such as providing rich contextual insight, high flexibility, and cost less time. It is worth noting that experts from industry solely employ qualitative risk management approaches for mortar systems. The scarcity of information and data on these systems, specifically probability of various failure modes, hinders the feasibility of conducting quantitative analyses.
No clear sources were found on an objective risk evaluation method to establish risk acceptance criteria

and/or could differentiate between intolerable, tolerable, and acceptable risks. Interviews with industry experts revealed that risk evaluation predominantly relied on subjective expert judgement. This limitation posed a significant challenge and highlights the need for further investigation in this area. Moreover, there was a scarcity of practical examples illustrating the application of risk management methods in the spaceflight industry through case studies.

Path 3 aimed to select methods through the lens of a socio-technical view, leading to the exploration of Human Reliability Analysis (HRA). However, HRA encompasses a wide array of methods and frameworks like THERP, HEART, SHERPA, CREAM, and SoTeRiA, making it challenging to navigate as a newcomer in this field. This study only scratched the surface of HRA, highlighting the need for extensive future investigations, particularly within the context of DARE. Given the case-specific nature of HRA, depending on the operator, culture, environment etc., it becomes challenging to generalise the analysis results to other parties. Lastly, incorporating qualitative HRA results within risk management methods proves difficult due to the absence of generated human error probabilities (HEPs) which is one common method of integration.

The methods identified through these three paths are synthesised into one proposed risk management approach (displayed in Figure 4.10), answering sub-research question SRQ3.

6.3. Application of synthesised approach to case study

While many risk management methods are often described in hypothetical scenarios or examples, the maximum value of these methods is realised when they are applied to real-world case studies. The practical application of risk management methods in a specific context offers significant advantages, as it allows others to witness their effectiveness and facilitates their broader adoption. Through case studies, the application of risk management methods becomes tangible and visible, providing valuable insights and practical guidance for others seeking to apply the same methods in their own settings. To pursue this added value in the current research, the proposed risk management approach is applied to a case study, in order to answer sub-research question SQR4: ”If the synthesised approach is applied to the DARE mortar case, what practical implications and limitations arise, and how can the approach be further enhanced for improved effectiveness?”. Key considerations are presented in this section and sorted on risk management phase.

Analysing the socio-technical system:

- The selection of the socio-technical system boundary is very case specific. For example, there is even a differentiation between launch site operators that are (not) included. It is also subject to changes in the system, so the boundary should be re-evaluated regularly.
- When reflecting on the socio-technical system boundary, there is a possibility that it should primarily encompass the technical hardware and the operator. Some definitions of socio-technical systems may suggest this perspective. In the context of this research, the design aspect of the risk management phases predominantly focuses on the operator as the key non-technical element. However, it is important to acknowledge that other elements, such as the launch provider and launch site operator, may assume greater significance when analyzing other types of risks, such as those related to project timelines or budgets.
- Applying the socio-technical approach to the technical system in this research proves beneficial for risk management beyond performance aspects such as safety. This broader scope provides unique insight into the case and context, which is invaluable to the risk management process.

Risk identification:

- The interviews with experts in this research focused predominantly over discussing which risk methods they utilised, resulting in a lowered emphasis on in-depth exploration of risks within the system.
- Interviews with experts and analysis of past incident reports proved to be the most valuable sources of information as they offered direct applicability to the case study at hand.
- It is important to note that interviews with experts and reliance on past incident reports may exhibit a bias towards failure modes that have already been identified or experienced. Conducting a comprehensive system review can help identify less prominent or visible risks that may not have been captured through these sources.

- It is essential to acknowledge that risk identification is an ongoing process and inherently non-exhaustive. No matter how thorough the identification efforts, there will always be additional risks present that have not yet been identified or surfaced. Continuous vigilance and review are necessary to identify and address emerging risks effectively.

Risk assessment:

- Objective collection and interpretation of data on the probability and severity of risks pose challenges in the research. Currently, reliance is primarily placed on the examination of past incidents along with engineering judgment. However, the limited documentation of failures in the DARE case study presents obstacles to reproducibility. This underscores the significance of comprehensive documentation throughout the system's development, including the production process, tests, and flights. Additionally, for other sounding rocket subsystems without an extensive usage history, there will be greater uncertainties in assigning severity, occurrence, and detection ratings in risk matrices and/or FMEA. Conducting analyses or tests may be necessary to fill these information gaps.
- In the assessment methods of FMEA and risk matrices, the use of objective rating scales is crucial to enhance research reproducibility.
- FMEA reveals sensitivity in the Risk Priority Number (RPN) to slight adjustments in severity, occurrence, or detection ratings, particularly for risks with higher RPN values. Consequently, risks that fall just below or above the intolerable boundary should be carefully reviewed during the evaluation phase.
- The implementation of FMEA on safety risks demonstrates limitations. Despite their perceived importance, safety risks often yield very low RPNs, primarily due to low detection ratings. The application of a detection rating appears to provide fewer advantages for safety risks compared to performance risks. Additionally, risks with well-implemented controls tend to yield lower RPN values. However, these controls must be monitored and maintained to sustain low-risk levels effectively, which is not apparent from the RPN.
- The HACCP method did not involve a detailed assessment, as many hazards were considered non-significant according to the HACCP assessment, despite their significance within the DARE society.
- The integration of human reliability analysis (HRA) with risk management lacks clarity and structure. This is partly due to the novelty of the topic for the researcher and the scarcity of practical examples, with most case studies focusing on quantitative approaches. A potential area for future research is exploring how qualitative HRA can be effectively combined with risk management.
- A limitation exists in the current use of HRA methods, which primarily assess factors influencing human reliability rather than identifying specific operational risks. The latter are captured through the process FMEA, drawing from past experiences and observations rather than a cognitive functions-based approach. Nonetheless, conducting a comprehensive HRA to evaluate the presence of prominent yet unidentified risks stemming from human error would be an intriguing avenue to explore.

Risk evaluation:

- The absence of structured methods and the subjective nature of risk evaluation pose significant limitations, contributing to challenges in achieving reproducibility.
- Currently, there is a lack of objective methods available to evaluate risks and establish acceptable risk levels. This process heavily relies on engineering experience and judgement, introducing subjectivity into the assessment.
- Determining acceptable risk levels is dependent upon mission criteria and objectives, as exemplified by the contrasting cases of two different sounding rockets from DARE.
- The applicability of ALARP is constrained by its inability to provide objective risk selection criteria. For the optimisation of tolerable risk, which is the main focus of the ALARP principle, more applicable methods are available as there are limited health and safety regulations that can be used to establish the ALARP level.
- While the bow-tie analysis is utilised to assess identified hazards, the research reveals the absence of a structured method for hazard identification and assessment.
- The analysis of controls is promptly applied to the redesign process, as there is no practical benefit in conducting it on the old design first.

Risk treatment:

- Due to the time constraints of this research, the documentation and explanation provided regarding the design and execution of the risk treatment strategy is not as detailed as desired.
- The selection of the redesign approach is conducted using a qualitative method that prioritises factors such as low risk and efficient utilisation of manpower over mass. However, it is important to note that these priorities may vary across different projects or organisations.
- It is worth acknowledging a slight bias within both DARE and the researcher towards utilising testing as a risk treatment method. This preference stems from a higher level of experience and the ready availability of hardware and equipment for testing purposes.
- While there were limitations in terms of financial resources available for risk mitigation activities, these constraints did not significantly hinder the execution of the planned activities.
- Mitigation activities were performed on nearly all critical (intolerable) risks, resulting in a reduction of their Risk Priority Numbers (RPNs) to below the threshold for intolerable risks.
- These risk mitigation efforts were accomplished with remarkably limited resources in terms of manpower (approximately 400 man-hours) and finances ($\leq$ €150,-), exemplifying an outstanding success and efficiency of the risk mitigation process.
- The design and development of a sabot capture net is the next essential step in risk mitigation on the DARE parachute mortar.

The practical implications encountered while applying the approach to the case study were evaluated after each risk management phase, answering SRQ4. A new Risk Management Guideline is presented in section 5.7, incorporating the main lessons learned and recommendations from the case study.

6.4. Risk management guideline

The main objective of this research is to construct a Risk Management Guideline which has a strong foundation of theoretical risk management methods, combined with lessons learned from a practical application from a case study. After applying the synthesised approach created in chapter 4 to the case study in chapter 5, the main research question is answered in section 5.7: "What are the design characteristics of a risk management guideline that enables the reduction of safety and performance risks of parachute mortar systems in sounding rockets?". The following key takeaways from the guideline can be highlighted:

- The socio-technical system approach brings immense value by providing the necessary context for the risk management process, even if the applicable methods are still in the early stages of development.
- Subjectivity remains a prevalent factor in both this research and the risk management approach, such as in determining the socio-technical system boundary, addressing biases in identified risks, and judging the assessment criteria. To mitigate this, it is crucial to thoroughly explain the reasoning behind these decisions.
- The lack of proper methods available to establish objective risk acceptance criteria contributes to the subjective nature of risk evaluation.
- The comprehensive guideline primarily consists of qualitative analyses, which offer valuable insights. The inclusion of quantitative aspects would have significantly increased the analysis time and created a substantial barrier of input data before effective risk management can be achieved.
- Although the current evaluation utilises the bow-tie method, this study did not find and/or test a suitable method for the identification, assessment, and evaluation of safety risks. Consequently, having a specific method for identification and/or assessment would greatly enhance the robustness of the framework.
- Integrating qualitative results from Human Reliability Analysis (HRA) into the risk management process presents challenges, primarily because the main practical examples predominantly rely on quantitative data usage.

Significant modifications were made between the original proposed risk management approach (Figure 4.10) and the final risk management guideline (Figure 5.30). This raises questions about the initial selection of suitable methods and why they differed so significantly from the final recommendation. The current presumption is that the disparity is primarily attributed to the researcher's limited detailed knowledge of the available risk management methods, compounded by the extensive variety of existing methods. However, the modifications also highlight the importance of validating the approach through practical application to a case study and incorporating the lessons learned. This iterative process ensures the feasibility of conducting all necessary analyses and enhances the overall value of the risk management approach.

While the risk management approach was validated through the use of a case study, there remains a challenge in confirming the accuracy or correctness of the analyses. Additionally, it is difficult to ascertain whether the proposed guideline represents the most optimal method for conducting risk management or if there are superior alternatives available. However, this research demonstrates the practicality of implementing the guideline in a real-world scenario, showcasing its potential to successfully identify, assess and mitigate the most critical risks present in the system.

6.5. Research landscape and alignment

The findings of this research contribute to the existing research landscape by offering a unique combination of the socio-technical system approach applied to a rocket subsystem. By drawing upon existing literature on socio-technical systems, various definitions are explored to establish a system boundary, providing a comprehensive framework for analysis. Furthermore, the research incorporates insights from existing literature on analyses performed on socio-technical systems in other case studies. This approach enhances the understanding of how these analyses can be effectively applied to assess the complex interactions between technical and non-technical elements within the context of the parachute mortar system.

Another significant contribution is the bridging of the gap between theoretical risk management methods and their practical application, specifically in the context of the parachute mortar. By integrating existing literature on risk management methods in spaceflight and the practical insights from a case study, the research provides a valuable link between theoretical concepts and their implementation within a specific subsystem. Additionally, the research draws upon existing literature on the design of other parachute mortar systems in spaceflight, enabling meaningful comparisons and bench-marking between mortar systems on sounding rockets and on interplanetary missions or human spaceflight missions. This comparative analysis enhances the understanding of differences between risk management strategies applied to various parachute mortar systems.

This research brings together multiple streams of existing literature to create a comprehensive framework for risk management in the parachute mortar subsystem, thereby advancing the understanding of socio-technical systems and their application in practical settings. Moreover, the inclusion of a comprehensive case study on the parachute mortar system adds significant value to the research findings. By applying the developed framework to a real-world scenario, the study goes beyond theoretical considerations and demonstrates the practical applicability of the socio-technical system approach in mitigating risks. The analysis of the parachute mortar system serves as a concrete example, showcasing how the integration of risk management methods from existing literature and the examination of design principles can lead to tangible improvements in system performance and safety. This empirical validation enhances the credibility and relevance of the research, providing valuable insights for both researchers and practitioners in the field. Overall, the combination of theoretical insights, practical application, and the case study's added value positions this research as a significant contribution to the research landscape, fostering advancements in risk management practices and the design of complex systems in the context of spaceflight.

Overall, this discussions chapter has highlighted the limitations, practical implications, and contributions of the research, providing a comprehensive understanding of the synthesised approach developed for risk management in parachute mortar systems. It underscores the importance of considering the broader socio-technical aspects, acknowledge the limitations of the methods applied while recognising their industry relevance, address challenges in data collection and interpretation, and discuss the need for a more inclusive scope of risks. The chapter also emphasises the practical application of the research and its contribution to bridging the gap between theoretical frameworks and real-life risk management in sounding rocket subsystems.

7 Conclusion

In conclusion, this thesis aimed to enable effective risk management for parachute mortars on sounding rockets by addressing safety and performance risks from a socio-technical perspective. The research identified several gaps in existing literature, including the lack of detailed coverage on risk identification, assessment, and evaluation in case studies, limited information on parachute mortar systems specific to sounding rockets, and the underutilisation of socio-technical systems in technical subsystems within spaceflight.

The main objective of this research was to develop a comprehensive risk management guideline tailored specifically to parachute mortar systems, incorporating a socio-technical systems view. The guideline ought to be rooted in conventional risk management practices while also validated through a practical case study to ensure its feasibility.

Throughout the research, significant progress was made, leading to the following key results. The initial synthesised risk management approach was formulated by evaluating conventional risk management methods, industry practices, and socio-technical perspectives. This approach was then applied to the DARE mortar case study, evaluating the usage and effectiveness of each method. The comprehensive risk management approach successfully facilitated a significant reduction of critical risks through redesign and various tests. The lessons learned during the case study were subsequently incorporated into a new Risk Management Guideline, combining theoretical foundations with practical insights, and answering the main research question: "What are the design characteristics of a risk management guideline that enables the reduction of safety and performance risks of parachute mortar systems in sounding rockets?".

By applying the developed framework to a real-world scenario, this study transcends theoretical considerations and demonstrates the practical applicability of the socio-technical system approach in mitigating risks. The unique combination of a practical case study on a sounding rocket subsystem with a socio-technical approach adds novelty and value to the field of risk management. Moreover, it enables and promotes further risk management activities on parachute mortars and socio-technical systems. Additionally, the developed grading scales, interpretation of risk management methods, and the identified risks can all provide valuable insights and serve as inspiration for risk management on other sounding rocket subsystems.

Looking ahead, several avenues for future research are recommended. These include conducting additional case studies on smaller technical subsystems within a socio-technical context, exploring definitions and boundaries of socio-technical systems to establish consensus, investigating the integration of qualitative results from Human Reliability Analysis (HRA) within risk management methods, searching for improved methods to identify and assess safety risks, and most importantly, defining or developing an objective method for risk evaluation and establishing risk acceptance criteria.

In summary, this thesis contributes to the research landscape by providing a comprehensive risk management guideline specifically tailored for parachute mortars on sounding rockets. By addressing research gaps, proposing a detailed risk management guideline, incorporating practical insights, and promoting the socio-technical system approach, this study serves as a valuable resource for researchers and industry practitioners alike seeking to enhance safety and mitigate performance risks in parachute mortar systems.

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A

Risk management methods and application

A.1. Selection of risk management methods

This sheet describes the selection of risk management methods from ISO31010 based on the selection criteria described in subsection 4.2.2.

Risk management methods selection

1. List of methods from ISO:31010, general relevance
2. Selection of methods "strongly applicable" to select risk management phase
3. Selection of methods with low/medium "starting data needs" and "specialist expertise"

* Risk analysis: three categories: consequence, likelihood and level of risk.
All should be "Applicable", of which one or more "Stronlgy Applicable"

Selection round 1	Selection round 2	Selection round 3	
Name	**Risk management phase** Minimally: "Strongly applicable"*	**Starting info/data** Maximally: "Medium"	**Specialist expertise** Maximally: "Moderate"
~~ALARP/SFAIRP~~	~~Risk evaluation~~	~~High~~	~~High~~
~~Bayesian analysis~~	~~None~~		
~~Bayesian networks~~	~~None~~		
Bow tie analysis	Risk analysis	Low	Low/moderate
Brainstorming	Risk identification	None	Low/moderate
~~Business impact analysis~~			
~~Causal mapping~~	~~None~~		
~~Cause-consequence analysis~~	~~Risk analysis~~	~~Medium/high~~	~~Moderate/high~~
Checklists, classifications, taxonomies	Risk identification	High to develop Low to use	Low/moderate
Cindynic approach	Risk identification	Low	Moderate
~~Conditional value at risk~~			
Consequence/likelihood matrix	Risk analysis	Low	Low to use Moderate to develop
~~Cost/benefit analysis~~	~~Risk evaluation~~	~~Medium/high~~	~~Moderate/high~~
~~Cross impact analysis~~	~~None~~		
Decision tree analysis	Risk analysis	Low/medium	Moderate
Delphi technique	Risk identification	None	Moderate
Event tree analysis (ETA)	Risk analysis	Low/medium	Moderate
Failure modes and effects analysis (FMEA)	Risk identification	Low/medium	Moderate
~~Failure modes and effects and criticality analysis (FMECA)~~	~~All phases~~	~~Medium/high~~	~~Moderate~~
~~Fault tree analysis (FTA)~~	~~None~~	~~(high for quant.)~~	
~~Frequency / number (F/N) diagrams~~			
~~Game theory~~	~~Risk evaluation~~	~~High~~	~~High~~
Hazard analysis and critical control points (HACCP)	Risk identification & evaluation	Medium	Moderate
~~Hazard and operability studies (HAZOP)~~	~~Risk identification~~	~~Medium~~	~~Facilitators high, participants moderate~~
~~Human reliability analysis~~	~~All phases~~	~~Medium~~	~~High~~

Sorting by phase	Name
Risk identification	Brainstorming/nominal group technique
	Checklists, classifications, taxonomies
	Cindynic approach
	Delphi technique
	FMEA
	HACCP
	Interviews
	Ishikawa analysis (fishbone diagram)
	Scenario analysis
	Surveys
	Structured what-if technique (SWIFT)
Risk assessment	Bow tie analysis
	Consequence/likelihood matrix
	Decision tree analysis
	Event tree analysis (ETA)
	Risk indices
	Scenario analysis
	Structured what-if technique (SWIFT)
Risk evaluation	HACCP
	Multi-criteria analysis (MCA)
	Pareto charts

Interviews	Risk identification	None	Moderate
Ishikawa analysis (fishbone diagram)	Risk identification	Low	Low/moderate
~~Layers of protection analysis (LOPA)~~	~~Risk analysis~~	~~Medium~~	~~Moderate/high~~
~~Markov analysis~~	~~None~~		
~~Monte carlo analysis~~	~~Risk evaluation~~	~~Medium~~	~~High~~
Multi-criteria analysis (MCA)	Risk evaluation	Low	Moderate
Nominal group technique	Risk identification	None	Low
Pareto charts	Risk evaluation	Medium	Moderate
~~Privacy Impact Analysis (PIA)~~			
~~Reliability centered maintenance (RCM)~~			
Risk indices	Risk analysis	Medium	Moderate to develop Low to use
~~S-Curves~~	~~Risk evaluation~~	~~Medium/high~~	~~Moderate/high~~
Scenario analysis	Risk identification & analysis	Low/medium	Moderate
Surveys	Risk identification	Low	Moderate
Structured what-if technique (SWIFT)	Risk identification & analysis	Medium	Low/moderate
~~Toxicological risk assessment~~			
~~Value at Risk (VaR)~~			

A.2. Application of risk management methods to the case study

This appendix displays the application of the selected risk management methods on the case study. The following risk methods are included: Failure Modes and Effects Analysis (FMEA), Hazard Analysis and Critical Control Points (HACCP), Severity/Likelihood matrix or 'risk matrix', and Multi Criteria Analysis (MCA).

FMEA - process (Source of template: Basics of FMEA)

ID	Process step	Potential failure mode	Potential effects of failure	Risk	S	Potential cause(s) of failure	O	Current controls, prevention	Current controls, detection	D	RPN	Priority	Comments on S/O/D rating
PPP_XX	**Part procurement/production**												Depends on safety factor imposed on casing design
PPP_01		Incorrect stock material is ordered for casing	Structural failure of casing	FP	9	Human error Documentation	5		Ejection test before design freeze	5	225	3	
PPP_02		Incorrect mesh size/material is ordered	Mesh fails during ignition, NTC is not fully burnt	FP	6	Human error Documentation	9		Ejection test before design freeze	5	270	2	
PPP_03		Parts are made to incorrect size/tolerance	Higher risk of no ejection due to parts that are stuck	FP	9	Inexperienced person Human error Technical specs incorrect	7		Assembly and/or ejection tests before launch	5	315	2	
PPP_04			Underperformance due to increased friction	FP	7		8			5	280	2	
PPP_05			Difficult integration, slight damage due to sharp edges	FP	3		9			5	135	4	
PPP_06			Leakage occurs as seals cannot function	FP	9		6		Proper functioning of seals can be observed during assembly.	6	324	2	
PPP_07		Casing has production errors	Lowered max. burst pressure, Structural failure of casing	FP	9	Inexperienced person Human error Documentation	6	Only experienced members produce canister	Visual inspection Ejection test before launch	7	378	1	Depends on safety factor imposed on casing design
PPP_08		Casing gains damage upon mold release (fibres)	Lowered max. burst pressure, Structural failure of casing	FP	7	Violent mold release, use of LN, difficult CFRP mold	5	Apply release agent	Visual inspection Ejection test before launch	5	175	3	Depends on safety factor imposed on casing design
PPP_09		Casing gains damage upon mold release (gelcoat)	Increased friction of casing	FP	6		6	Apply release agent	Visual inspection Ejection test before launch	5	180	3	
PPP_10		Pyrotechnic materials degradation	Gas generator charge does not ignite, or underperforms	FP	9	Incorrect storage (moisture, duration)	7	Proper storage in vacuum packs and containers	Visual/scent inspection	5	315	2	
PPP_11		Minor health hazard during production (cuts, scrapes)	Minimal harm to people	S	5	Human error Inexperienced person Unclear protocols on PPE use Time pressure	9	Wear PPE, explanation on use of workshop equipment	DARE members addressing each other in case of issues. Culture of also being responsible for each others safety.	2	90	4	
PPP_12		Major health hazard during production (carbon fibres in lungs)	Medium harm to people	S	8	Unclear protocols on PPE use, no PPE available, "Do something quickly" without PPE	5	Wear PPE, laboratory rules, online tests before getting lab access	Supervision in composites lab & DARE members addressing each other in case of issues. Culture of also being responsible for each others safety.	2	80	4	
PPP_13		General health hazard due to incorrect disposal of chemicals	Minimal harm to people	S	5	Inexperienced person Laziness Unclear protocols	5	Laboratory rules, online tests before getting lab access	Supervision in composites lab	3	75	4	
SAI_XX	**System assembly & integration for test or launch campaigns**												
SAI_01	**Part preparation**	Operator performs insufficient part preparation (cleaning, deburring)	Underperformance due to increased friction	FP	6	Lack of preparation, diligence Tight assembly time	10	Dress rehearsals, packing, procedures	Visual inspection, comments in procedures	3	180	3	
SAI_02			Difficult integration, slight damage due to sharp edges	FP	6		10			3	180	3	
SAI_03		Incorrect parts used (wrong fasteners/tape/O-rings...)	Underperformance (various)	FP	6		8			6	288	2	
SAI_04		Incorrect assembly due to wrong tools	Underperformance (various)	FP	6		9			3	162	3	
SAI_05	**Pyrotechnic preparation**	Ignitor bolt is not leak tight	Underperformance in low pressure environments	FP	7	Insufficient epoxy applied to squib/ignitor bolt (top)	8		Visual inspection	3	168	3	
SAI_06		Squib head closed off from charge	No ejection due to no ignition of charge	FP	9	Excessive epoxy applied to squib/ignitor bolt (bottom)	5		Visual inspection	3	135	4	
SAI_07		Squib leads (cables) shunt as insulation is damaged during assembly	No ejection due to shunting of circuit	FP	9	Damage insulation whilst routing squib cable through bolt	7		Visual inspection	3	189	3	
SAI_08		Squib fires unintentionally	Medium harm to people	S	8	ESD	5	ESD protection in relevant environment, wearing PPE during pyrotechnic operations	Feeling statical charge	6	240	3	Depends on assembly location
SAI_09		NTC charge fires unintentionally	Significant harm/damage to people/property	S	10	Spontaneous combustion	2	Stored in safety can		6	120	4	
SAI_10		Ignitor bolt thread fails	Ignitor bolt breaks during ascent. Ignitor bolt does not fire into charge.	FP	9	Lack of quality control in parts Overtorquing of part	8	Redundant ignitor bolt	Immediately visible and cannot rotate bolt anymore	2	144	4	
SAI_11		Gas generator is slightly underfilled (2-5% less than intended mass)	Slight underperformance	FP	6	Measurement equipment incorrect. Operator not paying sufficient attention. Rush, time constraints. (Underfilling: not all NTC pellets placed inside GG)	7	Scale is tared each time, regularly used. Ocasionally tared with provided weight. Quality of equipment.	Safety officer, operator and PA observe measurement	3	126	4	0-2% over- or underfilling is assessed to have nominal operating performance.
SAI_12		Gas generator is significantly underfilled (>5% less than intended mass)	Underperformance, potential failure to eject	FP	9		4			3	108	4	
SAI_13		Gas generator is overfilled (2-5% more than intended mass)	Slight overperformance	FP	5		9			3	135	4	
SAI_14		Gas generator is overfilled (>5% more than intended mass)	Overperformance, potential structural failure of casing	FP	7		4			3	84	4	

FMEA - process (Source of template: Basics of FMEA)

ID	Process step	Potential failure mode	Potential effects of failure	Risk	S	Potential cause(s) of failure	O	Current controls, prevention	Current controls, detection	D	RPN	Priority	Comments on S/O/D rating
SAI_15	Canister assembly	Different parachute is used than during (qualification) tests	Significant system under- or overperformance due to large change in compressibility	FP	9	System is used on different missions without additional tests	9	N.A.	It is known which parachutes have been used/tested in the mortar before. Their packing volume/density is unknown.	5	405	1	
SAI_16		Parachute is packed differently than during (qualification) tests	Slight system under- or overperformes due to minor change in compressibility	FP	7	Lack of dress rehearsals, no detailed procedures, or inexperienced member.	7	Clear assembly procedures on assembly pack	N.A. Not possible to inspect inside of mortar after packing.	7	343	2	
SAI_17		Parachute is packed differently than during (qualification) tests	Parachute subsystem entangles upon deployment	FP	7	Inherent variability of the parachute subsystem.	7	Dress rehearsals	N.A.	7	343	2	This borderes on risks in the parachute subsystem.
SAI_18		Sabot is placed slightly skewed	Sabot jams, no ejection.	FP	9		6	Dress rehearsals	Enters smooth y/n	5	270	2	
SAI_19		Sabot is placed upside down (change in plenum volume)	Slight over- or underperformance	FP	6	Lack of dress rehearsals, no detailed procedures, or inexperienced member.	8	Dress rehearsals		5	240	3	
SAI_20		Insufficient lubricant is applied to sabot	Additional friction, underperformance of system	FP	7		6	Dress rehearsals	Enters smooth y/n	3	126	4	
SAI_21		Canister assembled with insufficient number of shear bolts	Underperformance due to lower pressure build up	FP	7	Lack of quality control in parts Tight assembly time	6	Dress rehearsals	Visual inspection	3	126	4	
SAI_22		Canister assembled with non-symmetrical distribution of shear bolts	Lid jams, no ejection	FP	9	Lack of quality control in parts Tight assembly time	8	Dress rehearsals	Visual inspection	3	216	3	
SAI_23		Sharp edges or loose fibres in canister (shear bolt holes, top rim)	Medium harm to people	S	5	Poor post-processing and quality control on CFRP canister, and/or repeated use induces damage	7	Dress rehearsals	Quality control (insufficiently done) Limit use of one canister to X ejections	3	105	3	
SAI_24	General	Assembly mistakes (execution of procedures)	Underperformance due to various reasons	FP	7	Rush, time constraints	8			4	224	3	
SAI_25		Assembly mistakes (execution of procedures)	Underperformance due to various reasons	FP	7	Inexperience with system, ambiguity in procedures	7	Dress rehearsals	Procedures check-off	4	196	3	
SAI_26		Assembly mistakes (execution of procedures)	Underperformance due to various reasons	FP	7	Overestimation of experience, not using procedures	7			4	196	3	
SAI_27		Forgetting safety features / PPE / ESD checks	Unintended firing of pyrotechnics. Medium harm to people	S	8	Rush, time constraints	5	Safety briefing	Safety officer observes operations	3	120	4	Occurance rating here is lower than during final operations, as generally the pyrotechnic preparation is done under less time constraints.
SAI_28		Forgetting safety features / PPE / ESD checks	Unintended firing of pyrotechnics. Medium harm to people	S	8	Overestimation of experience, 'doing something quick', repetitive tasks	5			3	120	4	
SAI_29			Higher risk of no ejection due to parts that are stuck	FP	9		6			5	270	2	
SAI_30		Different sets of hardware do (not) fit together	Underperformance due to increased friction	FP	7	Parts are not made to correct size, no quality control	8	Dress rehearsals	Enters smooth y/n	5	280	2	
SAI_31			Difficult integration, slight damage due to sharp edges	FP	3		8			5	120	4	
OPS_XX	**Final operations at test or launch campaigns (=arming and working with loaded system)**												
OPS_01		Catastrophical failure during test	Medium harm to people	S	8	Insufficient safety precautions (distancing, shielding)	5	Shrapnel box and sandbags placed around setup. Safe distance from test.		2	80	4	
OPS_02		Misfire of the mortar	Increased exposure to live system	S	5	Unreliable squib, firing line	8	Ignition lead tests	Visual observation of test	4	160	3	
OPS_03		Forgetting safety features in procedures (PPE, shunting, ESD checks)	Unintended firing of pyrotechnics. Medium harm to people	S	8	Rush, time constraints	5	Safety briefing	Safety officer observes operations	3	120	3	
OPS_04		Forgetting safety features in procedures (PPE, shunting, ESD checks)	Unintended firing of pyrotechnics. Medium harm to people	S	8	Overestimation of experience, not using procedures	5			3	120	3	
OPS_05		Assembly mistakes due to rush, time constraints (forget RBF/incorrect arming/...)	No ejection	FP	9	Rush, time constraints	5	Dress rehearsals	Procedures check-off	3	135	4	
OPS_06		Assembly mistakes due to overestimation of experience (forget RBF/incorrect arming/...)	No ejection	FP	9	Overestimation of experience, not using procedures	4	Dress rehearsals	Procedures check-off	3	108	4	
OPS_07		Mortar firing whilst assembled in vehicle	Loss of vehicle systems	FP	10	Safety feature skipped over	4	Multiple inhibits		3	120	4	
OPS_08		Launch site imposes different assembly/operational procedures or measurements which are unpracticed	Assembly mistakes and/or forgetting safety features in procedures	FP/S	8	Miscommunication, unfamiliarity with system, different views on safety	6	Communication, discuss procedures in advance	Dress rehearsal on-site	3	144	4	
OPS_09		Launch site operator treats live system as safe	No use of PPE and/or attention to ESD, increased risk to unintended firing and harm	S	5	Insufficient communication about system status	6	Communication, allocated pyro prep space	Visual indication of hazards (red/white tape, signs)	3	90	4	

FMEA - process		(Source of template: Basics of FMEA)											
ID	**Process step**	**Potential failure mode**	**Potential effects of failure**	**Risk**	**S**	**Potential cause(s) of failure**	**O**	**Current controls, prevention**	**Current controls, detection**	**D**	**RPN**	**Priority**	**Comments on S/O/D rating**
OPS_10		Launch site operator/client/other launching parties are not aware of system danger	No use of PPE and/or attention to ESD, increased risk to unintended firing and harm	S	5	Insufficient communication about system, no location to perform dangerous assembly steps	6	Communication, allocated pyro prep space	Visual indication of hazards (red/white tape, signs)	3	90	4	
OPS_11		Launch site operator does not adhere to safety precautions set by launch provider	Decreased use of PPE and/or attention to ESD, increased risk to unintended firing and harm	S	7	Disagreement about correct safety precautions, insufficient communication on protocols	5	Communication, discuss hazards in advance	Provide feedback on (in)correct behaviour	4	140	3	
OPS_12		Launch provider does not adhere to safety precautions set by launch site operator	Decreased use of PPE and/or attention to ESD, increased risk to unintended firing and harm	S	7		5	Communication, discuss hazards in advance	Provide feedback on (in)correct behaviour	4	140	3	
OPS_13		(No ignition of electric matches) Pyrotechnics are live and armed during retrieval operations	Unintended firing of pyrotechnics. Medium harm to people	S	8	Insufficient power, battery. Vehicle did not reach correct state to initiate parachute deployment (issues with sensors, timers, breakwires). Vehicle breakup during flight.	5	Testing of electronics system, state machine and sensors.	Visual observation during retrieval operations. Wearing PPE in case of non-nominal scenario. Disarming equipment present.	4	160	3	

Severity rating scale - safety (S)	**Severity rating scale - functional performance (FP)**		**Occurance rating scale**		**Occurance rating scale (mortar case)**	**Detection rating scale (literature)**		**Detection scale (mortar case)**
Significant harm/damage to people/property	Complete system failure, loss of vehicle system(s) before re-entry	10	1 in 5	10		No design control or no chance of detection	10	Even if the risk is known, it is not possible at all to establish whether it will occur
	Complete system failure, no parachute ejection	9	1 in 10	9	Failure modes that occurred during previous mortar tests or sounding rockets with mortar systems	Very remote chance of detection	9	Very difficult to detect whether the risk will occur, for example, the failure may occur even if detection activities were performed.
Medium harm/damage to people/property		8	1 in 20	8		Remote chance of detection	8	The required effort/resources to detect the risk/issue is very high (e.g. extra test campaigns or expensive equipment are needed), generally not done
	Successful ejection but underperformance **or** risk of unsuccessful parachute inflation (damage/debris/entanglement)	7	1 in 50	7	Anything that has happened multiple times in DARE (other teams)	Very low chance of detection	7	The required effort/resources to detect the risk/issue is high (e.g. an extra test is needed), occasionally done for important missions
	Slight underperformance	6	1 in 100	6	Anything that has happened in DARE (other teams)	Low chance of detection	6	Detection is possible, but detection methods are not (standard) implemented in the procedures and/or test campaigns. Detection methods are only known/performed by experienced operators.
Minimal harm to people (cut, scrape, etc.)	Successful ejection but overperformance	5	1 in 500	5		Moderate chance of detection	5	Detection is possible, but detection methods are not (standard) implemented in the procedures and/or test campaigns. Detection methods are naturally done during operations and/or are known and performed by most operators.
		4	1 in 1000	4	Anything that has happened in the DreamHall, Delft University of Technology, or other student rocketry teams	Moderately high chance of detection	4	Detection is possible, currently implemented in procedures and test/launch campaigns, and requires a medium level of effort or they are occasionally skipped during the procedures.
	Successful ejection but loss of parts	3	1 in 2000	3		High chance of detection	3	Detection is possible, currently implemented in procedures and test/launch campaigns, and requires little to no effort.
		2	1 in 5000	2		Very high chance of detection	2	Detection is almost automatic, direct through observation or it is not possible to continue assembly, is recognizable by operators with little to no experience.
No harm/damage to people/property	Nominal system performance	1	Failure is eliminated	1		Cannot occur, or almost certain detection	1	Very low chance of failure mode to occur due to prevention in design

RPN	Priority rating
>349	1
250-349	2
150-249	3
<150	4

FMEA - product/design		(Source of template: Basics of FMEA)									
ID	**Component**	**Potential failure mode**	**Potential effects of failure**	**S**	**Potential cause(s) of failure**	**O**	**Current controls,**	**Current controls, detection**	**D**	**RPN**	**Priority**
CS_XX	**Canister**										
CS_01				10	Significant overperformance of GG, experienced pressure surpasses design pressure	3	Accurate measurement of NTC	Ejection tests	4	120	4
CS_02		Structural failure (radial burst) of canister	No ejection and damage to other subsystems	10	True burst pressure of canister lies below the design pressure or experienced pressure	5	Safety factor in design (true burst pressure unknown)	Ejection tests Hydrostatic test to burst pressure (not yet done on mortar system)	7	350	1
CS_03				10	Canister cannot withstand repeated application of design pressure (cyclic loading)	5	Safety factor in design	Hydrostatic tests to nominal operating pressure (not yet done on mortar system)	7	350	1
CS_04		Failure of glue joint between CFRP canister and attachment ring	Canister disattaches, shoots back into vehicle. Debris might hit parachute	7	Insufficient (and inconsistent) strength of glue joint	8	Extra care on part preparation (sanding, cleaning)	Ejection tests have proven not to be sufficient, attachment can still fail after previous successful tests.	8	448	1
CS_05		Structural failure of canister during ascent	Parachute exits mortar prematurely, may damage other subsystems	10	Canister cannot withstand acceleration/vibration loads during ascent	3	Safety factor in design	Vibration test is performed on full system for important launches	7	210	3
CS_06		Structural failure of attachment point during ascent	Parachute mortar disconnects and moves freely in sounding rocket. May induce damage to other subsystems.	10	Insufficient (and inconsistent) strength of glue joint	4	Safety factor in design	Vibration test is performed on full system for important launches	7	280	2
CS_07		Shear bolt holes damaged	Shear bolts weakened due to sharp edges, leading to slight underperformance	6	Poor post-processing and quality control on CFRP canister, and/or repeated use induces damage	8	Dress rehearsals	Quality control (insufficiently done) Limit use of one canister to X ejections	3	144	4
IG_XX	**Ignitors**										
IG_01		Ignition signal is not received from electronics subsystem	No parachute ejection	9	Damage to the cabling. No signal is given by electronics subsystem (see INT_04).	7	Redundancy in ignitors (2x firing channels and firing lines)	Pre-launch tests of electronics subsystem and integration with mortar	7	441	1
IG_02		Squib malfunctions	No parachute ejection	9	Squib malfunctions	3	Redundancy in ignitors	Visual inspection of squib head and leads	4	108	4
IG_03		Delay in firing	Late parachute ejection, risk of parachute malfunctioning	7	Signal propogation delay throughout cable. Delayed sensor detection (for example, due to slow pressure propagation through vehicle).	6	Usage of timers for actuation	Pre-launch tests of electronics subsystem and integration with mortar	3	126	4
IG_04		Squib fires before intended deployment moment (during re-entry)	Early parachute ejection, risk of parachute malfunctioning	7	Incorrect sensor readout or state switching	6	Usage of timers for actuation	Pre-launch tests of electronics subsystem and integration with mortar	3	126	4
GG_XX	**Gas generator**										
GG_01			No ignition, no ejection	9	Leaks in plenum volume during ascent, pressure in plenum volume <35mbar	5		N.A.	7	315	2
GG_02			Ignition, significant underperformance (>10% reduction in pressure), may result in no ejection	9	Leaks in plenum volume during ascent, pressure in plenum volume 35mbar-0,5bar	6	Application of teflon tape, dowty seals and O-rings to interfaces between plenum volume and the outside of the canister	Could do leak tests of the plenum volume (flight configuration) but this has not been done on the mortar yet.	7	378	1
GG_03			Ignitionm underperformance (<10% reduction in pressure)	7	Leaks in plenum volume during ascent, pressure in plenum volume 0,5-1bar	7			7	343	2
GG_04			No ignition, no ejection	9	Squib does not touch charge	5	Assembly procedures specify application	Visual inspection	3	135	4
GG_05		Charge does not (fully) ignite or underperforms	Underperformance	7	Charge is too dispersed	5	Packing charge with flashpaper to compress	N.A.	3	105	4
GG_06			Nominal performance, few loose NTC pellets	2	Mesh shears out	10	N.A.	N.A.	8	160	3

FMEA - product/design (Source of template: Basics of FMEA)

ID	Component	Potential failure mode	Potential effects of failure	S	Potential cause(s) of failure	O	Current controls,	Current controls, detection	D	RPN	Priority
GG_07			Underperformance	7	Lower temperature inside plenum volume upon ignition	4	Isolated in vehicle subsystems	Thermal cycling / testing	8	224	3
GG_08			Slight underperformance	6	Charge is slightly underfilled	7	Scale is tared each time, regularly used.	Safety officer, operator and PA observe measurement	3	126	4
GG_09			Underperformance, possibly no ejection	9	Charge is significantly underfilled	4			3	108	4
GG_10			Overperformance	5	Charge is slightly overfilled	9	Scale is tared each time, regularly used.	Safety officer, operator and PA observe measurement	3	135	4
GG_11		Charge overperforms	Structural failure of canister upon deployment	7	Charge is significantly overfilled	4			3	84	4
GG_12			Overperformance	5	Increased burn surface area due to vibrational load breaking up pellets	5	N.A.	N.A.	7	175	3
GG_13		Cannot withstand pressure during ignition	Structural failure of GG, no parachute deployment	9	Gas generator thread is significantly damaged and prone to shear out.	4	High safety factor in design	Visual inspection of parts	1	36	4
SB_XX	**Sabot**										
SB_01		Sabot moves down and plenum volume increases due to acceleration during ascent	Change in performance (unknown)	6	Vibration loading, available volume due to low parachute pack density	6	Assembly procedures	Ejection tests	7	252	2
SB_02		Sabot jams during parachute ejection	No ejection	9	Sabot wedges itself sideways	7	Tolerancing on parts	Ejection tests	5	315	2
SB_03		Increased friction during parachute ejection	Slight underperformance	6	More/less vaseline applied during assembly. Different O-rings used or damaged. Different CFRP canister (smoothness)	7	Assembly procedures	Ejection tests, Inspection during assembly	4	168	3
SB_04		Decreased friction during parachute ejection	Slight overperformance	5		7			4	140	4
SB_05		Sabot collides with parachute (pack) after deployment	No successful parachute inflation	7	Sabot is ejected from mortar, in the same direction as parachute assembly	8	N.A.	N.A.	8	448	1
SB_06		Hot gases and particles leak past sabot during ejection	Damaged parachute	6	O-rings do not close off well	4	Assembly procedures	Ejection tests, Inspection during assembly	2	48	4
LD_XX	**Lid & shear bolts**										
LD_01		Lid has insufficient momentum to pull the parachute from its bag (extraction)	No successful parachute inflation	7	Momentum (mass * ejection velocity) of lid is too low	7	Addition of pilot chute or drag cone for bag extraction	Ejection tests	3	147	4
LD_02		Lid has insufficient momentum to pull the parachute from its bag (extraction)	No successful parachute inflation	7	Momentum (mass * ejection velocity) of lid is too low	7		Flight testing	8	392	1
LD_03		Shear bolt(s) do not fail	No ejection	9	Shear bolts not properly loaded (assembled under an angle, or too much distance between tube and lid)	3	N.A.	Assembly ease Ejection tests	6	162	3
LD_04		Lid/shear bolts release during ascent, early release of parachute in vehicle	Parachute exits mortar prematurely	9	Shear bolts or lid cannot carry the load of the parachute assembly during ascent	2	High safety factor in design	(Optionally: vibration testing)	1	18	4
LD_05		Lid/shear bolts release during re-entry, early deployment of parachute	Early parachute deployment, leading to potential entanglement, inversion or increased reaction loads	7	Thermal loading	4	Evaluation of thermal loading during re-entry		4	112	4
EC_XX	**Endcap**										
EC_01		Structural failure of the endcap during ascent, decrease of plenum volume	Change in performance (unknown)	6	Endstop cannot carry the load of the parachute assembly during ascent	2	High safety factor in design	(Optionally: vibration testing)	1	12	4
INT_XX	**Interfaces between mortar and supporting systems**										
INT_01		Natural frequency of mortar hardware or	Inertial coupling of sounding rocket, full vehicle breakup	10	Natural harmonic behaviour of the system,	4	N.A.		7	280	2

FMEA - product/design		(Source of template: Basics of FMEA)									
ID	Component	Potential failure mode	Potential effects of failure	S	Potential cause(s) of failure	O	Current controls,	Current controls, detection	D	RPN	Priority
INT_02		Natural frequency of mortar hardware or subsystem is low and resonates with rocket	Fysical damage to parachute mortar system due to high amplitude vibrations at resonance frequencies	10	depending on materials, mass distribution and moving parts	4	N.A.	Vibration testing	7	280	2
INT_03		Packing density of the parachute subsystem is higher than during ejection testing	Overperformance of the system	6	Lack of dress rehearsals, no detailed procedures, or inexperienced member. Inherent variability of the parachute system.	7	Clear assembly procedures on assembly pack, dress rehearsals	N.A. Not possible to inspect inside of mortar after packing.	7	294	2
INT_04		Packing density of the parachute subsystem is lower than during ejection testing	Underperformance of the system, possibly no ejection	7		7			7	343	2
INT_05		No ignition signal is given from the electronics subsystem	No ejection of the parachute	9	Bad connections causing momentary power loss or system reset, faulty or damaged electronics component, general software bugs, sensor triggers for deployment set incorrectly (pressure, acceleration, timers, etc.), battery power low	7		Testing of electronics subsystem, including flight states and actuation	7	441	1
INT_06		Recovery bulkhead (mortar attachment point) fails upon parachute ejection	Damage to the recovery bulkhead. Impact depends heavily on specific design.	6	Higher reaction load than expected (GG overperformance), assymetric distribution of load, dynamic load case different from static	7		Ejection tests integrated in bulkhead	7	294	2
INT_07		Parachute entanglement during ejection	Unsuccessful parachute inflation	7	Complex interaction between parachute pack movement due to the mortar ejection and aerodynamics during descent	7	Careful parachute packing	Flight tests	8	392	1

HACCP (Source of template: HACCP a practical approach)

Process step / raw material	Hazard and source	Likelihood L/M/H	Severity L/M/H	Significant hazard Y	Significant hazard N	Control measures
CFRP	Loose carbon fibres, from processing / handling CFRP parts.	H	M	Y		Personal protective equipment: full face piece respirator, full body cover, gloves.
	Exposure to resins may cause irritation of eyes, nose, throat and skin, allergies and asthma.	H	M	Y		Personal protective equipment: safety glasses, gloves, long sleeves, mouth respirator (depending on resin).
Epoxy / resins	Flammable. Some resins may (when combined) have an exothermic reaction.	M	H	Y		Dispose of resins in appropriate manner (organised by university). Adhere to maximum amount of resin disposal in 1 batch.
Liquid nitrogen	Extremely low temperatures; cold burns, frostbite.	M	H	Y		Personal protective equipment: safety glasses, liquid nitrogen gloves.
	Loose flying dust or particles.	H	L		N	Personal protective equipment: safety glasses, mouth respirator (depending on material)
Production using power tools	Collision with power tool.	M	L		N	Safety culture in organisation: Operate machining equipment with care. Do not rush manufacturing.
Production using machining	Loose flying metal chips / particles.	H	L		N	Personal protective equipment: safety glasses, labcoat, working shoes.
Carrying heavy equipment	Potential energy of mass	H	M	Y		Personal protective equipment: working shoes.
Acetone / IPA	Highly flammable. Can irritate nose, lungs, hands.	H	L		N	Drip trays for large jugs. Keep working amounts of acetone or IPA dispensers. Wear nitrile gloves whilst using acetone/IPA.
Nitrocellulose	High energetic material, explosive hazard - may release high amount of energy (heat and flames) upon combustion	L	H		N	Use high energetic materials that display deflagration instead of detonation. Wear personal protective equipment when handling explosives (safety glasses). Measure and handle working quantities of NTC, not the full jar.
Flashpaper	Low energetic material	L	L		N	No control measure needed
E-matches	Low-hazard explosive - may release medium amount of energy (heat and sparks) upon ignition	M	M		N	Wear personal protective equipment when handling explosives (safety glasses). Discharge any static energy before handling e-matches. No phones on.

Severity / Likelihood matrix.

ID	Process step or part/subsystem	Potential failure mode	Severity	S	Likelihood	L	LxS
PPP_XX	**Part procurement/production**						
PPP_01		Incorrect stock material is ordered for casing	Structural failure of casing	4	Human error Documentation	2	8
PPP_02		Incorrect mesh size/material is ordered	Mesh fails during ignition, NTC is not fully burnt	3	Human error Documentation	3	9
PPP_03		Parts are made to incorrect size/tolerance	Higher risk of no ejection due to parts that are stuck	4	Inexperienced person Human error Technical specs incorrect	3	12
PPP_04			Underperformance due to increased friction	2		4	8
PPP_05			Difficult integration, slight damage due to sharp edges	1		4	4
PPP_06			Leakage occurs as seals cannot function	4		3	12
PPP_07		Casing has production errors	Lowered max. burst pressure, Structural failure of casing	4	Inexperienced person Human error Documentation	3	12
PPP_08		Casing gains damage upon mold release (fibres)	Lowered max. burst pressure, Structural failure of casing	3	Violent mold release, use of LN, difficult CFRP mold	2	6
PPP_09		Casing gains damage upon mold release (gelcoat)	Increased friction of casing	3		3	9
PPP_10		Pyrotechnic materials degradation	Gas generator charge does not ignite, or underperforms	4	Incorrect storage (moisture, duration)	3	12
PPP_11		Minor health hazard during production (cuts, scrapes)	Minimal harm to people	2	Human error Inexperienced person Unclear protocols on PPE use Time pressure	5	10
PPP_12		Major health hazard during production (carbon fibres in lungs)	Medium harm to people	4	Unclear protocols on PPE use, no PPE available, "Do something quickly" without PPE	3	12
PPP_13		General health hazard due to incorrect disposal of chemicals	Minimal harm to people	2	Inexperienced person Laziness Unclear protocols	2	4
SAI_XX	**System assembly & integration for test or launch campaigns**						
SAI_01	**Part preparation**	Operator performs insufficient part preparation (cleaning, deburring)	Underperformance due to increased friction	2	Lack of preparation, diligence Tight assembly time	5	10
SAI_02			Difficult integration, slight damage due to sharp edges	2		5	10
SAI_03		Incorrect parts used (wrong fasteners/tape/O-rings...)	Underperformance (various)	2		4	8
SAI_04		Incorrect assembly due to wrong tools	Underperformance (various)	2		4	8
SAI_05	**Pyrotechnic preparation**	Ignitor bolt is not leak tight	Underperformance in low pressure environments	3	Insufficient epoxy applied to squib/ignitor bolt (top)	4	12

Severity / Likelihood matrix.

ID	Process step or part/subsystem	Potential failure mode	Severity	S	Likelihood	L	LxS
SAI_06		Squib head closed off from charge	No ejection due to no ignition of charge	4	Excessive epoxy applied to squib/ignitor bolt (bottom)	2	8
SAI_07		Squib leads (cables) shunt as insulation is damaged during assembly	No ejection due to shunting of circuit	4	Damage insulation whilst routing squib cable through bolt	3	12
SAI_08		Squib fires unintentionally	Minimal harm to people	2	ESD	2	4
SAI_09		NTC charge fires unintentionally	Medium harm to people	4	Spontaneous combustion	1	4
SAI_10		Ignitor bolt thread fails	Ignitor bolt breaks during ascent. Ignitor bolt does not fire into charge.	4	Lack of quality control in parts Overtorquing of part	3	12
SAI_11		Gas generator is slightly underfilled (2-5% less than intended mass)	Slight underperformance	2		3	6
SAI_12		Gas generator is significantly underfilled (>5% less than intended mass)	Underperformance, potential failure to eject	4	Measurement equipment incorrect. Operator not paying sufficient attention. Rush, time constraints. (Underfilling: not all NTC pellets placed inside GG)	2	8
SAI_13		Gas generator is overfilled (2-5% more than intended mass)	Slight overperformance	2		4	8
SAI_14		Gas generator is overfilled (>5% more than intended mass)	Overperformance, potential structural failure of casing	3		2	6
SAI_15	**Canister assembly**	Different parachute is used than during (qualification) tests	Significant system under- or overperformes due to large change in compressibility	4	System is used on different missions without additional tests	5	20
SAI_16		Parachute is packed differently than during (qualification) tests	Slight system under- or overperformes due to minor change in compressibility	3	Lack of dress rehearsals, no detailed procedures, or inexperienced member. Inherent variability of the parachute subsystem.	4	12
SAI_17		Parachute is packed differently than during (qualification) tests	Parachute subsystem entangles upon deployment	3		4	12
SAI_18		Sabot is placed slightly skewed	Sabot jams, no ejection.	4		3	12
SAI_19		Sabot is placed upside down (change in plenum volume)	Slight over- or underperformance	3	Lack of dress rehearsals, no detailed procedures, or inexperienced member.	3	9
SAI_20		Insufficient lubricant is applied to sabot	Additional friction, underperformance of system	3		3	9
SAI_21		Canister assembled with insufficient number of shear bolts	Underperformance due to lower pressure build up	3	Lack of quality control in parts Tight assembly time	3	9
SAI_22		Canister assembled with non-symmetrical distribution of shear bolts	Lid jams, no ejection	4	Lack of quality control in parts Tight assembly time	3	12
SAI_23		Sharp edges or loose fibres in canister (shear bolt holes, top rim)	Medium harm to people	4	Poor post-processing and quality control on CFRP canister, and/or repeated use induces damage	3	12
SAI_24	**General**	Assembly mistakes (execution of procedures)	Underperformance due to various reasons	3	Rush, time constraints	3	9
SAI_25		Assembly mistakes (execution of procedures)	Underperformance due to various reasons	3	Inexperience with system, ambiguity in procedures	3	9

Severity / Likelihood matrix.

ID	Process step or part/subsystem	Potential failure mode	Severity	S	Likelihood	L	LxS
SAI_26		Assembly mistakes (execution of procedures)	Underperformance due to various reasons	3	Overestimation of experience, not using procedures	3	9
SAI_27		Forgetting safety features / PPE / ESD checks	Medium harm to people	4	Rush, time constraints	2	8
SAI_28		Forgetting safety features / PPE / ESD checks	Medium harm to people	4	Overestimation of experience, 'doing something quick', repetitive tasks	2	8
SAI_29			Higher risk of no ejection due to parts that are stuck	4		3	12
SAI_30		Different sets of hardware do (not) fit together	Underperformance due to increased friction	3	Parts are not made to correct size, no quality control	4	12
SAI_31			Difficult integration, slight damage due to sharp edges	1		4	4
OPS_XX	**Final operations at test or launch campaigns (=arming and working with loaded system)**						
OPS_01		Catastrophical failure during test	Medium harm to people	4	Insufficient safety precautions (distancing, shielding)	3	12
OPS_02		Misfire of the mortar	Increased exposure to live system	3	Unreliable squib, firing line	4	12
OPS_03		Forgetting safety features in procedures (PPE, shunting, ESD checks)	Medium harm to people	4	Rush, time constraints	3	12
OPS_04		Forgetting safety features in procedures (PPE, shunting, ESD checks)	Medium harm to people	4	Overestimation of experience, not using procedures	3	12
OPS_05		Assembly mistakes due to rush, time constraints (forget RBF/incorrect arming/...)	No ejection	4	Rush, time constraints	4	16
OPS_06		Assembly mistakes due to overestimation of experience (forget RBF/incorrect arming/...)	No ejection	4	Overestimation of experience, not using procedures	3	12
OPS_07		Mortar firing whilst assembled in vehicle	Loss of vehicle systems	5	Safety feature skipped over	2	10
OPS_08		Launch site imposes different assembly/operational procedures or measurements which are unpracticed	Assembly mistakes and/or forgetting safety features in procedures	3	Miscommunication, unfamiliarity with system, different views on safety	3	9
OPS_09		Launch site operator treats live system as safe	No use of PPE and/or attention to ESD, increased risk to unintended firing and harm	3	Insufficient communication about system status	3	9
OPS_10		Launch site operator/client/other launching parties are not aware of system danger	No use of PPE and/or attention to ESD, increased risk to unintended firing and harm	3	Insufficient communication about system, no location to perform dangerous assembly steps	3	9
OPS_11		Launch site operator does not adhere to safety precautions set by launch provider	Decreased use of PPE and/or attention to ESD, increased risk to unintended firing and harm	3	Disagremeent about correct safety precautions, insufficient communication on protocols	3	9
OPS_12		Launch provider does not adhere to safety precautions set by launch site operator	Decreased use of PPE and/or attention to ESD, increased risk to unintended firing and harm	3		3	9

Severity / Likelihood matrix.

ID	Process step or part/subsystem	Potential failure mode	Severity	S	Likelihood	L	LxS
OPS_13		(No ignition of electric matches) Pyrotechnics are live and armed during retrieval operations	Medium harm to people	3	Insufficient power, battery. Vehicle did not reach correct state to initiate parachute deployment (issues with sensors, timers, breakwires). Vehicle breakup during flight.	3	9
CS_XX	**Canister**						
CS_01		Structural failure (radial burst) of canister	No ejection and damage to other subsystems	5	Significant overperformance of GG, experienced pressure surpasses design pressure	2	10
CS_02				5	True burst pressure of canister lies below the design pressure or experienced pressure	3	15
CS_03				5	Canister cannot withstand repeated application of design pressure (cyclic loading)	3	15
CS_04		Failure of glue joint between CFRP canister and attachment ring	Canister disattaches, shoots back into vehicle. Debris might hit parachute	4	Insufficient (and inconsistent) strength of glue joint	4	16
CS_05		Structural failure of canister during ascent	Parachute exits mortar prematurely, may damage other subsystems	5	Canister cannot withstand acceleration/vibration loads during ascent	2	10
CS_06		Structural failure of attachment point during ascent	Parachute mortar disconnects and moves freely in sounding rocket. May induce damage to other subsystems.	5	Insufficient (and inconsistent) strength of glue joint	2	10
CS_07		Shear bolt holes damaged	Shear bolts weakened due to sharp edges, leading to slight underperformance	3	Poor post-processing and quality control on CFRP canister, and/or repeated use induces damage	4	12
IG_XX	**Ignitors**						
IG_01		Ignition signal is not received from electronics subsystem	No parachute ejection	4	Damage to the cabling. No signal is given by electronics subsystem (see INT_04).	4	16
IG_02		Squib malfunctions	No parachute ejection	4	Squib malfunctions	2	8
IG_03		Delay in firing	Late parachute ejection, risk of parachute malfunctioning	3	Signal propogation delay throughout cable. Delayed sensor detection (for example, due to slow pressure propagation through vehicle).	2	6

Severity / Likelihood matrix.

ID	Process step or part/subsystem	Potential failure mode	Severity	S	Likelihood	L	LxS
IG_04		Squib fires before intended deployment moment (during re-entry)	Early parachute ejection, risk of parachute malfunctioning	3	Incorrect sensor readout or state switching	2	6
GG_XX	**Gas generator**						
GG_01			No ignition, no ejection	4	Leaks in plenum volume during ascent, pressure in plenum volume <35mbar	2	8
GG_02			Ignition, significant underperformance (>10% reduction in pressure), may result in no ejection	4	Leaks in plenum volume during ascent, pressure in plenum volume 35mbar-0,5bar	3	12
GG_03			Ignitionm underperformance (<10% reduction in pressure)	3	Leaks in plenum volume during ascent, pressure in plenum volume 0,5-1bar	4	12
GG_04		Charge does not (fully) ignite or underperforms	No ignition, no ejection	4	Squib does not touch charge	2	8
GG_05			Underperformance	3	Charge is too dispersed	2	6
GG_06			Nominal performance, few loose NTC pellets	1	Mesh shears out	5	5
GG_07			Underperformance	3	Lower temperature inside plenum volume upon ignition	2	6
GG_08			Slight underperformance	2	Charge is slightly underfilled	3	6
GG_09			Underperformance, possibly no ejection	4	Charge is significantly underfilled	2	8
GG_10			Overperformance	2	Charge is slightly overfilled	4	8
GG_11		Charge overperforms	Structural failure of canister upon deployment	3	Charge is significantly overfilled	2	6
GG_12			Overperformance	2	Increased burn surface area due to vibrational load breaking up pellets	2	4
GG_13		Cannot withstand pressure during ignition	Structural failure of GG, no parachute deployment	4	Gas generator thread is significantly damaged and prone to shear out.	1	4
SB_XX	**Sabot**						
SB_01		Sabot moves down and plenum volume increases due to acceleration during ascent	Change in performance (unknown)	3	Vibration loading, available volume due to low parachute pack density	2	6
SB_02		Sabot jams during parachute ejection	No ejection	4	Sabot wedges itself sideways	3	12
SB_03		Increased friction during parachute ejection	Slight underperformance	2	More/less vaseline applied during assembly. Different O-rings used or damaged. Different CFRP canister (smoothness)	3	6
SB_04		Decreased friction during parachute ejection	Slight overperformance	2		3	6
SB_05		Sabot collides with parachute (pack) after deployment	No successful parachute inflation	3	Sabot is ejected from mortar, in the same direction as parachute assembly	4	12

Severity / Likelihood matrix.

ID	Process step or part/subsystem	Potential failure mode	Severity	S	Likelihood	L	LxS
SB_06		Hot gases and particles leak past sabot during ejection	Damaged parachute	3	O-rings do not close off well	2	6
LD_XX	**Lid & shear bolts**						
LD_01		Lid has insufficient momentum to pull the parachute from its bag (extraction)	No successful parachute inflation	3	Mass or ejection velocity of lid is too low	2	6
LD_02		Lid has insufficient momentum to pull the parachute from its bag (extraction)	No successful parachute inflation	3	Momentum (mass * ejection velocity) of lid is too low	4	12
LD_03		Shear bolt(s) do not fail	No ejection	4	Shear bolts not properly loaded (assembled under an angle, or too much distance between tube and lid)	1	4
LD_04		Lid/shear bolts release during ascent, early release of parachute in vehicle	Parachute exits mortar prematurely	4	Shear bolts or lid cannot carry the load of the parachute assembly during ascent	1	4
LD_05		Lid/shear bolts release during re-entry, early deployment of parachute	Early parachute deployment, leading to potential entanglement, inversion or increased reaction loads	3	Thermal loading	1	3
EC_XX	**Endcap**						
EC_01		Structural failure of the endcap during ascent, decrease of plenum volume	Change in performance (unknown)	2	Endstop cannot carry the load of the parachute assembly during ascent	1	2
INT_XX	**Interfaces between mortar and supporting systems**						
INT_01		Natural frequency of mortar hardware or subsystem is low and resonates with rocket	Inertial coupling of sounding rocket, full vehicle breakup	5	Natural harmonic behaviour of the system, depending on materials, mass distribution and moving parts	2	10
INT_02			Fysical damage to parachute mortar system due to high amplitude vibrations at resonance frequencies	5		2	10
INT_03		Packing density of the parachute subsystem is higher than during ejection testing	Overperformance of the system	3	Lack of dress rehearsals, no detailed procedures, or inexperienced member. Inherent variability of the parachute system.	4	12
INT_04		Packing density of the parachute subsystem is lower than during ejection testing	Underperformance of the system, possibly no ejection	4		4	16
INT_05		No ignition signal is given from the electronics subsystem	No ejection of the parachute	4	Bad connections causing momentary power loss or system reset, faulty or damaged electronics component, general software bugs, sensor triggers for deployment set incorrectly (pressure, acceleration, timers, etc.), battery power low	4	16

Severity / Likelihood matrix.

ID	Process step or part/subsystem	Potential failure mode	Severity	S	Likelihood	L	LxS
INT_06		Recovery bulkhead (mortar attachment point) fails upon parachute ejection	Damage to the recovery bulkhead. Impact depends heavily on specific design.	3	Higher reaction load than expected (GG overperformance), assymetric distribution of load, dynamic load case different from static	3	9
INT_07		Parachute entanglement during ejection	Unsuccessful parachute inflation	3	Complex interaction between parachute pack movement due to the mortar ejection and aerodynamics during descent	4	12

Severity rating scale - safety	Severity rating scale - performance		Likelihood rating scale	
Significant harm/damage to people/property	Complete system failure, loss of vehicle system(s) before re-entry	5	Almost certain (has occurred regularly in DARE and/or during mortar tests)	5
Medium harm/damage to people/property	Complete system failure, no parachute ejection	4	Likely (has happened on occasion during mortar tests)	4
	Successful ejection but underperformance **or** risk of unsuccessful parachute inflation (damage/debris/entanglement)	3	Moderate (exact or similar incident has happened sometimes in DARE)	3
Minimal harm to people (cut, scrape, etc.)	Slight underperformance or overperformance	2	Unlikely (has not yet happened in DARE, but similar incidents happened in other DreamTeams, TU Delft, or other student rocketry teams)	2
No harm/damage to people/property	Nominal system performance	1	Rare (no known occurance)	1

L	S	1 Insignificant	2 Minor	3 Significant	4 Major	5 Severe
5	Almost certain	GG-06	PPP-11 SAI-01, 02		SAI-15	
4	Likely	PPP-05 SAI-31	PPP-04, SAI-03, 04, 13 GG-10	SAI-05, 16, 17, 30 OPS-02 CS-07 GG-03 SB-05 LD-02 INT-03, 07	OPS-05 CS-04 IG-01 INT-04, 05	
3	Moderate		SAI-11 GG-08 SB-03, 04	PPP-02, 09 SAI-19, 20, 21, 24, 25, 26 OPS-08, 09, 10, 11, 12, 13 INT-06	PPP-03, 06, 07, 10, 12 SAI-07, 10, 18, 22, 23, 29 OPS-01, 03, 04, 06 GG-02 SB-02	CS-02, 03
2	Unlikely		PPP-13 SAI-08 GG-12	PPP-08 SAI-14 IG-03, 04 GG-05, 07, 11 SB-01, 06 LD-01	PPP-01 SAI-06, 27, 28 IG-02 GG-01, 04, 09	OPS-07 CS-01, 05, 06 INT-01, 02
1	Rare		EC-01	LD-05	SAI-09 GG-13 LD-03, 04	

Multi Criteria Analysis (MCA)	Failure mode	Effects (severity)	RPN	Risk treatment	New RPN	Risk reduction percentage	Risk reduction absolute	Cost: time (hours)	Cost: money (€)	MCA rating	Comments
Multipliers:							**0,0080**	**12,33/cost**	**11,3/cost**		
SAI_03	Incorrect parts used (wrong fasteners/tape/O-rings...)	Underperformance (various)	288	Detailed parts list, documentation, procedures	180	0,38	108	3	5	7,23	Replace incorrect parts
~~SAI_16~~	~~Parachute is packed differently than during (qualification) tests~~	~~Slight system under- or overperformes due to minor change in compressibility~~	~~343~~								
SAI_17	Parachute is packed differently than during (qualification) tests	Parachute subsystem entangles upon deployment	343	Integrated ejection testing	245	0,29	98	30	25	1,65	
SAI_18	Sabot is placed slightly skewed	Sabot jams, no ejection.	270	Include check in procedures	162	0,40	108	1	0,5	35,79	
SAI_29	Different sets of hardware do (not) fit together	Higher risk of no ejection due to parts that are stuck	270	Quality control on parts & dress rehearsals	162	0,40	108	8	5	4,67	1 hour of quality control 1 in 8 parts has to be remade 1x dress rehearsal 3hrx2p
SAI_30	Different sets of hardware do (not) fit together	Underperformance due to increased friction	280	Quality control on parts & dress rehearsals	168	0,40	112	8	5	4,70	""
PPP_02	Incorrect mesh size/material is ordered	Mesh fails during ignition, NTC is not fully burnt	270	Evaluate different meshes during ejection tests	168	0,38	102	20	25	1,88	
PPP_03	Parts are made to incorrect size/tolerance	Higher risk of no ejection due to parts that are stuck	315	Quality control on parts & dress rehearsals	189	0,40	126	8	5	4,81	""
PPP_04	Parts are made to incorrect size/tolerance	Underperformance due to increased friction	280	Quality control on parts & dress rehearsals	168	0,40	112	8	5	4,70	""
PPP_06	Parts are made to incorrect size/tolerance	Leakage occurs as seals cannot function	324	Quality control on parts & dress rehearsals	162	0,50	162	8	5	5,10	""
PPP_10	Pyrotechnic materials degradation	Gas generator charge does not ignite, or underperforms	315	Test of gas generator ignition before launch	135	0,57	180	4	5	6,78	
~~GG_01~~	~~Charge does not (fully) ignite or underperforms~~	~~No ignition, no ejection~~	~~315~~								
~~GG_03~~	~~Charge does not (fully) ignite or underperforms~~	~~Ignition underperformance (<10% reduction in pressure)~~	~~343~~								
~~CS_07~~	~~Structural failure of attachment point during ascent~~										
~~SB_01~~	~~Sabot moves down and plenum volume increases due to acceleration during ascent~~	~~Change in performance (unknown)~~	~~252~~								
SB_02	Sabot jams during parachute ejection	No ejection	315	Ejection tests with flight HW	180	0,43	135	20	25	2,15	
~~INT_01~~	~~Natural frequency of mortar hardware or subsystem is low and resonates with rocket~~	~~Natural frequency of mortar hardware or subsystem is low and resonates with rocket~~	~~280~~								
~~INT_02~~	~~Natural frequency of mortar hardware or subsystem is low and resonates with rocket~~	~~Natural frequency of mortar hardware or subsystem is low and resonates with rocket~~	~~280~~								
~~INT_03~~	~~Packing density of the parachute subsystem is higher than during ejection testing~~	~~Packing density of the parachute subsystem is higher than during ejection testing~~	~~294~~								
~~INT_04~~	~~Packing density of the parachute subsystem is lower than during ejection testing~~	~~Packing density of the parachute subsystem is lower than during ejection testing~~	~~343~~								
INT_06	Recovery bulkhead (mortar attachment point) fails upon parachute ejection	Damage to the recovery bulkhead. Impact depends heavily on specific design.	294	Integrated ejection testing	150	0,49	144	30	25	2,02	
						Average:	124,58	12,33	11,29166667		

B
Interviews with experts

This appendix contains the transcripts from the interviews conducted with two experts on parachute mortar systems: Al Witkowski and Charles Lowry. Lastly, the interview is added which was conducted to assess the objectivity and quality of the research questions.

Parachute mortar interview 1

Date: 05-04-2023.
Interviewer: Esmée Menting, Delft University of Technology. Notation: EM.
Interviewee: Al Witkowski, Katabasis Aerospace, LLC. Notation: AW.

Profile interviewee:
Al Witkowski is a renowned aerospace engineer with over 30 years of experience in the field. He is an expert in the design and development of mortar systems that deploy parachutes on space vehicles. Al has worked on various spaceflight projects throughout his career, including NASA's Mars Exploration Rover (MER), Mars Science Laboratory (MSL), and Phoenix mission, and has (co)authored several scientific papers on technologies in the field of Entry, Descent and Landing (EDL). With his expertise in the field, Al is a valuable source of information and insights into the challenges and opportunities of a parachute mortar system. He is the founder of Katabasis Aerospace, an engineering firm that specializes in developing innovative solutions for the aerospace industry and consulting on aerospace projects.

Introduction

EM: Within DARE (student rocketry group) we use a small pyrotechnic mortar system to deploy drogue parachutes of our sounding rockets. This system has been developed over the last ~4 years and flew on a high-altitude mission (SPEAR) last November, successfully deploying the parachute. However, due to the restricted project timeline the main focus was put on realising a functional system, there was not a lot of time to perform any risk management or make it more reliable. Because there are more DARE teams/missions that want to use the system, I'm working in my thesis to review the existing system and reduce the present risks such that it can be used safely and reliably in the future.

AW: And you're going to scale it. Likely it'll be altered for a bigger/smaller parachute in new missions.
EM: True – we already see some teams putting smaller chutes in the current mortar tube, leading to a variable packing density. It's likely that they will also adjust the size of the mortar in the future.

General information

EM: Which missions that you have worked on (or with) used a mortar system for parachute ejection?
AW: Almost every single one. It's easier to say that there were about 3-4 that I did not work on, mainly some military missions. Nearly all spacecraft missions use a parachute mortar because they're going supersonically, and you want to have the parachute ejected behind the wake of the vehicle. This can be done by a mortar or tractor rocket. Both options have pros and cons, but most space craft projects in NASA prefer to use heritage systems, so therefore most missions stuck with the mortar system. Even if in some cases the tractor rocket may have been a better solution, the advantage of an existing system outweighed the technical benefits.
Most commercial companies (incl. Aviation safety resources) are considering tractor rocket deployed parachute systems for aircraft and/or for VTVL vehicles (quadcopter type vehicles). If you don't have a lot of altitude and airspeed, it is best to do it with a tractor rocket as it then also becomes your pilot chute.
For supersonic missions you're generally using a pyrotechnic system, either a mortar or tractor rocket. For large missions such as capsules in human spaceflight, using a mortar to deploy a pilot chute is advantageous over other mechanisms. When considering UAVs, they have a lot of forward airspeed so in these cases a hatch can be deployed which pulls out a parachute. But this doesn't work very well in low density or supersonic velocities.

EM: Within DARE we also struggled with this question. How important is design heritage? How heavy should you weigh it?
AW: to move away from a heritage system, the advantages of a new system must be overwhelming, or provide a tremendous business case where you distinguish yourself as different. Heritage allows you to skip a part of verification and qualification activities as they have already been done before. This saves a lot of time and cost in the project.

EM: In other subsystems you do see these changes sometimes, where they move to a new design.
AW: yes, but even then, there are usually only small changes. Multiple incremental adjustments that move away from the original heritage system.

EM: Moving back to the projects you've worked on. Which functions did you have in these projects? What kind of responsibilities or tasks did this include with respect to the mortar system?
AW: specifically mortar systems? EM: yes.
AW: in the first 10 years of my career, it was part design, part test/analysis/development, and a part program management. For the last 20 years it would be mainly program management and more directing. Now within my consulting career I mainly advise and critique.

EM: Can you tell me a bit about the general development of the mortar system in these projects and the main challenges you encountered?
AW: for the big Mars systems we chose to use a subcontractor which was an ordinance company (General Dynamics Ordnance and Tactics Systems).
Here the challenge is that you have to come up with specification for all the requirements incl. acceptable ranges. Then you manage the subcontractors to keep within schedule/budget. For the risk management part, that means: if there is a problem during development and/or qualification testing, when something goes wrong, discuss if and how to tackle the problem. As a developer, in the past you could more easily build your mortars (or air mortars for ground testing) and test regularly.

AW: The general approach for a mortar design is as follows. Each parachute there is a minimum/maximum range of the ejection. Too fast; way too high snatch forces. Too slow; any crosswind will prevent deployment. You have to calculate this and then figure out what fits in the volume and come up with an acceptable design. There are rules of thumb on acceptable L/D ratios. Sometimes you have to go out of this range. For example: the genesis solar probe had a very short stubby mortar, which has a high reaction force when they fire and they are inefficient. Developing this was a challenge. We were supplied with the ordinances (a little pill) from a company, but developed the rest of the gas generator (GG), mortar tube, lid, etc. ourselves.

EM: Did you mainly use a charge with loose powder/pellets or did you use a solid propellant grain?
AW: Genesis, the little pill I mentioned, was a charge with powder. There are also grains. "Ball propellant" also more like small grains. These choices result in a different time to peak pressure. You can also buy a COTS gas generator (GG). We regularly use a NASA standard initiator (NSI). This will produce 700psi in a 10cc closed bomb – for a small mortar this is already enough.
EM: did you always use an additional charge next to the NSI?
AW: We used one system, that was similar to the NSI, in 1990, which had 4 pins (electrical connection) and a similar output to a NSI. In this case the mortar just ran on the single initiator. It was tested but never qualified in flight.

AW: We also developed a system that works on cold gas for one of the X-planes (small remotely piloted one). They have a flight termination system (FTS) that they did not want ordinances in it and it had to be reusable.

EM: We've also used a cold gas system before in DARE but moved to pyrotechnics due to mass and volume savings. Have you ever encountered other cold gas systems? What are other pros/cons of this system?
AW: No, the problem is what you've just said. It requires a pressurized tank. Allocation space is always a challenge. Then there is "space" space – the tank has to be robust in the flight/re-entry/vacuum environment. We did once make a tractor rocket system based on cold gas – basically a bottle rocket – to pull out the parachute.

Risk management process applied to the mortar system

EM: In the full development cycle of the mortar system (design, production, testing etc.) how prominent was risk management in the project? How was the general approach towards that?
AW: we didn't really have a formal risk management program. We had more of a risk management culture, and it was more organic. It was inbred into the mindset of everyone throughout the full project. By always having multiple back-up plans, looking at things that can go wrong. It wasn't formalized, but very prominent.

EM: In DARE it is also more informal, was wondering how this was in other organizations.
AW: nowadays it is more formalized, you have to in order to be certified to certain standards. Now it is formalized by default. Which may be a better thing, because people can always make mistakes, and getting more people to look at it (as people are reviewing the documents made) can always help. It's a lot of work but there is definitely a benefit.
Especially with safety, everyone has their own set of experiences, and brings their own perspective to what is going on, even if they do not have a specific technical knowledge/expertise. They will still come up with relevant questions that will make you think of new points.

EM: How did your organisation/team identify and/or assess risks on the parachute mortar (sub)system? Did you apply certain risk identification methods or tools?

AW: we did, but not formalized. When you design a parachute system, you have to make a crude selection of your materials and overall design, which is then all based on high margins. As the design gets more fleshed out, these margins are lowered. Throughout this process you already think about risks that can come up. If my analysis turns out to be wrong, what am I going to do? In the proposal phase of the project, you also come up with potential other solutions on a cost and schedule base. If you come across a design which is stronger or overdesigned, you keep it in your bucket, and know you can go back there if your original design is not strong enough.

EM: Within these risk assessment methods, did you mainly perform quantitative or qualitative analyses? Did you or your team have a preference or priority for one of these methods? Why?

AW: we performed quantitative performance and structural analyses, for example simulating the heat expansion and gas expulsion in the mortar system. But we did not do quantitative risk analyses. You were just talking about the less dense parachute pack, we also encountered problems with that. Friction is another problem with mortars, you don't know what it is. You have to guess, and usually put a large range on that. It's qualitative within quantitative methods.

AW: There is a qualitative assessment of risk. After a while you have a general idea of how much a Mars mortar system will cost in terms of money and time. If you design your project, I can calculate the number of hours and people and compare it to past projects.

EM: How did your team establish a level of acceptable risk?

AW: Experience. That's fully qualitative. Unless, you have good confidence in your calculations and in your margins. And you can show: if this risk were to come true, we're still going to meet the minimum functional requirements, so we do not mitigate it. That's so rare in the parachute industry though, that it is mostly based on experience. It does happen occasionally. Not so much with mortars, but the parachute system in total, for example with joints or the structure of the parachute.

EM: can you think of examples of accepted risks on the mortar?
AW: No. Some non-mortar ones yes, but not for the mortar.

EM: is this perhaps inherent to the mortar system? That most risks cannot be accepted because there is no 'middle ground' functioning below the nominal operations that is still acceptable.
AW: you might accept the risk that your deployment may be faster. That you can still calculate, do tests to quantify the effect, and evaluate whether the increased snatch forces are acceptable. You would accept a higher velocity but not lower velocity.

EM: What is the (rough) ratio between accepted risks versus risks that undergo mitigation steps?
AW: most of them are tackled. In terms of a mortar system you have to mitigate them in most cases. There are maybe some, regarding the material finish etc., that can be accepted. But in terms of performance or structure there are few that you would not mitigate.

EM: How did your team document the risk management throughout the project? Given it was more informal, this was perhaps not the case?
AW: documentation is poor for most of the projects I worked on. There was very limited time and resources available to spend on documenting, and there also was no good system in place, in part due to the more organic organization structure. This means that important lessons learnt on "a risk arose and was mitigated", were not properly documented. I'm now working on re-writing these items together with NASA to keep this information.

EM: Do you have an example of how risk management influenced the design of these mortar systems?
AW: The mortar on the Mars exploration rover (MER). This was originally planned to have the same parachute and mortar size as on Mars pathfinder. But the rover mass got too big, so the parachute size and therefore mortar size had to increase. Because of the space allocation, the mortar had to become a very skinny thin-walled tube. Eventually the structure of the mortar was insufficient for the dynamics of deployment and parachute opening, and we fixed that by attaching the back-shell of the craft to the mortar.
EM: how was this issue spotted/risk identified?
AW: this was pretty clear by analysis. We had a mortar subcontractor, who informed us that we were thinning the walls so much that this issue would arise during firing. The risk was identified by the subcontractor. We worked together as a middleman between mortar subcontractor and JPL.

Risk identification and assessment of mortar systems

EM: What were the main risks identified on the mortar systems functionality in flight? (Top 3-5) in multiple projects.
AW: the mortar system is/has a gas generator that generates a reaction force that pushes out the pack in a velocity range. The risks are mainly in the transient pressure vessels of the GG (20.000-30.000 psi), and your mortar tube (250-500psi) – (numbers are very rough ballparks). The "typical mortar system" has an L/D ratio of 1.75-2.25, muzzle velocity 32-42 m/s, and deployment at Mars. Your GG design must be robust to those pressures, contain propellant, have adequate hermetic sealing (pass a helium leak check). Choices on propellant based on long vs. short range missions.

AW: Some of the main risks are then;

- GG doesn't withstand leak check, can't withstand pressure, bad routing of the initiator to start it, is too heavy.
- Mortar tube cannot withstand a certain load, cannot contain the parachute.

EM: is there a difference between components in terms of having a higher risk?
AW: The sabot is typically fairly simple. The tube and GG provide the biggest risks.

EM: What if mass optimisation is not a problem? What risks drop or become more prominent?
AW: if mass is not a problem, the tube is not so much of a challenge. For example: Mars pathfinder, insight, phoenix, etc., all have the same mortar tube which is fairly robust. The GG was updated based on supply source, but it wasn't changed from an overall design perspective.
In that sense the GG has the highest remaining risk.

EM: What were the main "hazards" or "accident scenario's" that were identified?
What were the main risks identified on the operator's safety during assembly/integration/testing activities on the mortar system?

AW: absolutely, this was certainly considered. It's a projectile – like stepping in front of a gun. When it has initiators, static discharge is a risk, when the initiators are not in, it is relatively safe (no matter if the GG is inserted in mortar system).
When the initiators are in, it has to be grounded, shorted, and the area in front of the mortar needs to be cleared. Sometimes hearing protection is needed as some mortars can be quite loud. Eye protection is used against burning particulates, if you are standing somewhat close. Stand at a safe distance.
EM: what distance did you usually observe during mortar tests?
AW: this varied on a case-to-case basis. For MSL we were quite far away as it used a lot of propellant. At a subcontractor we used a location in a bunkhouse. Even though this was not strictly necessary it was available on location.
For smaller mortar systems maybe 30ft, whilst standing behind something. A large distance is mainly relevant in the development phase, as in the qualification phase you are pretty convinced that it's going to do what it's supposed to do. For tests in the open air, the safe distance was determined by whatever reach the parachute system has.

EM: Were most risks identified at the start of the project, or during the testing or production phase?
AW: you are accounting for certain risks during the proposal phase. You account for different risks during development. The risks change as the project mature. Safety risks are identified during test planning and preparation.

EM: Are you familiar with any sounding rockets that use mortar systems for parachute deployment?
AW: there is a paper in the 80s where they did atmospheric soundings and it used a mortar system. They tried some weird stuff with DGBs. PEPP and ASPIRE all used mortars.

EM: Would you recommend certain risk management methods or design philosophy for mortar systems on sounding rockets?
AW: in the case of the ones for NASA, these missions aimed to test the parachute. If you're not doing that, you're recovering to bring back the device or the instrumentation. You would use the exact same design guidelines or risk management posture for all other mortars. The PEPP test bed and ASPIRE were all parachute tests, so they really altered the rocket to meet the parachute requirement. The mortars were specifically designed for the mission.

Parachute mortar interview 2

Date: 05-04-2023.
Interviewer: Esmée Menting, Delft University of Technology. Notation: EM.
Interviewee: Charles Lowry, Airborne Systems. Notation: CL.

Profile interviewee:
Charles Lowry is an experienced aerospace engineer with over 15 years of practice in the field. He is an expert in the design, testing, and implementation of parachute mortar systems. Charles has worked on a variety of spaceflight projects, including NASA's Mars2020 mission and various crewed capsules such as Orion, Dragon, and New Shepard. He is currently associated with Airborne Systems, a company that specializes in developing parachute systems for military and space applications. With his extensive knowledge on mortar systems in spaceflight, Charles is a valuable source to gain insight into the design and testing of parachute mortars.

Introduction

EM: Within DARE (student rocketry group) we use a small pyrotechnic mortar system to deploy drogue parachutes of our sounding rockets. This system has been developed over the last ~4 years and flew on a high-altitude mission (SPEAR) last November, successfully deploying the parachute. However, due to the restricted project timeline the main focus was put on realising a functional system, there was not a lot of time to perform any risk management or make it more reliable. Because there are more DARE teams/missions that want to use the system, I'm working in my thesis to review the existing system and reduce the present risks such that it can be used safely and reliably in the future.

General information

EM: Which missions that you have worked on (or with) used a mortar system for parachute ejection?
CL: most of all space missions have a mortar system. It's just the most reliable way to get a parachute out. We'll get into that later.
Mars2020: airborne did not develop the mortar but we were involved in the development. Orion, all the Artemis systems, there are 5 mortars on that (for 2 drogue parachutes and 3 pilot chutes). All capsule systems – blue origin, SpaceX Dragon. We've worked on all of these mortars. There is a ton of different uses, these are just the big ones. There are lots of small space companies around us with missions on the SpaceX rideshare programs, who use mortars that are closer in size to the one you're talking about. Mortars in the base principle are very simple: it's a tube, with some way to create pressure. They're actually pretty straightforward. [Shows example mortar system].

EM: Can you tell me a bit about the gas generator (GG) on this mortar?
CL: This gas generator is an off-the-shelf model that Airborne has a lot of. Procuring a gas generator for spaceflight is hard to do and takes a long time – the lead time might be a year. We now have 200 of these GGs in stock at any time. This mortar has 2 ports in the bottom, one for the GG and one for a pressure measurement.

EM: This gas generator is smaller than the one used in DARE (in a similarly scaled system). How do you select the GG size?
CL: When you design mortars, you have a lot of requirements, and the power to influence the vehicle in a very bad way through reaction loads. If you have a more powerful, fast GG this results in a high reaction load.
EM: So then the aim is to balance between the reaction load and other design parameters?
CL: Yes, and you have more things to balance than just ejection velocity and reaction load. Can also play with the pyrotechnic or exchange it for a cold gas system.

EM: Have you used cold gas systems before?
CL: Yes, we have. EM: what is your experience with it?
CL: It will never be lighter. Pyrotechnics are the most energy efficient (energy/mass ratio). You need a lot more volume to store gas. And in a lot of cases you need a pyro valve anyway for reliable and fast actuation.
EM: Are there any other advantages besides 'no pyro'? In case no pyro valve is used.
CL: in general, cold gas system has a much lower reaction load. It is also much easier to calculate the functioning of a cold gas system than pyrotechnics.
EM: For pyrotechnic systems, do you calculate it (simulations/analysis), or mainly rely on testing?
CL: We mainly rely on testing for the pyrotechnic side.

EM: Which function(s) do/did you have in these projects? What kind of responsibilities or tasks did this function include with respect to the mortar system?
CL: For Mars2020 I was lead project engineer. With regards to the mortar system, we did 20 or so mortar tests or supported them. Here we installed the parachute system, followed the procedures, and got out of the way for the actual GG installation and final check-outs.
We've also done a lot of our own mortar testing here. For this we get a lot of explosives training, we also have a yearly class with explosives handling training and refresher training.
EM: Who participates in these trainings?
CL: All engineering staff, the parachute packing department, anyone who has exposure to explosives. It's mostly awareness training, not practical on wiring etc. For example, information on what PPE you need to wear, what not to touch.
EM: That's very interesting, haven't heard about such a training before.
CL: There are multiple industries that have this kind of training, like construction (for dynamite) and the military.
EM: Do you organise this in-house or hire a company?
CL: There is a 3-4 day training class provided by an outside company, and then there are people trained inside the company that do refresher trainings.

EM: Can you tell me a bit about the general development of the mortar system in these projects and the main challenges you encountered?
CL: mortars are pretty simple and most of the development that's done on them is early on. Determining the propellant characteristics; how much output does it have. You really have to understand the requirements of your mission. The main challenges is not "can we design a mortar that shoots the parachute out" but more about deploying in specific environment. For example for Dragonfly: we deploy at 70K, in a methane rich environment, the GG has to be in space for 7 years and cannot outgas, whilst it gets hot and cold a certain number of times. It's pretty easy to say "let's use this cartridge" that we have used before, but then you have to think about all these environments that are not easy to replicate. Main challenges is how to simulate the environment.

EM: What do you measure during the GG tests? Pressure, temperature?
CL: During closed bomb tests, we're mainly looking at pressure, not even temperature. You may take the chamber to a specific temperature to evaluate how it works when it's cold/hot. Mainly interested in the pressure profile. Early on risk reduction consists of: does this propellant work, and in does it work in the relevant environments?

EM: When looking at the pressure profile, do you have a preset curve in mind?
CM: Then you're looking for a total impulse, pressure over area over time. How much force do I need to get the parachute out at X velocity? You want to get to this velocity gradually, basically want to reach this right before the sabot exits the tube. Then you have a goal for the burn rate, and you try to match that.

EM: What kind of parameters in the GG design do you tweak with the most?
CL: We use the same propellant for each device. You put the propellant through a chamber, can change the size of the pellets/grains, and you can finetune by changing the orifice.

CL: Here there is this big range of acceptable risk, what do you test, what do you focus on? You have to choose; maybe this reaction load is 4kN and with 4 months of development you can get it down to 3kN, which might not be worth it, so you choose not to do it.

EM: the "burn rate goal" presumes you know the friction and/or force needed. Do you have models or test data for this?
CL: You have a mass that you want to move, and you need to do work on that mass. You have the rivets to keep the lid, and that takes perhaps 200pounds to break. After that you have an entire mortar length to do work. You have friction along the tube, but if you can put the sabot in by hand this should be OK. How much friction is that in the grand scheme of things? Every time the GG will burn differently, +/- 10%. The fact of rivets, friction, etc. then don't make that much of a difference anymore.

Risk management process applied to the mortar system

EM: How did your organisation/team identify risks on the parachute mortar (sub)system?
Did you apply certain risk identification methods or tools? Were certain methods more/less useful?
CL: This is a really complicated topic. Airborne is a subcontractor – we're not designing our own rocket. The risks that we identify are only a small part of a very big risk program that a client might have on a really large mission.
We have to do an FMEA and we keep a risk register, we continuously maintain these registers. In my opinion, this information on risk management is mostly used to communicate to management what they should be spending their money on. At a mission level, let's say they have 1$B to spend. Some of it is towards building the product, keeping the staff, and then 200$M for testing. Checking the hardware to see if it meets the requirement. They essentially have these different pieces of the spacecraft, and they need to divide this budget based on what people communicate as present risks. It's really complicated, because to me the highest risk might be "I don't know how my mortar will work in cold environments", so I want to test this, and it'll cost 20$M. If they are more worried about other risks, the money will also go there. They have all kinds of experts that also observe and evaluate this. In a lot of cases, they don't make the decision based on your review of the risk.
EM: Then you also may see that subteam X might overstate their risks to get more budget to test.
CL: Yes, because no one wants to make the system that fails in the end. Risk is just really: where are you putting your funds now. The highest risk gets the most money.
If you are a student team, and you don't have money, you will have high risk. This is also acceptable, because you're not blowing up a 10M$ project on the pad. It's such a sliding scale, and we see that all the time. A customer might say: we want to use a parachute that has already been tested and a mortar that has flight heritage. Or a customer does not want to spend money on test campaigns, so if the system fails during flight, they take the responsibility (and risk). Whilst we, as a company, have a recommended test program for parachutes and mortars when putting it in a system. If they want to change that it's OK – but it needs to be clear up front.

EM: You mentioned that you perform FMEA on your systems. When looking at examples, I encountered two variants: one that reviews each part in the system, and one that reviews process steps. Which do you use?
CL: I don't do the analysis myself, but it is based on the components. We have each component listed out and then all risks are registered – from material acquisition to end of life.

EM: How did your team establish a level of acceptable risk?
CL: As project engineer I approach it differently than how a systems engineer would do it. I look at all specifications and requirements that the customer has given me, and I look at my verification matrix. For mortars, if the requirement is: you eject at this altitude/temperature/dynamic pressure/planet, you mortar needs to eject the parachute at an acceptable velocity. We need to determine the acceptable deployment velocity range ourselves.
When you do a verification/validation matrix, you need to say “I am meeting this requirement” by test, heritage, analysis, or demonstration. Demonstration is kind of like tests, but for a bit lower priority risk, indicating I’m OK with verifying this requirement through one of the more extensive system level tests than a separate ground test.
I review it by: which requirements are really important for success, which ones do we not have heritage for, do I not trust analysis for, and which one do I not want to demonstrate in flight.
Unfortunately – for most things on parachutes, analysis is not good enough, especially inflation in the supersonic realm. For mortars, I cannot tell you how much loading we have or granulates we need, when working on a new system. On these aspects I want a lot of testing to be done. If the mortar doesn’t work – it’s game over.
But some other requirements, like you don’t want to eject any FOD (foreign objects and debris), this is OK by demonstration.
EM: So like a sabot capture net?
CL: This would be a different requirement, as in a lot of cases this is critical for the parachute functioning. FOD is more like break ties or pieces of TPS that would fly away.
Also evaluate risks by reviewing; for which requirements would I be really nervous on a launch day? What do I want to worry about for 7 years?
EM: Do you sometimes worry multiple years about these risks?
CL: There is always something on which you’re like; did we do this right? Did we test this enough?
EM: Some level of stress before the launch. We also had this for our last launch in November.
CL: The stress is the human side of risk management. That’s the difficult thing of risk – it’s fear based. Everyone has different fears. It is also probability based, but how to determine that? How many tests do you need to do to establish a correct probability?

EM: How did your team evaluate the identified & assessed risks against this level?
CL: In a qualitative way, by reviewing with the team.

CL: One last thing, that I’m sure you’ve addressed, regarding mortars and how to reduce their risk. Explosives are pretty deterministic, if you ignite them, they explode (unless degradation, moisture, vacuum environment). In flight the absolute biggest risk by many orders of magnitude is that it never receives a signal to fire. Some other part of the system does not initiate it.
And issues with initiation – this is why you always, on any flight system, see two initiators. A lot of those initiators have two bridge wires in them. In total 4 separate circuits in the spacecraft will fire that mortar. Your test program is based on verifying that this redundancy works.

EM: What is the risk that the initiator does not work?
CL: This heavily depends on the initiator. The ones we use now are a couple thousand euros each.

EM: In the current design we do have 2 initiators that are actuated separately.
CL: that’s good. For a project like yours, if I’m the mortar designer, I’d pay a lot of attention to the electronics team, to ensure that they have a good design and qualification.

In addition to the semi-structured qualitative interview, Charles Lowry has also submitted written answers to the prepared interview questions. These can be found below.

General information

Which missions that you have worked on (or with) used a mortar system for parachute ejection?

Many- Mainly Mars 2020, CPAS/ORION, currently Dragonfly.

Which function(s) do/did you have in these projects? What kind of responsibilities or tasks did this function include with respect to the mortar system?

Project engineer, lead. Support engineer in some cases. Mortar test support, mortar integration & Testing. Explosives handling

Can you tell me a bit about the general development of the mortar system in these projects and the main challenges you encountered?

Mortars are fairly simple devices. Pyrotechnics generate pressure that is then used to push out the parachute pack. Early development is based on selection of the propellant and determining the propellant loading needed to meet the design goals. The environment that the mortar will be used in determines the type and loading of the propellant. The environment also determines the need for sealing of the gas generator.

Risk management process applied to the mortar system

In the full development cycle of the mortar system (design, production, testing etc.) how prominent was risk management in the project?

Risk management plays a huge role in the development of the project as it determines the design. Most systems require redundant initiation. What this means is that two initiators are required to ignite the propellant charge. These initiators are often fired by two separate circuits. Some initiators can be fired by two circuits themselves, so you can have four separate channels that can initiate the propellant.

The testing that is completed is essentially ensuring that the system functions if the designed in redundancy is utilized. Example, fire one initiator to see if the performance is the same. AIAA S-113A-2016 specifies the testing required for explosive devices. 80/120% testing important.

How did your organisation/team identify risks on the parachute mortar (sub)system?
By comparing specification environments with current test data. If there is a mismatch then testing is needed to buy down risk.

Did you apply certain risk identification methods or tools? Were certain methods more/less useful?

FMEA. Best way to chase down risks is to follow the testing specs and do the expensive testing. Best way to track risks in this case is a V&V matrix. Tracks requirements against your methods of verification.

Within these risk assessment methods, did you mainly perform quantitative or qualitative analyses?

For risks, we assess them qualitatively. We do not spend much time diving into the statistics and probability of failure. From a technical standpoint, we typically verify performance of a mortar system with a mixture of analysis, heritage, and test. Analysis shows us that a mortar will perform

slightly different on Mars than Earth due to a number of factors. We take those into account, but still conduct testing to verify that the mortar is doing what we would expect it to do on earth. Heritage shows us that that methodology of verification is adequate.

Did you or your team have a preference or priority for one of these methods? Why?

Test is always preferred, analysis comes in second. Relying on heritage alone is dangerous. As far as risk management goes, our method of tracking risks via a risk register or FMEA is helpful to keep track of risks. Its biggest function is relaying to Management the importance of testing.

(In case quantitative methods were applied): how did your team collect input data for this analysis?

It isn't usually applied, since mortar shots and parachute tests are very expensive. We typically don't have enough chances to test to get decent reliability data.

How did your team establish a level of acceptable risk?

Acceptable risk in many cases is relative to the riskiest portions of the program. In practice, money reduces risks. If there is a riskier part of a program elsewhere, the money will go to it instead. Risk posture is determined by the contract. In some cases, it is ok to fly a untested unit. In other cases, you would never fly a unit that hasn't undergone 20+ tests. It all comes down to system value and the risk posture of the entire program. If it is human rated, our answer changes and we will make sure that each mortar system is very well understood and tested, no matter what our customers ask.

How did your team evaluate the identified & assessed risks against this level?

Testing.

What is the (rough) ratio between accepted risks versus risks that undergo mitigation steps?

1:10-20?
Example: We accept that the mars atmosphere is different than Earths.

How did your team document the risk management throughout the project?

Weekly risk updates presented to customers. Risk Register documenting all risks and their probability as well as impact to the program.

Do you have an example of how risk management influenced the design of these missions?

Some systems choose to heat their mortar components so that they are in similar environments to past missions.

Risk identification and assessment of mortar systems

What were the main risks identified on the mortar systems functionality in flight? (Top 3-5)

1. **No Signal Received**
2. **Retention of parachute not adequate**
3. **Poor performance due to environment**

What were the main risks identified on the operator's safety during assembly/integration/testing activities on the mortar system?

1. **Inadvertent firing**

Which activities did you undertake to address these risks?

1. **Proper grounding/bonding**
2. **Antistatic garments & wristbands**
3. **Zero voltage checks on firing lines**
4. **Lockout procedures on firing system (Keys held by multiple operators)**
5. **Weather checks (lightning)**
6. **No cell phones**

What differences do you think are most prominent between risk management of mortar systems in interplanetary/human spaceflight missions versus mortar systems on sounding rockets?

Redundancy & Verification of Redundancy

Would you recommend certain risk management methods for mortar systems on sounding rockets?

Qualification testing of mortar in a cold environment. Only 2 or so needed to verify that ejection velocity is met.

Evaluation of Parachute mortar interview

General information

T: Which missions that you have worked on (or with) used a mortar system for parachute ejection?

- Stratos III, IV and SPEAR. Stratos III was a cold gas system and Stratos IV and SPEAR were pyrotechnic systems.

T: Which function(s) do/did you have in these projects? What kind of responsibilities or tasks did this function include with respect to the mortar system?

- For Stratos IV I was managing the recovery team, so supervising the members that were designing the mortar system. For SPEAR I was mainly involved with production and testing, so more the day-to-day activities for the development of the system.

T: So you did a bit of both, the overview/managerial part and working on it yourself? E: yes.

T: Can you tell me a bit about the general development of the mortar system in these projects and the main challenges you encountered?

- The main challenge was the strict timeline in which we tried to develop the system. This constrained a lot of testing efforts and led to our focus on creating a functional system. Besides this, we regularly had issues with our data acquisition system. It also did not have our highest priority at that time but in retrospect more data would have been very valuable.

Risk management process applied to the mortar system

T: In the full development cycle of the mortar system (design, production, testing etc.) how prominent was risk management in the project?

- It was not very conscious. More throughout the design and discussing which tests to do. We did adjust the design and perform quite some tests to evaluate or mitigate different risks.

T: were you able to use lessons learnt or methods from other (similar) projects in your organisation?

- Throughout Stratos III we encountered similar issues during testing, especially on the data acquisition system. However we had limited improvements on this during the new projects, so I guess we did not learn enough from the earlier failures.

T: How did your organisation/team identify risks on the parachute mortar (sub)system?
Did you apply certain risk identification methods or tools? Were certain methods more/less useful?

- We did not specifically do risk identification. It was sometimes done during the design phase or when discussing tests. This did lead us to focus quite a bit on one risk that we found important, whilst others were only identified later on in the project.

T: Would you have done this differently in hindsight?

- Yes, include a risk identification process. Elaborate a bit more on the assessment as well.

T: How did your organisation/team assess risks on the parachute mortar (sub)system?
Did you apply certain risk assessment methods or tools? Were certain methods more/less useful?

- We used a risk matrix (probability/severity) for some risk assessment as we were obliged to submit this to the launch provider. On the technical aspect this was quite limited. On the safety/operational aspect this was more elaborate. It worked OK for us, an easy method to evaluate different risks.

T: Is this a common approach in your industry/company?

- Yes the risk matrix is used quite often in DARE and the industry.

T: Within these risk assessment methods, did you mainly perform quantitative or qualitative analyses? Did you or your team have a preference or priority for one of these methods? Why?

- We only performed the qualitative analysis, as we didn't have any input or the time/knowledge to perform quantitative analyses.

~~(In case quantitative methods were applied): how did your team collect input data for this analysis?~~

T: How did your team establish a level of acceptable risk?

- We didn't. Not really anyway. The acceptable level of risk was primarily determined by the available resources. When we saw that a lower pressure in the plenum volume led to underperformance, we could not research and quantify this further due to limited time. Therefore it was accepted that, as long as the parachute did deploy, it was possible that the ejection velocity was lower than required.

T: How did your team evaluate the identified & assessed risks against this level? (Not applicable)

T: What is the (rough) ratio between accepted risks versus risks that undergo mitigation steps?

- As mentioned, we did not really actively identify all risks. All the risks that were not probable or severe enough were not really documented or reviewed. If I had to give an estimation, and we would take all these risks into account, for about 1/10 or 1/8 risks we either redesigned or tested for the risk.

T: How did your team document the risk management throughout the project?

- We had to submit our documentation every few months to the launch provider, which included the risk matrices that we made.

T: Did this documentation reduce the risk of knowledge loss in case of a team handover?

- Maybe a bit. It's a good start, but practical experience is also very important. Documentation by itself isn't enough.

Do you have an example of how risk management influenced the design of these missions?

- In order to keep the plenum volume at 1bar pressure, it was sealed as much as possible during assembly, by O-rings and Teflon tape. Besides this, it was originally the idea to use a canister that had been tested many times. However, when we saw that the carbon fibre got damaged after a few fires around the shear bolts, we decided to use a new canister for the launch that had only been tested once.

Risk identification and assessment of mortar systems

T: What were the main risks identified on the mortar systems functionality in flight? (Top 3-5)

- Plenum volume leakage leading to underperformance of the gas generator or no ignition at all.
- Structural failure of the CFRP canister due to difficult production process, inexperienced members in CFRP production and no structured quality control.
- That the bridle lines would obstruct the parachute subassembly from shooting out of the mortar. All mortar tests were done without parachute line attachment to the test bench, so the full parachute assembly was ejected. During launch assembly I was concerned the bridle lines would block the deployment path.

T: Were most risks identified at the start of the project, or during the testing or production phase?

- The plenum volume risk and some others were identified at the start or during the design. A number of them, amongst which the CFRP canister issues and bridle line blockage, were only observed during the production/testing/integration phases.

T: Do you think it is possible to identify most risks at the start of the project, or do they only appear later on?

- I think it depends on the experience of the team members. If we were to redo the risk identification process now, I think we could include more risks than we identified at the start. So a more experienced team will identify risks earlier on in the development cycle.

T: What were the main risks identified on the operator's safety during assembly/integration/testing activities on the mortar system?

- That the pyrotechnic charge would be ignited when connecting the ignitors to the launch box during testing.
- The charge igniting due to ESD (electrostatic discharge) at Esrange.
- Radial burst failure of the mortar tube during a test, ejecting a lot of (small) debris in all directions.

T: Which activities did you undertake to address these risks? (already discussed).

T: What differences do you think are most prominent between risk management of mortar systems in interplanetary/human spaceflight missions versus mortar systems on sounding rockets?

- Required reliability and available resources are far higher for interplanetary or human spaceflight missions. Everything for sounding rockets is much smaller. So there will be much less analyses and tests for mortars on sounding rockets.

T: Would you recommend certain risk management methods for mortar systems on sounding rockets?

- Any risk identification method would already have been better than none. For risk assessment, the matrix works well and was a really simple method to implement, but it feels a bit subjective.

T: Thank you for your time and information.

C
Mitigation activities

This appendix contains additional documentation on the various mitigation activities. Currently, it includes:

- Rocket Check Form (RCF) of PyRocket
- Updated procedures for PyRocket
- Visual parts list and visual support of procedures for PyRocket
- Test Specification and Test Procedures (TSTP) of the ESA vibration test campaign
- Test procedures (separate file) for the ESA vibration test campaign
- Test Readiness Review (TRR) for DUT1 and DUT2
- Post Test Review (PTR) of the full vibration test campaign

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Rocket Check Form (RCF)

This is the Rocket Check Form. This form should be filled in at the Rocket Check by the Rocket Check responsible under supervision of the present Safety Officer. This form has 3 outcomes, Go for launch, Conditional-Go or a No-Go. Measured rocket data and necessary changes are written up in this form.

NOTE: Measure center of gravity and all locations, from tip of the nosecone to the top of the element.

General rocket data

Launchday	SLD 2023 – 02		
Project/Team name	Pyrocket		
Project/Team leader	Esmee		
Rocket name	Pyrocket		
Rocket length [mm]	907	Rocket colour	Silver
Rocket mass [kg] (without engine)	3165	Apogee** [m]	1080
Center of gravity [mm] (without engine)	390	Rocket Cd* [-]	0.8

Safety data

Engine type	IRM
Position of engine [mm] (from tip to top of engine)	475
Rocket has other safety critical system	Mortar Pyro assembly order: -full mortar first + reefing system -then gas generator -pyrobolt to be attached before system assembly

Recovery data

Drogue/pilot parachute

Deployment method	Main parachute reefed				
Deployment time [s]	15.5	Parachute Cd* [-]	0.253	Production area [mm²]	0.792
Parachute type	Reefed ringsail	Parachute colour	Blue white		

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Main parachute					
Deployment method	Undoing reefing				
Deployment time [s]	25.5	Parachute Cd* [-]	0.64	Production area [mm²]	0.792
Deployment altitude [m]	time: 25.5	Parachute colour	blue-white		
Parachute type	ringsail	Flight time** [s]	90.0		

Launch Readiness

Go	x
Conditional Go	
No go	

Remarks:

Put arm switch on the outside of the rocket

Will put in camera cover, and perhaps put the riser in more nicely

*assumed value, **simulated value

Mortar Test Procedures

Test ID: Mortar-LC-02
(PyRocket)

Friday 12th May, 2023

Test Location:
ASK 't Harde
Eperweg 149
8084 HE

OSO:	______________
TC:	______________
TO:	______________
CP:	______________

Version: V4.1
Author: Esmée Menting

1 Changelog

Date	Version	Changes	Names
05-11-2019	V2.0	Adjusted full procedures to last test campaign	Esmée Menting
27-10-2022	V3.0	Adjust to SPEAR launch campaign, including feedback from Simon Westerlund	Esmée Menting
03-05-2023	V4.0	Adjust after procedures review	Esmée Menting
05-05-2023	V4.1	Adjust to be generic assembly procedures for launches and tests	Esmée Menting
10-05-2023	V4.2	Minor adjustments & JST crimps	Esmée Menting
Wednesday 10th May, 2023		Date of Download	

In case of emergency: (112 & +46706853804)

Low risk/priority	Medium risk/priority	High risk/priority
• Test-setup is safe to approach • No safety gear required	• Only authorized personnel in test area • Wear appropriate safety gear	• Clear all personnel from test area • Do not approach the test-setup

CP	Control Post	**OSO**	Operational Safety Officer	**TL**	Test Leader
DAQ	Data Acquisition	**PPE**	Personal Protective Equipment	**TO**	Test Operator
NTC	Nitrocellulose	**TC**	Test Conductor		

Overview of the Test

Purpose of the preparation:

- PyRocket launch: one parachute deployment by a mortar during flight.
- Mortar R&D: one or more mortar ejection tests.

ID	Project	Amount of NTC (g)	Number of nylon bolts	Canister
1	PyRocket	0.5	6	Aluminium
2	Mortar R&D	0.5	6	Aluminium

The system works by igniting nitrocellulose in the gas generator. This builds pressure. At a certain pressure the nylon bolts holding the lid on will shear and the sabot will be ejected along with the lid and the parachute.

Safety Considerations

The maximum pressure considering a combustion temperature of 2700 K is 66 bar assuming the sabot does not move at all. Once the gas cools down to 300 K the internal pressure will be 7.4 bar.

However 0.4 grams was enough to compress the parachute 52.6 mm. So assuming the the parachute compresses the same as in the last test and that the bolts do not shear, the max pressure will be 20.1 bar and 2.2 bar after it cools down. The pressure vessel is based off of Martin's BEM casing which yields (GG shear out) at 100 bar.

Equation 1 was used with values taken from proprop. The shear pressure was calculated to be about 1 bar per bolt according to Stratos III reports.

$$P = \frac{Mgas * Rsp * Tc}{V} \quad (1)$$

2 Preparations

Prep location:
Starting time:

			A - Collect tools and parts	
ID	**Check**		**Operation**	**Remarks**
System Status: • A table is made free for packing and preparation. Procedures are printed.				
A1			**Collect all the following parts:**	
A2			Canister	
A3			Gas generator bulkhead	
A4			O-rings for bulkhead	79.1mm diameter O-rings
A5			Snap rings 80mm	
A6			Endstop (3D printed ring)	
A7			Sabot	Small O-ring version
A8			O-rings for sabot	79.1mm diameter O-rings
A9			Parachute subasssembly	
A10			Lid	
A11			Nylon M4 shear bolts x6 (+ spares)	
A12			Gas generator	Large volume version (1cm deep internally)
A13			Ignitor bolt x2	Hex M8x10mm bolt with holes for e-match.
A14			Crimps [**type!!!**]	
A15			JST connectors [**type!!!**]	
A16			Pre-made shunts with JST connectors	
A17			Dummy ignitor bolt x2	Any Hex M8 bolt, preferably short (M8x10mm)
A18			Teflon tape	
A19			Ensure the following pyrotechnics will be present upon final assembly: flash paper, NTC, e-matches	Do not collect yet without OSO
A20			Mesh	Pre-cut to dimensions
A21			Retainer ring	Aluminium version
A22			Retainer bolts x4 (Hex socket head cap M3x6mm)	To close retainer ring
A23			Attachment bolts x4 (M8x120mm)	Depending on mortar attachment
A24			**Collect all the following tools:**	
A25			Scissors	
A26			Pen	
A27			Blue paper (for cleaning)	
A28			White paper (for pyro prep)	
A29			Vaseline	
A30			Acetone	
Continued				

ID	Check		Operation	Remarks
A31			Cutting pliers	
A32			Stripping pliers	
A33			Crimping pliers	
A34			Regular pliers	
A35			Pliers for 80mm snap rings	Ideally multiple
A36			Safety glasses x2	
A37			Hammer or rod	To push in/out sabot and bulkheads
A38			Snap ring groove fillers (3D printed half-ring, thin)	To insert bulkhead past snap ring groove
A39			Allen key for M3 bolts	
A40			Wrench 13 for M8 (ignitor) bolts	
A41			Small adjustable wrench for GG	Test-fit if it closes well around gas generator head
A42			Ratchet wrench 7 for M4 shear bolts	**Double-check size**, or
A43			Screwdriver with head that fits over M4 shear bolts	

			B - Part preparation	
ID	**Check**		**Operation**	**Remarks**
System Status: • The following required parts are present: • Gas generator x1, Ignitor bolts x2, Mesh x1, Retainer ring x1, M3x6 bolt x4 • GG bulkhead & Canister • Acetone, Nitrile gloves, Blue paper				
B1			Check ignitor bolts for sharp metal burs	
B2			See which mesh fits well onto the retainer ring. Prefit bolts.	
B3			Ensure grooves of the bulkhead and tube are not sharp	
B4			Check if O-rings are not damaged	
B5			Check that M8 threads of ignitor bolts and gas generator are okay	
B6			Check that M30 threads of gas generator (GG) and gas generator bulkhead are okay	
B7			Test fit gas generator into GG bulkhead	
B8			Clean gas generator using Acetone	Use nitrile gloves whilst cleaning
B9			Ensure lid is free of nylon shear bolts	
B10			Test fit nylon shear bolt into lid holes	
System Status: • Ready for pyro prep and assembly				

3 Pyro Prep

			C - Igniter bolt preparation	
ID	**Check**		**Operation**	**Remarks**
C1			Fill out time	Time:
			All personnel wear safety jackets, safety glasses, safety shoes, phones are off	
				
C2			Area is cleared of unnecessary personal	OSO & TO present.
System Status: • Table is clear aside from required parts and tools • Required parts are present: squibs, ignitor bolts, double-component epoxy, crimps, JST connector, pre-made JST shunt • Required tools are present: mixing spoon, multimeter, M8 nut, cutting pliers, stripping pliers, crimping pliers, regular pliers • Safety precautions are near by: Fire extinguisher, bucket of water & first aid kit				
C3			Notify others in workspace that pyrotechnic activities are being executed	
C4			Perform all steps below for the total number of ignitor bolts that should be prepared	
C5			Squib is unpacked	
C6			TO unshunts squib leads - Announce verbally -	= Untwisting squib leads (bare ends of electrical wires).
C7			Squibs are measured for resistivity	Should be around 1-3 ohms.
C8			TO shunts squib leads, confirms when finished	Shunting by twisting squibs leads.
C9			Remove the red plastic blast cap from the squib	
C10			Squib leads are led through hole in bolt, leave match head a bit above the bolt (3-5mm)	Insert squib leads from threaded end, pull through bolt head
C11			Check if the cable is not damaged/partly stripped	Mainly if the fit through the bolt is tight.
C12			Two part epoxy is thoroughly mixed	Mix quantity for 1 bolt, it dries quickly.
C13			Epoxy is applied thoroughly to the lead below the match head	Do not cover the top of the match head.
C14			Pull squib into final position (match head is fully inside the bolt)	Move back and forth / wiggle to ensure good spread of epoxy.
C15			Apply small amount of epoxy on top of hex head to cover hole fully	
C16			Wait for epoxy to dry, keep an eye on the match head not moving too much	
C17			Resistivity is measured between squib leads and bolt	Should not have electrical contact
Continued				

ID	Check		Operation	Remarks
C18			Check with M8 nut if the thread is free of epoxy	
C19			TO unshunts squib leads - Announce verbally -	Only for launches
C20			Cut squib leads to correct length	Only for launches
C21			Strip squib leads	Only for launches
C22			Apply crimps to squib leads	Only for launches
C23			Place JST connector on squib leads	Only for launches
C24			Place prepared shunt on JST connector	Only for launches
C25			Bolt is packed into a propellant box ready for transport or further assembly	
System Status: • Igniter bolts are finished and ready for transportation or further assembly				
C26			Fill out time	Time:

	D - Gas generator preperation			
ID	**Check**		**Operation**	**Remarks**
D1			Fill out time	Time:
	All personnel wear safety jackets, safety glasses, safety shoes, phones are off			

System Status:

- Table clear, printed procedures are present
- Required parts are present: Gas generator, dummy ignitor bolts x2 (M8x10-16 mm) flash paper, box of Nitrocellulose, mesh (pre-cut to size), retainer ring, retainer bolts x4 (M3x6mm)
- Required tools are present: Gas generator holder, small scale, sufficient sheets of A3 paper, scissors, pen, allen key 2.5 for M3 bolts, wrench 13 for M8 bolts
- Safety precautions are near by: Fire extinguisher, bucket of water & first aid kit

ID	Check		Operation	Remarks
D2			Perform all steps below for the total number of gas generators that should be prepared	
D3			Cut flash paper into circle shape of Gas generator bottom.	Use large hole in retainer ring as template
D4			Insert dummy ignitor bolts into gas generator	
D5			Place gas generator into GG holder	if present
D6			Place flash paper circles in gas generator	You can put two layers to cover it better
D7			Put retainer bolts through ring and mesh	
D8			Cut a piece of paper and fold double twice	Rough size 10x15 cm
D9			Tare scale	The piece of paper should be present whilst taring
D10			Pour in small bits of Nitrocellulose onto the folded piece of paper	.... grams NTC depending on test
D11			Pour NTC from piece of paper into the gas generator	
D12			Put away box of Nitrocellulose	
Continued				

ID	Check		Operation	Remarks
D13			Make little swabs of flash paper to fill up the remaining open volume	Fill up with flash paper and softly press down.
D14			Screw retainer ring and mesh on the gas generator using retainer bolts	The mesh should press down on the NTC slightly. Do not over-tighten.
D15			Place gas generator in anti-static bag	
D16			Place generator into pyrotechnic box	
D17			Fill out time	Time:

System Status:

- Gas generators is ready for transport and/or further assembly

4 Mortar assembly

Test location:	
Starting time:	

			E - Mortar canister assembly	
ID	**Check**		**Operation**	**Remarks**
E1			Fill out time	Time:
System Status: • All required tools and parts are present (see Preparations)				
E2			Place O-rings on the GG bulkhead	Apply vaseline over O-rings and bulkhead side
E3			Insert GG bulkhead into canister from the side with the snap ring groove. Orientation: the flat side (no attachment holes) enters first.	If needed, insert snap ring groove fillers
E4			Put on safety glasses and clear area as much as possible	Only for snap ring insertion
E5			Insert snap ring into snap ring groove	One member should hold the canister
E6			Push the GG bulkhead to the bottom	It should rest on the snap ring
E7			Place the endstop inside the canister on top of the GG bulkhead	
E8			Place O-rings on the sabot	Apply vaseline over O-rings and sabot side
E9			Insert sabot into canister, on top of endstop	The flat side should face the endstop
E10			Remove excess vaseline from the inside of the canister	Use blue paper
E11			Place parachute assembly into canister	
E12			Place lid inside canister, on top of parachute assembly	Align with shear bolt holes
E13			Fasten lid with shear bolts, spaced symmetrically	Number: ..... bolts.
E14			Tighten shear bolts until they are fully in	No need to apply high torque
System Status: • Mortar is assembled • Ready for final test/launch operations				

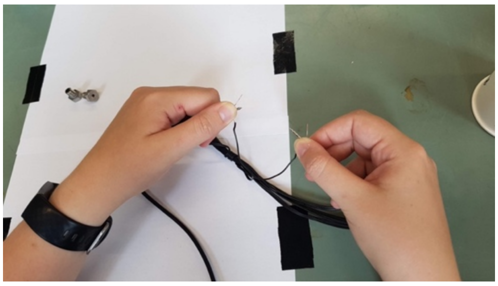
			F - Gas generator and ignitor bolt installation	
ID	**Check**		**Operation**	**Remarks**
F1			Fill out time	Time:
	All personnel wear safety jackets, safety glasses, safety shoes, phones are off			

Continued

ID	Check		Operation	Remarks
System Status: • Gas generator is fully prepared • Ignitor bolts are fully prepared • Mortar canister is fully assembled				
F2			Unpack gas generator.	
F3			Apply teflon tape to GG thread	2-3 layers, in the opposite direction of thread
F4			Screw gas generator into GG bulkhead	Ensure it is properly attached to the system, hand tighten with wrench
F5			Unpack ignitor bolts	Ensure squibs are still shunted
F6			Remove dummy bolt(s)	Check that the NTC has not leaked or come out
F7			Apply teflon tape to ignitor bolt threads	cut tape in half width, apply 2-3 layers in opposite direction of thread
F8			Screw ignitor bolts into the gas generator	
System Status: • All pyrotechnics are assembled • Ready for final test/launch operations				

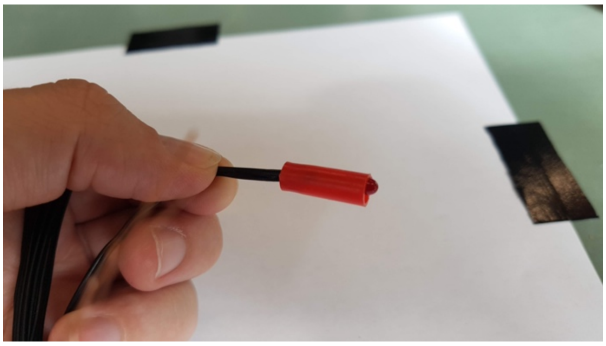
Mortar - visual assembly steps

Pyro prep – Ignitor bolts

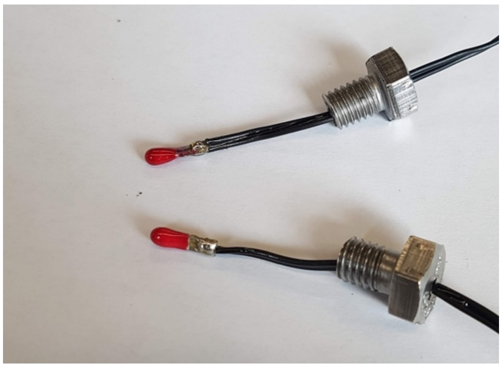


C7

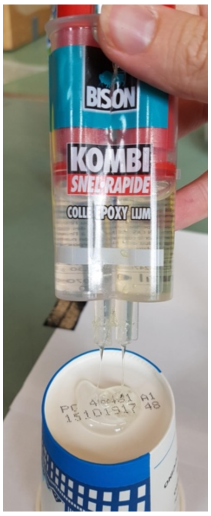
C7



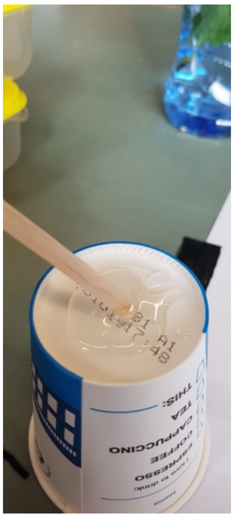
C9

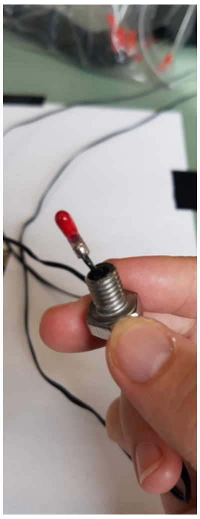


C10



C12





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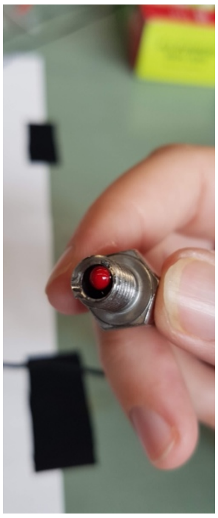

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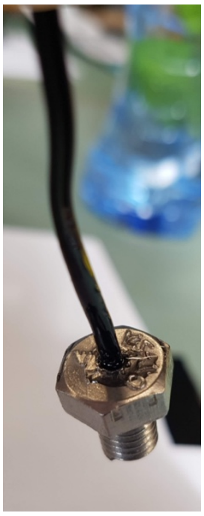
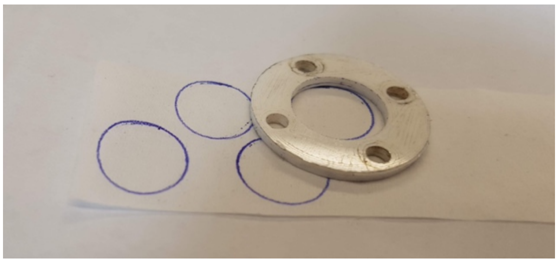
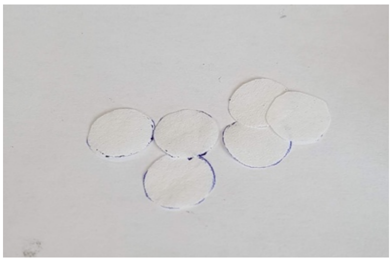


C15

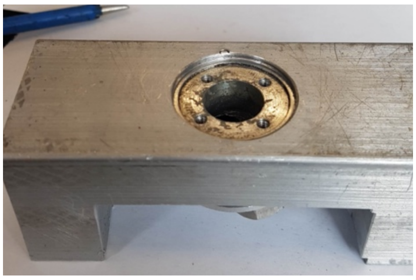
Pyro prep – Gas generator





D3

D4



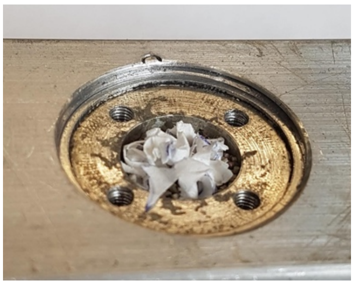
D5

D6

D9/D10

D11

D13



D13

D13

D14

Mortar - visual parts list


Endstop


O-rings

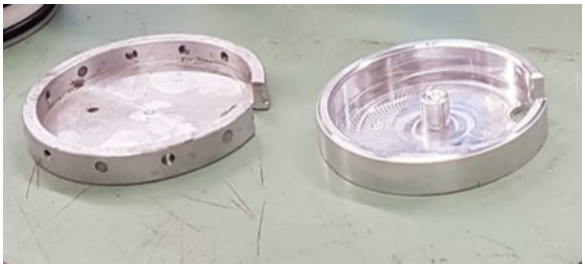

Shear bolts

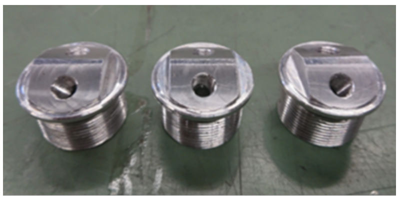

Sabot


Canister


Snap rings


Gas generator bulkhead


Lid


Gas generator


Ignitor bolts


Dummy ignitor bolts


Mesh


Retainer ring


Retainer bolts


Teflon tape

VIBRATION TEST SPECIFICATION & TEST PROCEDURES FOR THE PARACHUTE MORTAR [MOR_TSTP]

Prepared by Esmée Menting, team leader

Document Type	TSTP
Reference	Mortar system
Issue/Revision	V1.1
Date of Issue	31/05/2023
Status	

APPROVAL

Title	VIBRATION TEST SPECIFICATION & TEST PROCEDURES FOR THE PARACHUTE MORTAR [MOR_TSTP]		
Issue Number	V1.1	Revision Number	
Author	Esmée Menting, team leader	Date	14/05/2023
Approved By		Date of Approval	

CHANGE LOG

Reason for change	Issue Nr	Revision Number	Date
First draft version of test objectives	0	0	23/03/2023
First draft version of full TSTP (excl. procedures)	0.1		25/04/2023
Feedback from TSTP version included	1.0		26/04/2023
Minor adjustments after greenlight review	1.1		14/05/2023

CHANGE RECORD

Issue Number	Revision Number		
Reason for change	Date	Pages	Paragraph(s)

DISTRIBUTION

Loris Franchi / ESA ESEC

Gilberto Grassi / ESA ESEC

INTRODUCTION

This document describes the test setup and test procedures intended to use during the vibration test campaign in June 2023 on the DARE parachute mortar system.

Table of Contents

1. VIBRATION TEST SPECIFICATION & TEST PROCEDURES [VIBE_TSTP]

1.1. Introduction

This document describes the proposed test setup and test procedures for a vibration test of the parachute mortar system in June 2023. The document describes the test goals, requirements, test setup and procedures. A short description and picture of the mortar system are given below.

The parachute mortar is a short, smooth tube that is sealed at one end and is attached to the rocket. When the parachute needs to be deployed, an electrical signal is sent to a small explosive charge at the sealed end of the tube. The explosion propels the parachute out of the tube and away from the rocket. The charge consists of nitrocellulose pellets contained in a gas generator. The parachute assembly is contained by a lid with shear bolts, which break at a predetermined pressure in order to expel the parachute at the desired velocity. The parachute mortar has been regularly used in DARE, as mentioned above, but there is a need within the society to increase the system size in order to deploy larger parachutes to recover larger payload masses. A prototype of this new version has been created and test fired in 2022. Overall, there are still risks identified in the system that have not yet been mitigated, such as a pressure drop in the plenum volume during flight due to rocket vibrations. If the pressure in the plenum volume drops to a vacuum, testing has indicated that the pyrotechnic charge will not ignite. A pressure drop in the plenum volume, even if ‘only’ 0.5 bar, will still lead to a performance decrease of the system. To mitigate this risk, it is desirable to test the pressure seal of the mortar under the vibration profile of the rocket. The proposed test setup would include a mortar subsystem mounted on the vibration table, where it would undergo the vibrational spectrum of the REXUS qualification test. The primary test goal would be to verify whether the plenum volume (max. 1 bar > external pressure) maintains a steady pressure under the vibration profile of the rocket launch, or whether it leaks. This test will increase the TRL of the mortar system, allowing various DARE teams to integrate this system in more missions, without extensive additional testing efforts and therefore without major impact on their budget and timeline.

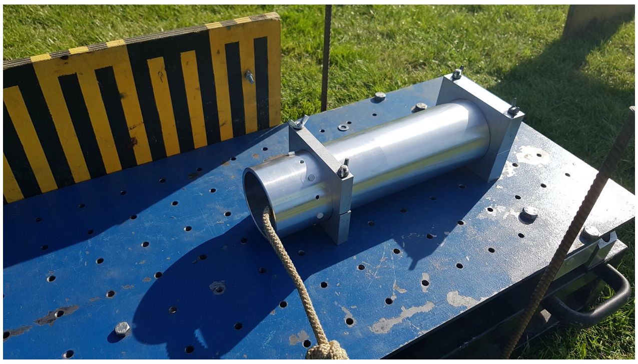


Figure 1 – Parachute mortar on test bench

1.2. Requirements Verification

The intended test focuses on the risk reduction of the parachute mortar subsystem. The main focus is therefore on mitigating the risk of plenum volume leakage (see MOR-04). Secondarily, the structural integrity and function of containing the parachute will be confirmed (MOR-01, MOR-02, MOR-03).

ID	Requirement
MOR-01	The parachute mortar shall contain the parachute subsystem during ascent and re-entry.
MOR-02	The parachute mortar shall withstand a minimal vibration load of 12.7 G_{RMS}.
MOR-03	The parachute mortar shall withstand a minimal acceleration load of 12 g.
MOR-04	The plenum volume shall have a maximum pressure drop of 0.1 bar whilst undergoing vibrations during ascent, at a maximum pressure differential of 1 bar.

Table 1 – Requirements intended to verify through vibration test campaign

1.3. Test Description

1.3.1. Test objectives

- Evaluate the risk of pressure leakage from the plenum volume due to vibrational loads experienced during ascent.
- Confirm the structural integrity of the parachute mortar, containing a parachute, under the vibrational loads experienced during ascent.

1.3.2. Test pre-requisites

The following pre-requisites shall be met before the start of the test campaign:

- All parts have been produced at least 1 week before the start of the test campaign.
- The plenum volume test setup has been assembled at least 1 week before the start of the test campaign, to confirm successful integration.
- The mortar system test setup has been assembled at least 2 weeks before the start of the test campaign, to confirm successful integration.
- The pressure sensor, used in the test setup, has been tested to confirm its functionality and test reading out the data.
- The compressor, including the adapters to the test setup, has been tested to confirm it can pressurize the plenum volume to 2 bar.
- System pressurization tests have been performed to establish no leaks occur when the system is assembled and the plenum volume is pressurized to 2 bar, without vibration loading.
- DUT1 and DUT2 have been test assembled onto the adapter.

1.3.3. Test requirements

- The plenum volume test setup shall be subjected to a leak test before and after each vibration test.
- [**Optional**] the pressure in the plenum volume shall be observed throughout each vibration test.
- The mortar system shall be mounted to the test adapter through its normal attachment points.
- Random vibration tests shall be conducted in launch configuration for all axes.

- In order to evaluate the integrity of the mortar test setup, a resonance search shall be performed before and after the random vibration test.
- The success criteria for the resonance search shall be (note: not a pass/fail criteria)
    - i. less than 5 % in frequency shift, for modes with an effective mass greater than 10 %;
    - ii. less than 20 % in amplitude shift, for modes with an effective mass greater than 10 %.
- Sinusoidal vibration tests shall be conducted in launch configuration for all axes, when requested by the launch authority.
- A resonance search shall be performed before and after the sinusoidal vibration test to determine resonance frequencies to evaluate the integrity of the mortar test setup.
- The success criteria for the resonance search shall be (note: not a pass/fail criteria)
    - i. less than 5 % in frequency shift, for modes with an effective mass greater than 10 %;
    - ii. less than 20 % in amplitude shift, for modes with an effective mass greater than 10 %.
- Detailed visual checks shall be carried out prior and after test to check for visual damage.
- The plenum volume pressure shall be checked out prior and after tests to ensure no leakage is present. In case of leakage, this shall be located, assessed, and possibly helped before a next test.
- The maximum acceptable levels for the induced cross axis accelerations at the attachment points shall be 10%.
- For the mortar test campaign, the following documents shall be produced when necessary: TSTP, minutes of test readiness and post-test review, photographs of test activity, vibration test report, functional test reports (if applicable).

1.3.4. Test Sequence

The following functional tests and inspections will be carried out before/after tests:

Plenum volume tests (DUT1):
- Visual inspections
- Measurement of pressure in the plenum volume
- (In case of a pressure drop) leak testing using leak detection spray or soap

Parachute mortar tests (DUT2):
- Visual inspections
- Measurement of spacing between gas generator bulkhead and sabot (only after all axes)
- ~~Centre of gravity measurement (optionally, needs to be tested whether this differs sufficiently to indicate a movement of parachute mass distribution)~~

Optional: final test with DUT1 including a sabot. The same test procedures and functional tests will be used as the original plenum volume tests.

Figure 2 – Mortar Vibration Test Campaign Flow

1.3.5. Test Item Description

There are two devices under test: a plenum volume test setup and a regular parachute mortar.

The first device under test consists of a small section of a mortar tube with the same inner volume as the plenum volume. It is closed off by two bulkheads: one bulkhead (bottom) which houses the gas generator and connection points, and one sensor bulkhead (top). Nearly all parts are made from aluminum, except for the snap rings and fasteners (steel) and the endstop (PLA). Note: the valve connecting to the compressor is not modelled in CAD.

A table with all part numbers and names can be found below the figures.

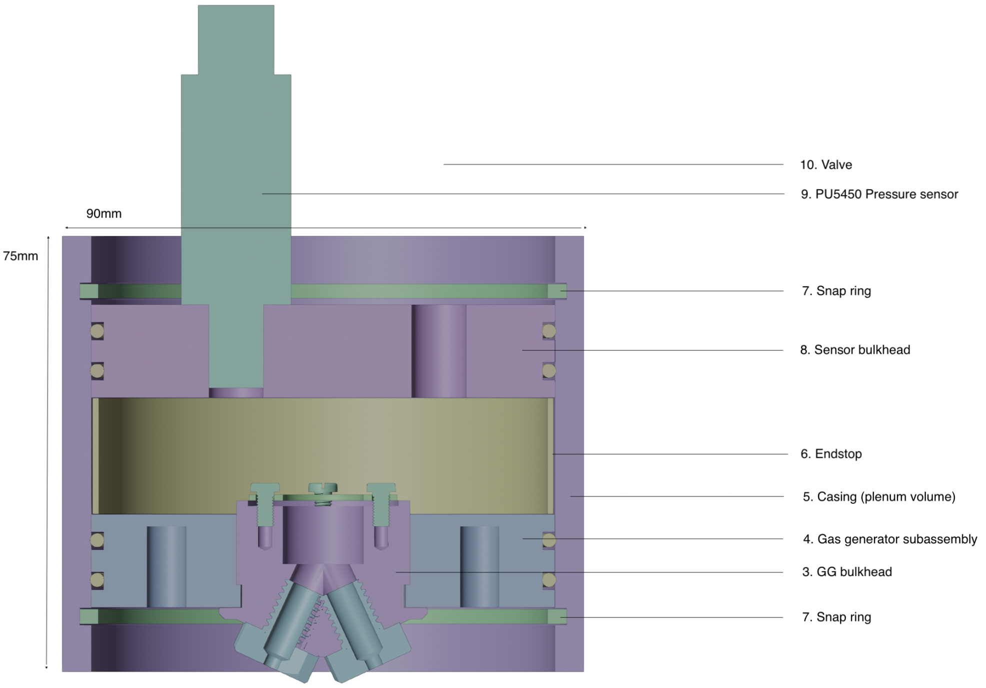


Figure 3 – Cut through overview of Plenum volume test object

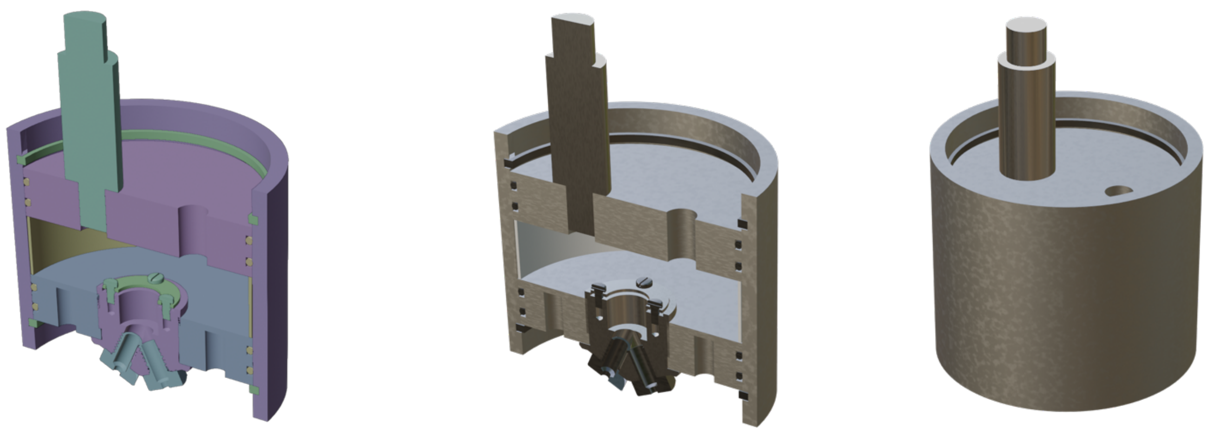


Figure 4 – Isometric views of Plenum volume test object

Part table of the DUT1 – plenum volume test object:

Part Nr.	Item	Unit mass [g]	# [-]	Total mass [g]
1	Armature		1	N.A.
2	Test adapter	1100	1	1100
-	M10x35 bolt	40	8	320
3	Gas generator bulkhead	166	1	166
-	M8x35 bolt	32	4	128
4	Gas generator subassembly	36	1	36
5	Canister plenum volume	250	1	250
6	Endstop	20	1	20
7	Snap ring	23	2	46
8	Sensor bulkhead	218	1	218
9	PU5450 pressure sensor	48	1	48
10	Valve	155	1	155
11	Connector valve – compressor tube	[tbd]	1	[tbd] est. 50-100
-	Total mass Total expected mass (incl. valve/PU5450)		-	2487 est. 2587

Table 2 – Part overview of DUT1: the plenum volume test object

The following items are connected to the sensor bulkhead:

- A PU5450 pressure sensor, connected by a 1m long cable to GSE.
- A valve connecting to an Airpress H215/6 compressor (max. pressure 8 bar).

Figure 5 – PU5450 sensor

Figure 6 – Valve

Figure 7 – Airpress H215/6

The following parts within the gas generator subassembly have a specified torque:

Part	Size [mm]	Applied torque [Nm]
Ignitor bolt	M8x10mm (hollow)	1Nm
Retainer bolt	M3x6mm	0.5Nm

Be very careful not to over-torque the ignitor bolt, as the threads can break. The 3Nm torque may be evaluated on site.

All connections to the sensor bulkhead will be torqued up to 2Nm and it will be evaluated whether this ensures sufficient tightness during leak testing. If leaks appear during (functional) leak testing before or after vibration tests, the torque level can be increased to evaluate whether this reduces the leaks.

The second device under test is the parachute mortar itself. This has the same GG bulkhead at the bottom but has a longer canister which houses a parachute assembly, and it is closed off by a lid at the top. Note: the parachute subassembly is not modelled in CAD. A table with all part numbers and names can be found below the figures.

Optional: the 'parachute cup' may be assembled to assess the change in resonance frequency.

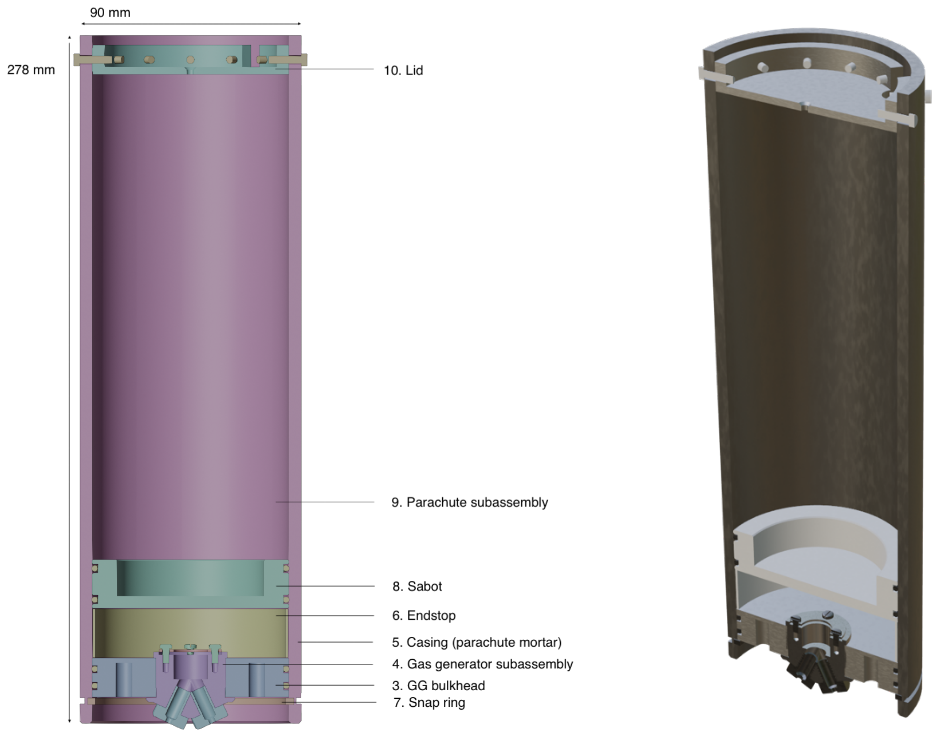


Figure 8 – Cut through overview and isometric view of Parachute mortar test object

Part table of the DUT2 – parachute mortar test object:

Part Nr.	Item	Unit mass [g]	# [-]	Total mass [g]
1	Armature		1	N.A.
2	Test adapter	1100	1	1100
-	M10x35 bolt	40	8	320
3	Gas generator bulkhead	166	1	166
-	M8x35 bolt	32	4	128
4	Gas generator subassembly	36	1	36
5	Canister parachute mortar	870	1	870
6	Endstop	20	1	20
7	Snap ring	23	2	46
8	Sabot	92	1	92
9	Parachute subassembly	500-750	1	500-750
10	Lid	46	1	46
-	Total mass		-	3324 - 3574

Table 3 – Part overview of DUT2: the parachute mortar test object

1.3.6. Test set-up description

The DUT(1/2) is attached to the adapter plate via 4x M8x35 bolts. The adapter plate is attached to the armature via 8x M10x35 bolts. A technical drawing of the adapter plate can be found in Appendix A. Specifications of the bolts can be found below:

Dimensions [mm]	Type	Applied torque [Nm]
M8x35 mm	DIN192	12
M10x35 mm	DIN192	20

Table 4 – Bolt specification

Images on the integration of DUT1 on the shaker:

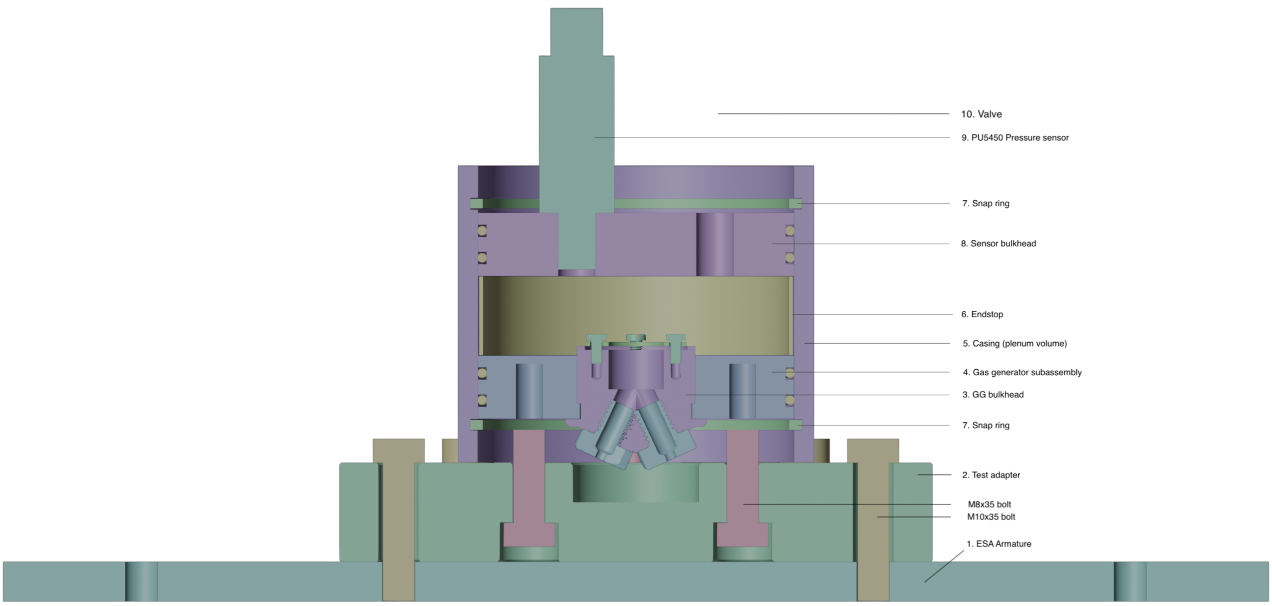


Figure 9 – Cut through overview of Plenum volume test setup

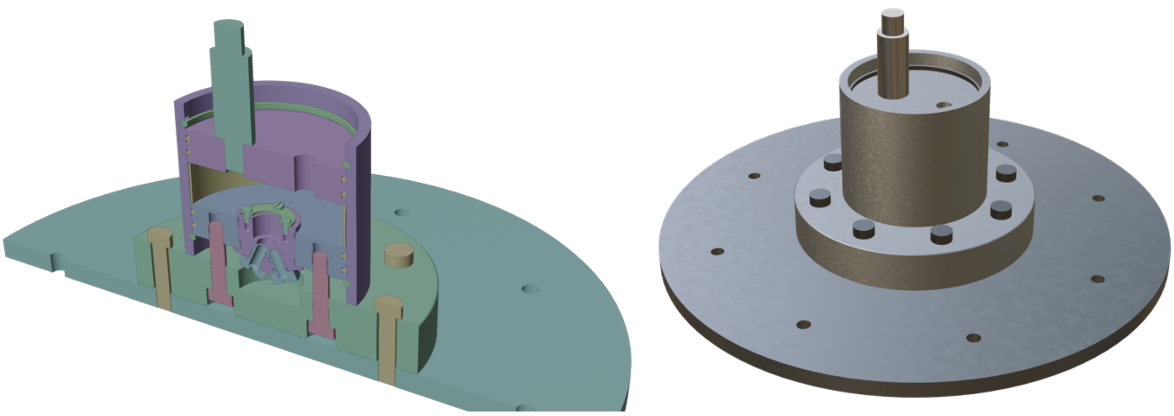


Figure 10 – Isometric views of Plenum volume test setup

Images on the integration of DUT2 on the shaker:

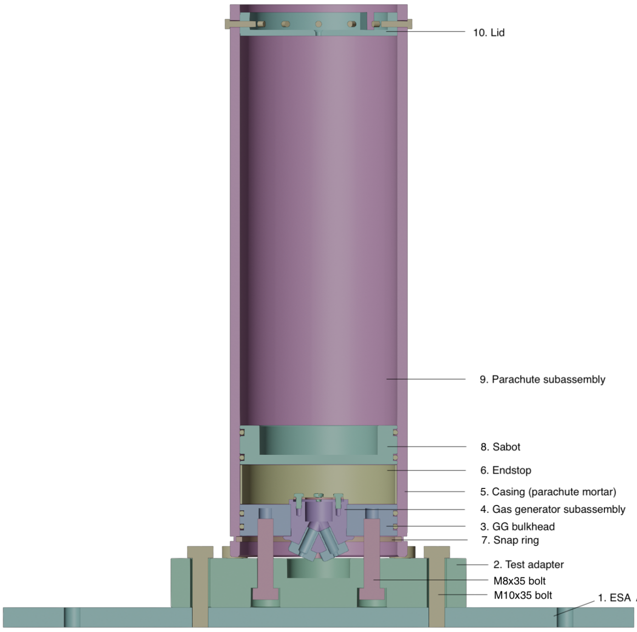


Figure 11 – Cut through overview of Parachute mortar test setup

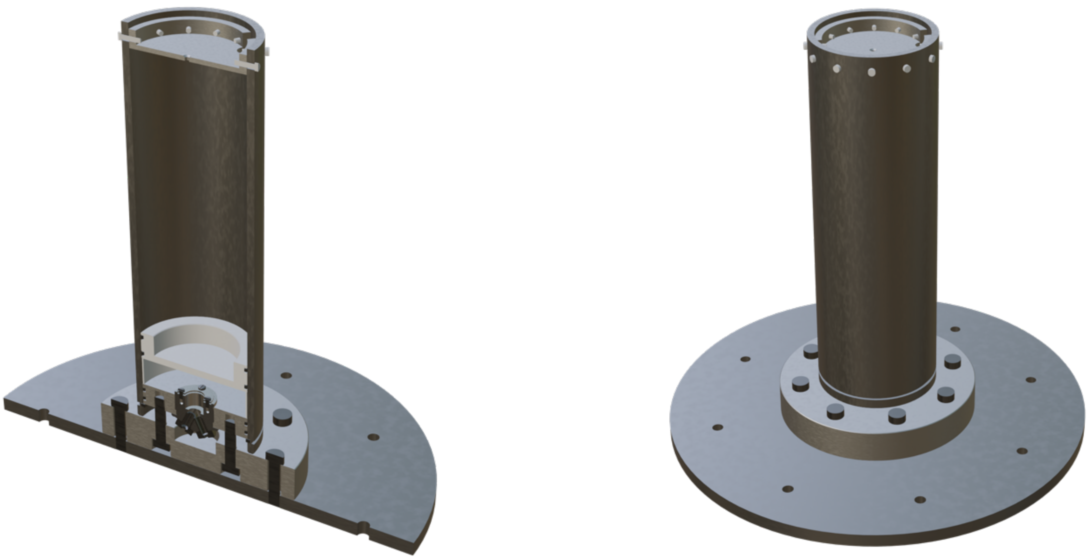


Figure 12 – Isometric views of Parachute mortar test setup

1.3.7. Ground Support Equipment

The following ground support equipment is needed:

ID	Item	Purpose	Provided by
GSE-01	Compressor	Increase pressure in the plenum volume to 2 bar	Team
GSE-02	Power supply 24V	Pressure sensor supply power (TBD)	Site
GSE-03	Multimeter	Pressure sensor readouts	Team / Site
GSE-04	PC	Logging of test results	Team
GSE-05	SCADAs	Accelerometer sensors readouts (provided)	Site
GSE-06	Camera	Film the vibration tests	Site

Table 5 – Overview of required GSE

The following tools are needed [work in progress]:

Table 1 - List of equipment.

Item	Requirements	Picture	Responsible
Wrench set	Sizes 7, 8, 13	-	Team
Adjustable wrench	Min. diameter 7mm, Max. diameter >45mm	-	Team
Allen key set	Contains sizes 2-8	-	Team
Snap ring pliers	Multiple ones, good teeth	-	Team
Snap ring fillers		-	Team
Vaseline		-	Team
M4 hex head screwdriver	To insert nylon bolts	-	Team
Leak detection spray		-	Team
Soap		-	Team
Safety glasses (x2)		-	Team
Loctite	TBD	-	Team
Torque screwdriver	Hex head for M8/M10, torque range 12-20Nm	-	Site
Torque screwdriver	Hex head for M3, torque range 0.3Nm	-	Site
Torque wrench	Wrench size 13 (M8), 19 (1/4G), torque range 1-5 Nm	-	Site

Table 6 – Overview of required tools

1.4. Test facility requirements

1.4.1. Test instrumentation

Tri-axial accelerometers can be placed in the following locations on DUT1 and DUT2:

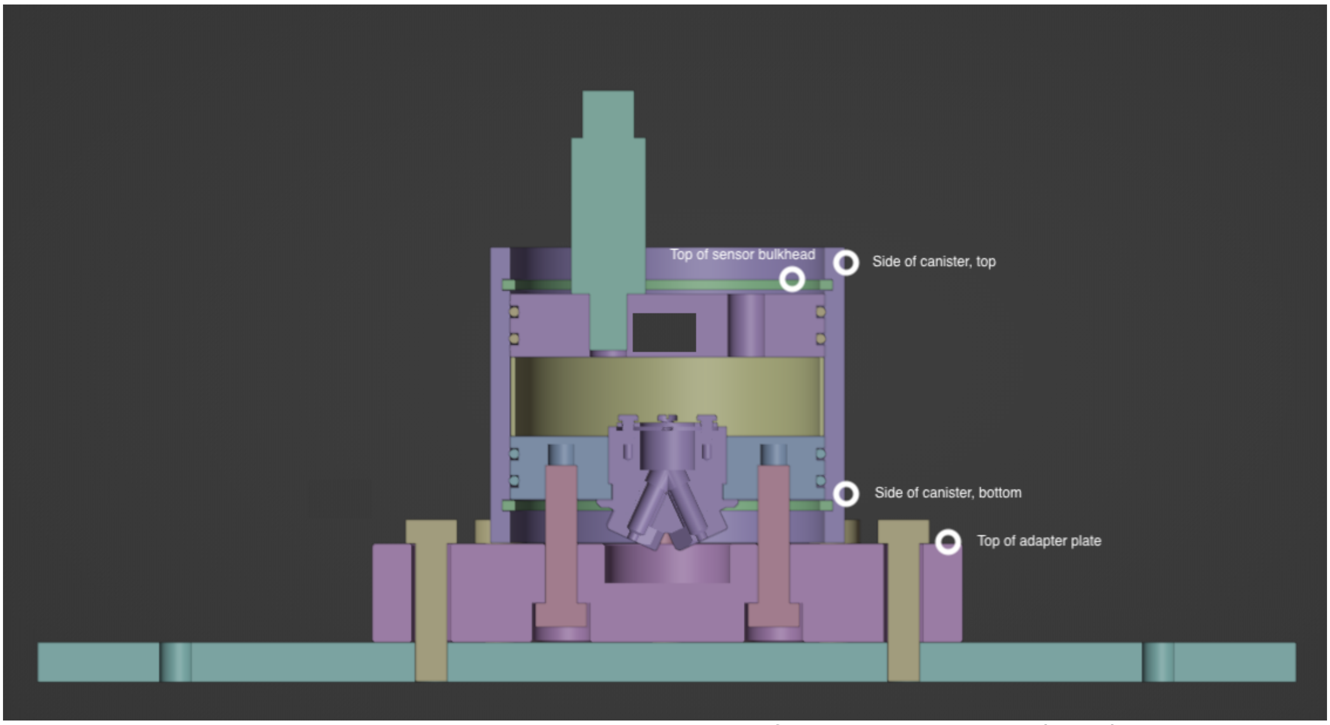


Figure 13 – Proposed accelerometer placement of plenum volume setup (DUT1)

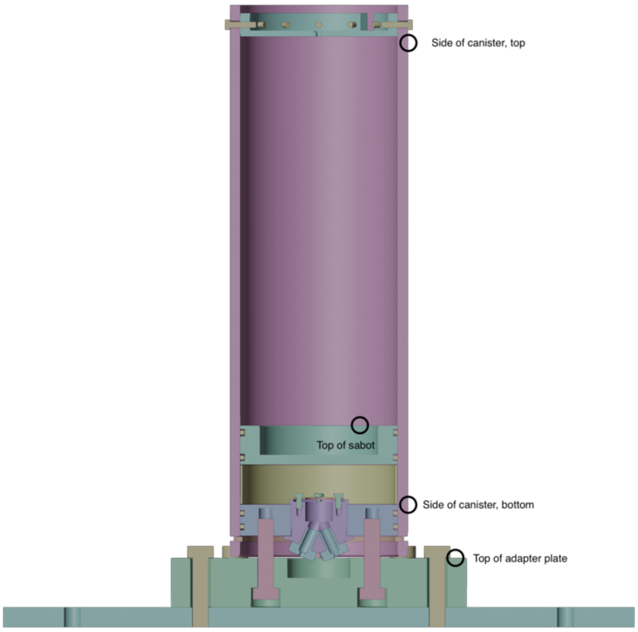


Figure 14 – Proposed accelerometer placement of parachute mortar setup (DUT2)

1.4.2. Cleanliness and Environment

- There are no requirements on the cleanliness or environment.

1.4.3. EMC & ESD

- There are no requirements on EMC and/or ESD.

1.4.4. Test tolerances

The desired test tolerances can be viewed in the table below.

Acceleration	**Tolerances**
Steady state and static load	-0 / +10%
Sinusoidal Vibration	**Tolerances**
Frequency (5Hz to 2000 Hz)	± 2 % (or ± 1 Hz whichever is greater)
Amplitude	± 10 %
Sweep rate (Oct/min)	± 5 %
Random Vibration	**Tolerances**
Amplitude (PSD, frequency resolution better than 10Hz)	20 Hz – 1000 Hz: -1 dB / +3 dB 1000 Hz – 2000 Hz: ± 3 dB
Overall g.r.m.s.	± 10%

Table 7 – Tolerances for mortar vibration tests

1.4.5. Other Requirements

- There are no other requirements on the facility towards the test setup.

1.5. Test Levels and Test Parameters

The test levels followed during the vibrational test will be the ones prescribed by the REXUS program. Additionally, the sine burst levels are specified to the highest acceleration in the lateral and axial directions prescribed by the REXUS user manual. These specifications are given below. Note that the current test is being designed for qualification level according to the REXUS program specifications.

The sinusoidal vibration is performed in all three axes, with a sweep rate of 4 oct/min. The test profile goes as follows:

• 0.097536 m/s 5-24 Hz
• 1.53 g 24-110 Hz
• 3.50 g 110-800 Hz
• 12.0 g 800-2000 Hz

In each of the three axes, a random vibration is performed with a duration of 50s per axis. The spectrum for all axes is given by the following:

• 12.7 grms
• 0.01 g2/Hz 20 Hz
• 0.10 g2/Hz 1000 Hz (on 1.8 dB/oct. slope from 20 to 1000)
• 0.10 g2/Hz 1000-2000 Hz

The resonance search is performed at 0.25 g on the range 20-2000 Hz with a sweep rate of 2 oct./min, in all axes.

1.5.1. Notching

- No notching will be applied to the mortar vibration test spectrum.

1.6. Pass/Fail Criteria

The pass/fail criteria of the vibration test setups (DUT1 and DUT2) are described below.

ID	Requirement	Fail criteria
PFD1-01	The plenum volume shall remain sealed during the vibration test	The pressure drops more than 5% (Plenum v. pressure <1.9 bar)
PFD1-02	All parts shall remain in place during testing and structurally intact	A part has changed position or orientation, visual observation

Table 8 – Pass/fail criteria for DUT1 – plenum volume test object

ID	Requirement	Fail criteria
PFD2-01	All parts shall remain in place during testing and structurally intact	A part has changed position or orientation, visual observation

Table 9 – Pass/fail criteria for DUT2 – parachute mortar test object

The following items shall be monitored after tests with DUT2:

ID	Requirement	Monitor
MD2-01	The resonance frequency of the mortar system should be >60Hz	Resonance frequency of the mortar
MD2-02	The plenum volume should not significantly increase	The distance between the bulkhead and sabot

Table 10 – Monitoring during DUT2 testing – parachute mortar test object

1.7. Health and Safety

The following three health and safety risks are present:

- Pressurized system (up to 8 bars maximally).

The compressor can provide a pressure up to 8 bar. The intended pressure is 2 bar. All systems of the mortar tube are designed for a nominal operating pressure of 36 bar, with a minimum safety factor of 1.5. When performing leak testing on the system, the operator(s) should wear safety glasses.

- Loose parts due to vibration loading.

In case cabling or a fastener is not properly attached, it may vibrate loose and disconnect. The test personnel should keep a safe distance from the vibration table whilst it is operating. Thorough procedures should prevent any incorrect assembly of fasteners and/or cables.

- Snap ring spring loading.

The snap rings used to fasten the GG and sensor bulkheads are spring loaded when compressed, during (dis)mounting of the snap rings in the tube. The snap ring may fly loose during (dis)assembly and jump away due to its elastic potential energy. All members (dis)mounting snap rings should wear safety glasses, and a minimal number of members should be present during this step in the operations.

1.8. Test Organisation

The test organisation section is a work in progress.

A first draft of the test campaign schedule can be seen via this link:

https://docs.google.com/spreadsheets/d/1-LW5kqDtOdsInPOHD27thQgE4ql9p9I_kqqFBOix8jI/edit?usp=sharing

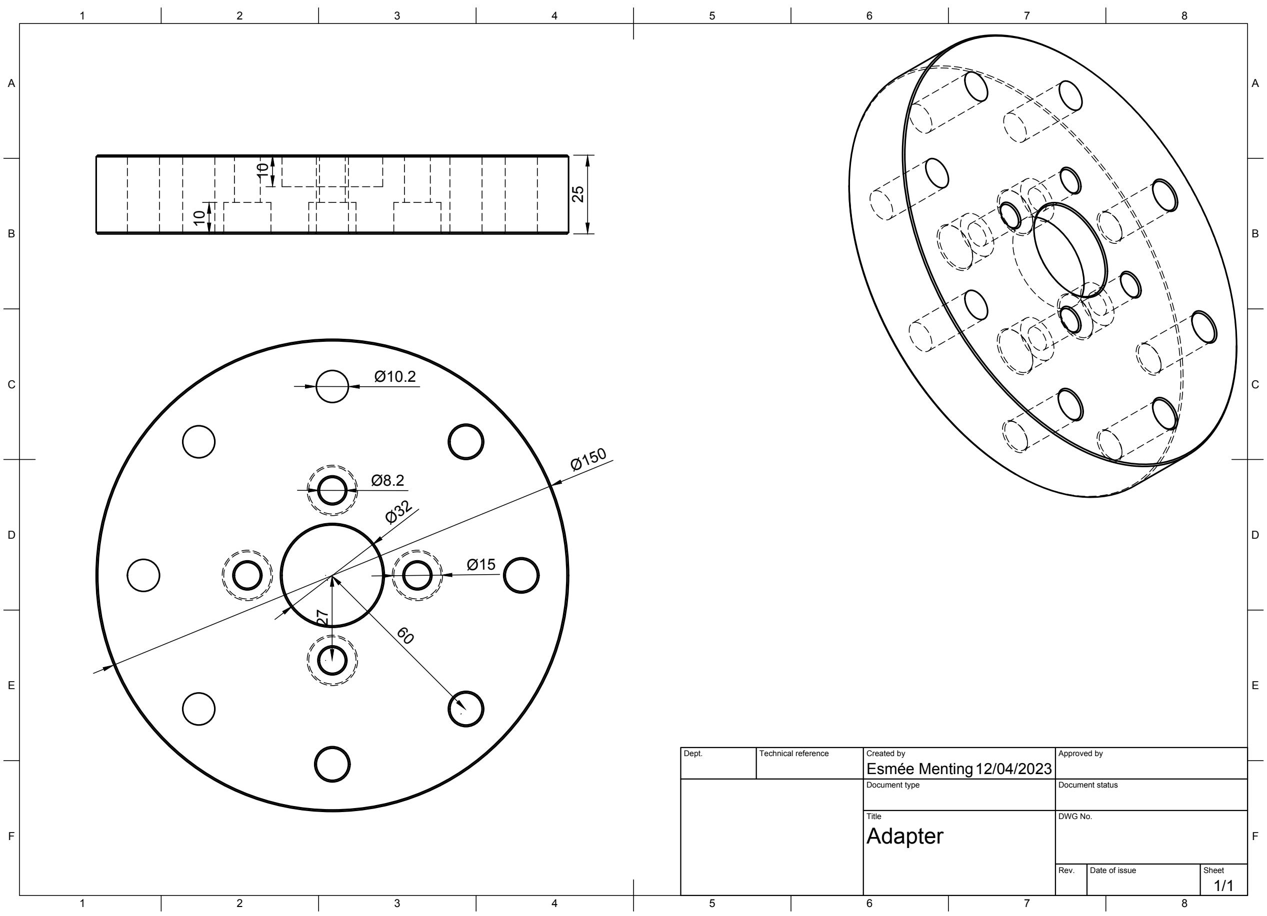
1.9. Step-by-step Procedures

The test procedures are a work in progress.

1.10. Appendices to the TSTP document

1.10.1. Appendix A – Drawings of Interface to Shaker

One test adapter will be made for the mortar vibration tests. A technical drawing of the adapter plate can be found below.

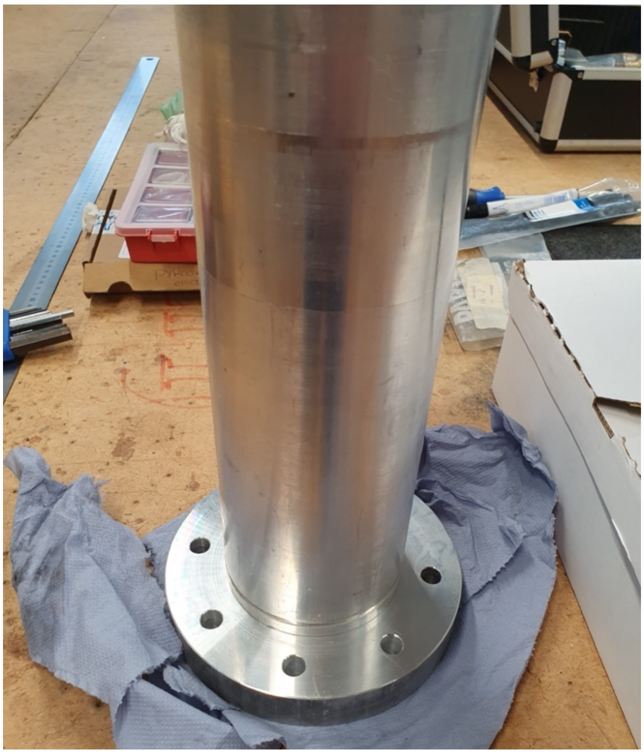


1.10.2. Appendix B – Test Predictions

- Work in progress.

1.10.3. Appendix C – Verification of Test Set-Up

The two test objects, DUT1 and DUT2, have been test fitted on the test adapter. The M10x40 bolts have been test fitted in the test adapter. DUT1 and DUT2 have been fully assembled to confirm integration is possible. Some images of the assembly tests and fittings can be seen below.




Integration of DUT2

Integration of DUT1

1.10.4. Appendix D – Hardware status overview

This appendix will show the status of different parts and/or any relevant comments.

Part Nr.	Item	Status	Comments
1	Armature	Present at site	
2	Test adapter	Finished	
-	M10x35 bolt	Ordered and arrived	
3	Gas generator bulkhead	Finished	
-	M8x35 bolt	Ordered and arrived	
4	Gas generator subassembly	Finished	
5	Canister plenum volume	Finished	
6	Endstop	Finished	
7	Snap ring	Finished	
8	Sensor bulkhead	Finished	
9	PU5450 pressure sensor	Finished	
10	Valve	Finished	
11	Connector valve – compressor tube	Ordered and arrived	

Table 11 – Status overview of parts in DUT1: the plenum volume test object

Part Nr.	Item	Status	Comments
1	Armature	Present at site	
2	Test adapter	Finished	
-	M10x35 bolt	Ordered and arrived	
3	Gas generator bulkhead	Finished	
-	M8x35 bolt	Ordered and arrived	
4	Gas generator subassembly	Finished	
5	Canister parachute mortar	Finished	
6	Endstop	Finished	
7	Snap ring	Finished	
8	Sabot	Finished	
9	Parachute subassembly	Finished	
10	Lid	Finished	

Table 12 – Status overview of parts in DUT2: the parachute mortar test object

Delft Aerospace Rocket Engineering

Mortar Vibration Test Procedures

Test ID: Mortar-VIB-01

PRG - Mortar R& D

Wednesday 7th June, 2023

Test Location:
ESEC Galaxia
Devant les Hêtres 2
2649XQ Libin

TC: Esmée Menting
TO: Claudio Rapisarda

Version: V1.0
Author: Esmée Menting

Printed: 12/06/2023 - TPC2.1

1 Changelog

Date	Version	Changes	Names
04-06-2023	V1.0	First version	Esmée Menting
Monday 12th June, 2023		Date of Download	

In case of emergency: (112 & +46706853804)

Low risk/priority	Medium risk/priority	High risk/priority
• Test-setup is safe to approach • No safety gear required	• Only authorized personnel in test area • Wear appropriate safety gear	• Clear all personnel from test area • Do not approach the test-setup

CP Control Post
DAQ Data Acquisition
NTC Nitrocellulose
OSO Operational Safety Officer
PPE Personal Protective Equipment
TC Test Conductor
TL Test Leader
TO Test Operator

Overview of the Test

Purpose of the preparation:

- Vibration test of one plenum volume canister, to establish whether leaks occur at 1 bar overpressure under vibration.
- Vibration test of one parachute mortar, to establish structural integrity under vibration.
- Vibration test of one parachute mortar with/without parachute cup, to establish the difference in natural frequency between those configurations.

Safety Considerations

The maximum pressure provided by the compressor is 8 bar. The canister has withstood pressures of up to 36 bar during the Low-Pressure Ignition test campaign.
The 80mm snap rings store some kinetic energy when compressed, and care should be taken when (dis)assembling them.

2 Part preparation

Prep location:
Starting time:

		A - Collect tools and parts		
ID	**Check**		**Operation**	**Remarks**
System Status: • A table is made free for packing and preparation. Procedures are printed.				
A1			**Collect all the following parts:**	
A2			Canister parachute mortar	
A3			Canister plenum volume test	
A4			Gas generator bulkhead	
A5			Sensor bulkhead	
A6			Valve	
A7			PU5404 pressure sensor	
A8			O-rings for bulkhead	79.1mm diameter O-rings
A9			Snap rings 80mm	
A10			Endstop (3D printed ring)	
A11			Sabot	Small O-ring version
A12			O-rings for sabot	79.1mm diameter O-rings
A13			Parachute subasssembly	
A14			Lid	
A15			Nylon M4 shear bolts x6 (+ spares)	
A16			Gas generator	Large volume version (1cm deep internally)
A17			Ignitor bolt x2	Hex M8x10mm bolt with holes for e-match.
A18			Teflon tape	
A19			Mesh	Pre-cut to dimensions
A20			Retainer ring	Aluminium version
A21			Retainer bolts x4 (Hex socket head cap M3x6mm)	To close retainer ring
A22			Attachment bolts x4 (M8x35mm)	
A23			**Collect all the following tools:**	
A24			Scissors	
A25			Pen	
A26			Blue paper (for cleaning)	
A27			Vaseline	
A28			Acetone	
A29			Cutting pliers	
A30			Stripping pliers	
A31			Regular pliers	
A32			Pliers for 80mm snap rings	Ideally multiple
A33			Safety glasses x2	
Continued				

ID	Check		Operation	Remarks
A34			Hammer or rod	To push in/out sabot and bulkheads
A35			Snap ring groove fillers (3D printed half-ring, thin)	To insert bulkhead past snap ring groove
A36			Allen key for M3 bolts	
A37			Wrench 13 for M8 (ignitor) bolts	
A38			Small adjustable wrench for GG	Test-fit if it closes well around gas generator head
A39			Screwdriver with head that fits over M4 shear bolts	

			B - Part preparation	
ID	**Check**		**Operation**	**Remarks**
System Status: • The following required parts are present: • Gas generator x1, Ignitor bolts x2, Mesh x1, Retainer ring x1, M3x6 bolt x4 • GG bulkhead & Canister • Acetone, Nitrile gloves, Blue paper				
B1			Check ignitor bolts for sharp metal burs	
B2			See which mesh fits well onto the retainer ring. Prefit bolts.	
B3			Ensure grooves of the bulkhead and tube are not sharp	
B4			Check if O-rings are not damaged	
B5			Check that M8 threads of ignitor bolts and gas generator are okay	
B6			Check that M30 threads of gas generator (GG) and gas generator bulkhead are okay	
B7			Test fit gas generator into GG bulkhead	
B8			Clean gas generator using Acetone	Use nitrile gloves whilst cleaning
B9			Ensure lid is free of nylon shear bolts	
B10			Test fit nylon shear bolt into lid holes	
System Status: • Ready for assembly				

3 Preparation of the plenum volume canister

Test location:
Starting time:

C - Plenum volume canister assembly				
ID	**Check**		**Operation**	**Remarks**
C1			Fill out time	Time:
System Status: • All required tools and parts are present (see Preparations)				
C2			Place O-rings on the GG bulkhead	Apply vaseline over O-rings and bulkhead side
C3			Insert snap ring groove fillers	
C4			Insert GG bulkhead into canister from one. Orientation: the flat side (no attachment holes) enters first.	
C5			Remove snap ring groove fillers	Use small pliers and/or screwdrivers
C6			Put on safety glasses and clear area as much as possible	Only for snap ring insertion
C7			Insert snap ring into snap ring groove	One member can hold the canister, whilst one member places the snap ring
C8			Push the GG bulkhead to the bottom	It should rest on the snap ring
C9			Thread the gas generator subassembly into the gas generator bulkhead, until fully flush	Apply dowty seal
C10			Place the endstop and a red spacer inside the canister on top of the GG bulkhead	
C11			Thread the valve into the sensor bulkhead	Seal with 1x dowty seal. Tighten properly.
C12			Thread the pressure sensor into the sensor bulkhead	Seal with O-ring. Tighten properly.
C13			Ensure the valve can still open and close, and is not obstructed by the pressure sensor.	
C14			Place O-rings on the sensor bulkhead	Apply vaseline over O-rings and bulkhead side
C15			Insert snap ring groove fillers	
C16			Insert sensor bulkhead into canister from the other side. Orientation: the flat side (sensor/valve) enters first.	
C17			Remove snap ring groove fillers	Use small pliers and/or screwdrivers
C18			Put on safety glasses and clear area as much as possible	Only for snap ring insertion
C19			Insert snap ring into snap ring groove	One member can hold the canister, whilst one member places the snap ring
Continued				

ID	Check		Operation	Remarks
C20			Wipe excess vaseline away with blue paper.	

System Status:
- Plenum volume canister is assembled
- Ready for leak testing

			D - Plenum volume leak testing	
ID	**Check**		**Operation**	**Remarks**
D1			Fill out time	Time:

System Status:
- The plenum volume canister is fully assembled

D2			Connect the cabling to the pressure sensor	
D3			Check continuity of cables between power supply and connector	
D4			Read output voltage from pressure sensor	Should be 0V
D5			Open valve	
D6			Connect compressor via eurosteeknippel tube to canister setup	
D7			Rotate compressor pressure setting knob to a pressure of approximately 1.5 bar and turn on	
D8			Confirm correct pressure sensor measurement	pressure = voltage + 1 [bar]
D9			Pressurise canister to 3 bar	
D10			Close valve. Disconnect compressor	
D11			Observe pressure drop over time for at least 5 minutes or a pressure drop of $\geq 1bar$	
D12			If a pressure drop is observed, apply leak spray to identify the location(s) of the leak(s)	
D13			Fix leaks	Many possibilities: • Reapply lubricant to O-rings • Replace O-rings • Tighten connectors/bolts more • Reapply dowty seal to connection
D14			Document identified leaks and steps taken to mitigate them	
D15			Re-do leak testing	
D16			When a pressure drop of $/leq0.2bar$ within 5 minutes is observed, the canister passes the leak testing stage.	

System Status:
- Plenum volume canister is assembled and leak tight

	E - Mounting of DUT1 to vibration table			
ID	**Check**		**Operation**	**Remarks**
E1			Fill out time	Time:
System Status: • Parachute mortar is fully assembled				
E2			Route 4x M8x35mm bolts through the test adapter and align with the plenum volume tes canister	Place canister sideways, test adapter sideways
E3			Thread each M8 bolt slightly into the gas generator bulkhead	
E4			Tension each M8 bolt a few turns turn one by one	
E5			Apply a torque of 12Nm to the bolt. If this feels to high, review torque levels. Do not damage the setup.	
E6			Route 8x M10x40mm bolts through the test adapter and align with the vibration table	
E7			Thread each M10 bolt slightly into the vibration table	
E8			Tension each M10 bolt a few turns turn one by one	
E9			Apply a torque of 20Nm to the bolt. If this feels to high, review torque levels. Do not damage the setup.	
E10			Apply 5-axis accelerometers to relevant locations	Indicated in TSTP
System Status: • System is ready for vibration testing				

	F - Testing of DUT1			
ID	**Check**		**Operation**	**Remarks**
F1			Fill out time	Time:
System Status: • Parachute mortar is fully assembled				
F2			Measure the pressure	Overpressure = bar
F3			Connect compressor to DUT1	
F4			Increase pressure to 1.9-2.2 bar total (0.9-1.2 bar overpressure)	Use dial on compressor
F5			Close valve and disconnect compressor	
F6			Note down overpressure (=voltage) and time	Overpressure = bar, time =
F7			Observe leakage for 5 minutes, note down overpressure and time	Overpressure = bar, time =
F8			Disconnect pressure sensor and valve handle	
F9			Perform resonance sweep	
F10			Connect pressure sensor, note down overpressure	Overpressure = bar
F11			In case of leaks, apply leak detection spray to identify location	
F12			In case of leaks, change the setup to continuous pressure sensor readout	Video of multimeter, note down important values
F13			In case of leaks, re-pressurise to 2 bar	
F14			In case of no leaks, disconnect pressure sensor	
Continued				

ID	Check		Operation	Remarks
F15			Perform random vibration test (RND) in X axis	
F16			Connect pressure sensor and note down pressure	Overpressure = bar
F17			In case of leaks, apply leak detection spray to identify location	
F18			Perform resonance sweep (RS) post RND	
F19			Rotate setup to Y-axis	
F20			In case of leaks, change the setup to continuous pressure sensor readout	Video of multimeter, note down important values
F21			In case overpressure is below 0.9 bar, re-pressurise to 1.0 bar	
F22			Observe leakage for 5 minutes, note down overpressure and time	Overpressure = bar, time =
F23			Disconnect pressure sensor and valve handle	
F24			Perform resonance sweep	
F25			Connect pressure sensor, note down overpressure	Overpressure = bar
F26			Perform random vibration test (RND) in Y axis	

System Status:

- System is ready for vibration testing

4 Mortar assembly

Test location:
Starting time:

G - Parachute mortar assembly (DUT2)				
ID	**Check**		**Operation**	**Remarks**
G1			Fill out time	Time:
System Status: • All required tools and parts are present (see Preparations)				
G2			Place O-rings on the GG bulkhead	Apply vaseline over O-rings and bulkhead side
G3			Insert snap ring groove fillers	
G4			Insert GG bulkhead into canister from the side with the snap ring groove. Orientation: the flat side (no attachment holes) enters first.	
G5			Remove snap ring groove fillers	Use small pliers and/or screwdrivers
G6			Put on safety glasses and clear area as much as possible	Only for snap ring insertion
G7			Insert snap ring into snap ring groove	One member can hold the canister, whilst one member places the snap ring
G8			Push the GG bulkhead to the bottom	It should rest on the snap ring
G9			Thread the gas generator subassembly into the gas generator bulkhead, until fully flush	
G10			Place the endstop inside the canister on top of the GG bulkhead	
G11			Place O-rings on the sabot	Apply vaseline over O-rings and sabot side
G12			Mount accelerometer to the sabot	May not be feasible in combination with the parachute cup
G13			Insert sabot into canister, on top of endstop	The flat side should face the parachute assembly
G14			Remove excess vaseline from the inside of the canister	Use blue paper
G15			Place parachute assembly into parachute cup	Optional, depending on configuration
G16			Place parachute assembly (and parachute cup) into canister	
G17			Place lid inside canister, on top of parachute assembly	Align with shear bolt holes, loop accelerometer cable through
G18			Fasten lid with 6 shear bolts, spaced symmetrically	
G19			Tighten shear bolts until they are fully in	No need to apply high torque
Continued				

ID	Check		Operation	Remarks
System Status: • Mortar is assembled • Ready for final test/launch operations				

H - Mounting of DUT2 to vibration table				
ID	**Check**		**Operation**	**Remarks**
H1			Fill out time	Time:
System Status: • Parachute mortar is fully assembled				
H2			Route 4x M8x35mm bolts through the test adapter and align with the mortar	Place mortar upright, test adapter on top
H3			Thread each M8 bolt slightly into the gas generator bulkhead	
H4			Tension each M8 bolt a few turns turn one by one	
H5			Apply a torque of 12Nm to the bolt. If this feels to high, review torque levels. Do not damage the setup.	
H6			Route 8x M10x40mm bolts through the test adapter and align with the vibration table	
H7			Thread each M10 bolt slightly into the vibration table	
H8			Tension each M10 bolt a few turns turn one by one	
H9			Apply a torque of 20Nm to the bolt. If this feels to high, review torque levels. Do not damage the setup.	
H10			Apply 5-axis accelerometers to relevant locations	Indicated in TSTP
System Status: • System is ready for vibration testing				

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DARE PARACHUTE MORTAR (MOR) DUT1 - TEST READINESS REVIEW (TRR)

Meeting Date	08/06/2023	**Ref**	/
Meeting Place	ESEC, Redu, VC3	**Chairman**	Loris Franchi
Minute's Date	08/06/2023	**Participants**	***ESA*** *Loris Franchi* *Maximilian Nuermberger* ***MOR*** *Claudio Rapisarda* *Jasper Jonk* *Kristina Vukosavljević* *Esmée Menting*
Subject	DARE PARACHUTE MORTAR (MOR) DUT1 - TEST READINESS REVIEW MoM	**Copy**	DARE, Fly Your Satellite!

AGENDA

1. Introduction
2. Test Facility Readiness
3. Review of Test Responsibilities
4. Review of Procedure & Pass / Fail Criteria
5. Status of RIDs/RFWs/NCRs/Open Actions Affecting IUT
6. Test Pre-Requisites
7. Test vs Flight Configuration
8. Review of Test Set-up (As Installed)
9. Review of Test Levels
10. Other topics
11. Conclusion

APPLICABLE AND REFERENCE DOCUMENTS

Table 1 - Applicable and Reference Documents

AD/RD #	Reference	Title	Issue/Rev	Date
AD1	MOR_TSTP_2023-05-31_V1.1	Vibration Test Specification & Test Procedures for the Parachute Mortar [MOR_TSTP]	V1.1	14/05/2023
AD2	RX_UserManual_v7-17_26Nov21	REXUS User Manual	V7.17	26/11/2021

1 INTRODUCTION

The **Vibration** test campaign for the **DARE Parachute Mortar** will be performed in the CubeSat Support Facility (CSF) in ESEC Galaxia from **06th** June to **09th** June 2023.

The intended test focuses on the risk reduction of the parachute mortar subsystem. The main focus is therefore on mitigating the risk of plenum volume leakage (see AD1: MOR-04). Secondarily, the structural integrity and function of containing the parachute will be confirmed (see AD1: MOR-01, MOR-02, MOR-03).

There are two devices under test: a plenum volume test setup (DUT1) and a regular parachute mortar (DUT2). Both will be tested subsequently and undergo qualification level testing at test levels defined in the REXUS Unser Manual [AD2], with added sine vibration tests in all axes.

This TRR is held for the vibration test of the Mortar DUT1.

2 TEST FACILITY READINESS

Prior to the start of the test campaign, a Facility Readiness Review was performed to ensure that the facility would be ready to receive the hardware and would meet the requirements for the test.

During the sine vibration test, it will not be possible to perform a sudden change in the applied loads at 110 HZ and 800 Hz as described in the TSTP [AD1] and REXUS User Manual [AD2]. Instead, a short slope will be used to change between vibration loads, as shown in Table below.

Frequency (Hz)	Acceleration (g)	Velocity (m/s)
5	0.31246	0.097536
24.4832	1.53	0.097536
110	1.53	
115	3.5	
800	3.5	
840	12	
2000	12	

The procedure followed is found in the Facility Readiness Review (FRR) checklist archive and can be made available to the team upon request.

3 REVIEW OF TEST RESPONSIBILITIES.

Table 2 - Test Responsibilities

Name	Organisation	Test Responsibilities

Loris Franchi	ESA	Test Operator and campaign responsible
Maximilian Nuermberger	ESA	Test support and REXUS/BEXUS representative
Claudio Rapisarda	DARE	Test Operator
Jasper Jonk	DARE	Vibration Specialist
Kristina Vukosavljević	DARE	
Esmée Menting	DARE	Test Lead, Hardware Engineer, PA

4 REVIEW OF PROCEDURE & PASS/FAIL CRITERIA

The procedure followed is provided in the TSTP [AD1]. A discrepancy between procedures described in section 1.3.4 and section 1.5 was fund. After clarifications from DARE team, the procedure to be used shall be identical to REXUS, with sine vibration only in z axis.

The TSTP [AD1] also contains all pass/fail criteria utilized in the test.

5 STATUS OF RID/RFD/RFW/NCR/OPEN ACTIONS AFFECTING IUT

No remaining RID/RFD/RFW/NCR or open actions.

6 TEST PRE-REQUISITES

All test pre-requisites described in the TSTP [AD1] are fulfilled.

7 TEST VS FLIGHT CONFIGURATION

DUT1 is not a flight item. Main deviations from the parachute mortar flight configuration are:

- DUT1 only contains the plenum volume of the MORTAR system and not the parachute volume. Hence the overall length of the canister is shorter.
- A valve and pressure sensor have been added to DUT1 which are not present in the flight model.
- Accelerometer sensors are installed to the DUT1, which add small mass and therefore might change resonance frequencies slightly.

8 REVIEW OF TEST SETUP (AS INSTALLED)

The following work has been performed inside the ESEC Galaxia workshop:

- DUT1 was unpacked and cleaned.
- Correct torque levels were applied to igniter bolts and witness marks were applied.

- A leak test was performed, and a leak was identified on the gas generator bulkhead.
- DUT1 was disassembled and all O-rings were checked for damage. One damaged O-ring was replaced.
- Grooves in the bulkhead were cleaned.
- DUT1 was re-assembled and the leak test repeated. A pressure drop of 0.02 bar within a 5h timespan was measured, which fulfils requirements.
- The vibration adaptor plate was adjusted to fit the DUT1 with added dowty seals. For this, the existing pocket in the adaptor was increased by approximately 1mm with a Dremel.
- DUT1 was mounted and torqued to the adaptor plate.

The following work was performed inside the CSF cleanroom:

- DUT1 with vibration adaptor plate was mounted and torqued to shaker slip table.
- A leak test performed, measuring a pressure drop of 0.02 bar within a 3.5h timespan, which is in line with requirements.
- The filling valve handle was removed from DUT1. It was decided to run vibration tests without handle.
- Instrumentation was applied to DUT1 as shown in Figure 1. The accelerometer on the vibration test adaptor flange was not added, as the flange has already been characterized during testing of DUT2.
- A visual inspection was performed, including taking pictures.
- The electrical connection to the pressure sensor was disconnected. It was decided to run the first resonance sweep without connected pressure sensor and evaluate afterwards if the pressure sensor should be connected for later test runs.

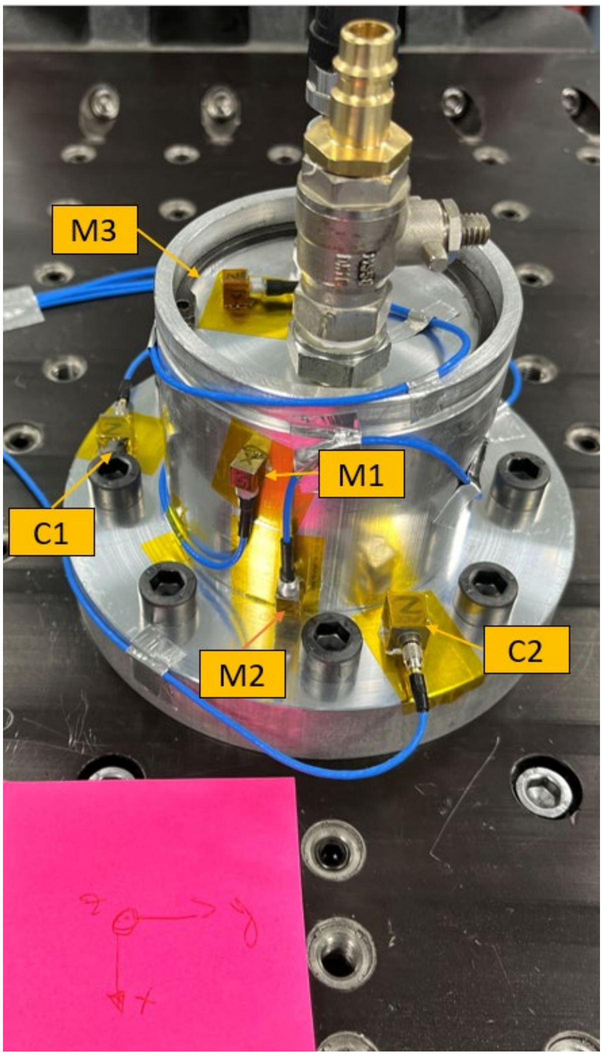

Figure 1 – Sensor placement on MORTAR DUT 1

Table 3 – Sensor Axes Alignment

Sensor	C1	C2	M1	M2	M3
sensor x-Axis corresponds to DUT axis	x	-x	z	-z	-y
sensor y-Axis corresponds to DUT axis	y	-y	-y	y	x
sensor z-Axis corresponds to DUT axis	z	z	x	x	z

9 REVIEW OF TEST LEVELS

Test levels shall be qualification levels of REXUS described in the REXUS User Manual [AD2]. With a modification in the slope of the sine vibration test levels, as described under section 2.

10 OTHER TOPICS

No other topics.

11 CONCLUSION

There are no open issues preventing the initiation of the Mortar DUT1 vibration test.

Therefore, by mutual agreement between the MORTAR test lead and ESA, the test will commence in accordance with the provided reference documents and the alterations made within this document.

SIGNATURE PANEL

Signatures	
(On behalf of ESA)	
(On behalf of MORTAR)	

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DARE PARACHUTE MORTAR (MOR) DUT2 WITH PARACHUTE CUP VIBRATION TEST - TEST READINESS REVIEW (TRR)

Meeting Date	06/06/2023	**Ref**	/
Meeting Place	ESEC, Redu, VC3	**Chairman**	Loris Franchi
Minute's Date	06/06/2023	**Participants**	***ESA*** *Loris Franchi* *Maximilian Nuermberger* ***MOR*** *Claudio Rapisarda* *Jasper Jonk* *Kristina Vukosavljević* *Esmée Menting*
Subject	DARE PARACHUTE MORTAR (MOR) DUT2 WITH PARACHUTE CUP VIBRATION TEST - TEST READINESS REVIEW MoM	**Copy**	DARE, Fly Your Satellite!

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AD2	RX_UserManual_v7-17_26Nov21	REXUS User Manual	V7.17	26/11/2021

1 INTRODUCTION

The **Vibration** test campaign for the **DARE Parachute Mortar** will be performed in the CubeSat Support Facility (CSF) in ESEC Galaxia from **06th** June to **09th** June 2023.

The intended test focuses on the risk reduction of the parachute mortar subsystem. The main focus is therefore on mitigating the risk of plenum volume leakage (see AD1: MOR-04). Secondarily, the structural integrity and function of containing the parachute will be confirmed (see AD1: MOR-01, MOR-02, MOR-03).

There are two devices under test: a plenum volume test setup (DUT1) and a regular parachute mortar (DUT2). Both will be tested subsequently and undergo qualification level testing at test levels defined in the REXUS Unser Manual [AD2], with added sine vibration tests in all axes.

This TRR is held for the vibration test of the Mortar DUT2, with a parachute cup added inside the assembly.

2 TEST FACILITY READINESS

Prior to the start of the test campaign, a Facility Readiness Review was performed to ensure that the facility would be ready to receive the hardware and would meet the requirements for the test.

During the sine vibration test, it will not be possible to perform a sudden change in the applied loads as described in the TSTP [AD1] and REXUS User Manual [AD2]. Instead a short slope will be used, to change between vibration loads.

The procedure followed is found in the Facility Readiness Review (FRR) checklist archive and can be made available to the team upon request.

3 REVIEW OF TEST RESPONSIBILITIES.

Table 2 - Test Responsibilities

Name	Organisation	Test Responsibilities
Loris Franchi	ESA	Test Operator and campaign responsible
Maximilian Nuermberger	ESA	Test support and REXUS/BEXUS representative
Claudio Rapisarda	DARE	Test Operator
Jasper Jonk	DARE	Vibration Specialist
Kristina Vukosavljević	DARE	
Esmée Menting	DARE	Test Lead, Hardware Engineer, PA

4 REVIEW OF PROCEDURE & PASS/FAIL CRITERIA

The procedure followed is provided in the TSTP [AD1]. A discrepancy between procedures described in section 1.3.4 and section 1.5 was fund. After clarifications from DARE team, the procedure to be used shall be the one described in section 1.5, meaning a sine vibration test shall be performed in all three axes.

The TSTP [AD1] also contains all pass/fail criteria utilized in the test. Here, the criteria on frequency shift (MD2-01) might be considered as pass/fail criteria after evaluating results of first resonance search.

5 STATUS OF RID/RFD/RFW/NCR/OPEN ACTIONS AFFECTING IUT

No remaining RID/RFD/RFW/NCR or open actions.

6 TEST PRE-REQUISITES

All test pre-requisites described in the TSTP [AD1] are fulfilled.

7 TEST VS FLIGHT CONFIGURATION

- Parachute mortar lid is SPEAR mission design with a 3D printed part on top.
- The DUT2 includes a 3D printed parachute cup.

8 REVIEW OF TEST SETUP (AS INSTALLED)

The following work has been performed inside the ESEC Galaxia workshop:

- DUT2 was unpacked and cleaned.
- Correct torque levels were applied to igniter bolts and witness marks were applied.

The following work was performed inside the CSF cleanroom:

- DUT2 was mounted and torqued to the test adaptor.
- Instrumentation was applied to DUT 2, as shown in Figure 1. Sensor M3 was not added due to the parachute lid being in the way.
- DUT2 with the test adaptor was mounted and torqued to the shaker in vertical position.
- A visual inspection was performed, including taking pictures.

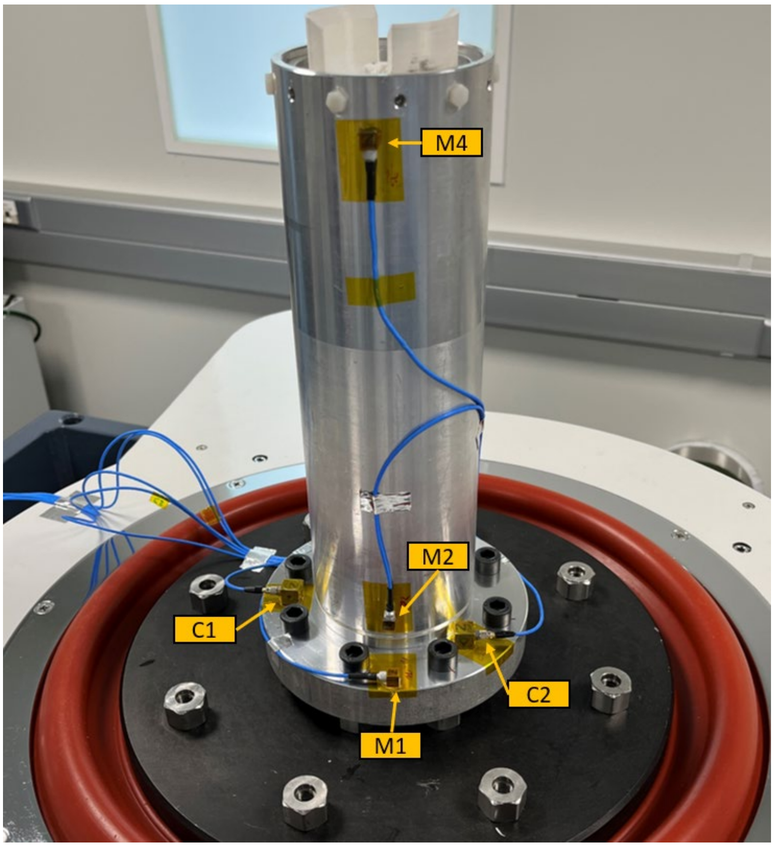

Figure 1 – Sensor placement on MORTAR DUT 1

Table 3 – Sensor Axes Alignment

Sensor	C1	C2	M1	M2	M3	M4
sensor x-Axis corresponds to DUT axis	-x	x	-x	-z	n.a.	z
sensor y-Axis corresponds to DUT axis	-y	y	-y	-x	n.a.	x
sensor z-Axis corresponds to DUT axis	z	z	z	y	n.a.	y

9 REVIEW OF TEST LEVELS

Test levels shall be qualification levels of REXUS described in the REXUS User Manual [AD2]. With a modification in the slope of the sine vibration test levels, as described under section 2.

10 OTHER TOPICS

No other topics.

11 CONCLUSION

There are no open issues preventing the initiation of the Mortar DUT2 vibration test.

Therefore, by mutual agreement between the MORTAR test lead and ESA, the test will commence in accordance with the provided reference documents and the alterations made within this document.

SIGNATURE PANEL

Signatures	
(On behalf of ESA)	
(On behalf of MORTAR)	

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DARE PARACHUTE MORTAR (MOR) - POST TEST REVIEW (PTR)

Meeting Date	09/06/2023	**Ref**	/
Meeting Place	ESEC Galaxia	**Chairman**	Loris Franchi
Minute's Date	09/06/2023	**Participants**	***ESA*** *Loris Franchi* *Maximilian Nuermberger* ***MOR*** *Claudio Rapisarda* *Jasper Jonk* *Kristina Vukosavljević* *Esmée Menting*
Subject	DARE PARACHUTE MORTAR (MOR) - POST TEST REVIEW (PTR)	**Copy**	DARE, Fly your Satellite!

AGENDA

1. Overview of Test Campaign
   a. Day-by-day Summary
   b. Overview of modifications to the test set-up & procedure
   c. Preliminary results of post test functional checks
   d. Post test status of the facility and GSE
   e. Confirmation of test data acquired, recorded, and archived
2. Overview of possible non-conformances
3. Action Summary
4. Other topics
5. Preliminary Conclusion
6. Feedback and Lessons Learned

APPLICABLE AND REFERENCE DOCUMENTS

Table 1 - Applicable and Reference Documents

AD/RD #	Reference	Title	Issue/Rev	Date
AD1	MOR_TSTP_2023-05-31_V1.1	Vibration Test Specification & Test Procedures for the Parachute Mortar [MOR_TSTP]	V1.1	14/05/2023
AD2	RX_UserManual_v7-17_26Nov21	REXUS User Manual	V7.17	26/11/2021
AD3	MOR-DUT1_TRR_2023_08_06_V0.1	DARE Parachute Mortar (MOR) DUT1 - Test Readiness Review (TRR)	V1.0	
AD4	MOR-DUT2_TRR_2023_06_06_V0.1	DARE Parachute Mortar (MOR) DUT2 - Test Readiness Review (TRR)	V1.0	

1 OVERVIEW OF TEST CAMPAIGN

1.1 Day-by-day Summary

The **Vibration** test campaign for the **DARE Parachute Mortar** took place in the CubeSat Support Facility (CSF) in ESEC Galaxia from **06th** June to **09th** June 2023. The following work was performed during the test campaign:

- **Day 1 – 06th June 2023:**
  - The student team arrived at ESEC Galaxia and unpacked DUTs and GSE.
  - DUT2 was installed and torqued on vertical shaker.
  - TRR was performed for DUT2, as described in [AD4].

- **Day 2 – 07th June 2023:**
  - DUT2 was tested along its z-axis according to procedure and levels described in [AD4] with no anomalies on the DUT2.
    - Resonance frequency and amplitude shifts were used as pass/fail criteria for DUT2.
    - During visual inspection after the random vibration test run, damage to accelerometer M4 occurred due personnel tripping over the sensor cable. The accelerometer was replaced with previously prepared M3.
  - DUT2 was removed from shaker.
  - The shaker was rotated to horizontal position.
  - DUT2 was mounted and torqued on the slip table for testing along the DUT2 x-axis.
  - Vibration tests for DUT2 x-axis have been performed following procedure and test levels described in [AD4], with the below adaption:
    - During the resonance search following high level sign vibration, it was noticed that bolt connecting the DUT2 shaker adaptor to the shaker slip table was loose. The bolt was torqued to the correct level.
    - High level sign vibration and resonance search along DUT2 x-axis have been repeated with no further anomalies.
  - DUT2 was dismounted, rotated and retorqued on the shaker slip table for testing along the DUT2 y-axis.
  - Vibration tests for DUT2 y-axis have been performed following procedure and test levels described in [AD4], with no anomalies.

- **Day 3 – 08th June 2023:**
  - The Mortar adaptor plate has been modified to fit DUT1, as described in [AD3].
  - DUT1 was prepared for vibration testing, as described in [AD3].
  - DUT1 was installed on shaker slip plate, as described in [AD3].
  - TRR was performed for DUT1, as described in [AD3].
  - DUT1 was tested along its x- and y-axes, following procedure described in [AD3], i.e. with valve handle and pressure sensor cable removed. The following occurrences happened during testing:
    - During the random vibration test along the DUT1 x-axis, the control software stopped due to software issue at a test duration of 49.49s.
    - DUT1 remained pressurized along all tests. A slight increase in pressure was recorded, presumably due to heat transfer from warm oil flowing through the shaker slip plate.

- DUT1 was left pressurized overnight.

- **Day 4 – 09th June 2023:**
  - Pressure inside DUT1 was measured, with no significant leakage identified.
  - DUT1 was removed from shaker slip table and shaker was rotated into vertical position. DUT1 was then re-mounted.
  - DUT1 tested along its z-axis following procedures and test levels described in [AD3], with the following occurrence:
    - The high-level sign vibration test was aborted due to slightly disconnected accelerometer C1. The accelerometer connection was fixed, and high-level sign vibration test was repeated.
    - DUT1 remained pressurized throughout all tests.
  - It was decided to test DUT2 again along its z-axis, without the parachute cup installed. For this:
    - Accelerometers M1, M2 and M3 were removed from DUT1. Accelerometers C1 and C2 remained glued on the shaker adaptor.
    - DUT1 was removed from shaker and dismounted form the adaptor.
    - DUT2 without parachute cup was mounted to the adaptor.
    - Accelerometers M1 and M2 installed on DUT2. Both were placed on the outside of the mortar cylinder. M1 at the cylinder top, M2 at the cylinder bottom.
    - DUT2 without parachute cup was tested along its z-axis, following the same test levels and procedures used for DUT2 earlier, described in [AD4].
    - No anomalies occurred during testing of DUT2 without parachute cup.
    - DUT2 (without parachute cup) was dismounted from shaker.
  - All Mortar equipment was packed.

1.2 Overview of modifications to the test set-up & procedure

The test set-up was performed according to the [AD1] with the following modifications:

For the DUT1:
- The valve handle was removed for the vibration tests.
- The pressure sensor cable was disconnected for all test runs.
- The adaptor plate was slightly modified to fit dowty seals. For this, the existing pocket in the adaptor was increased by approximately 1mm with a Dremel.

For the DUT2 **with** parachute cup
- The DUT2 was tested with 3d printed parachute cup, which is not described in [AD1].
- The accelerometer on top of the sabot inside the mortar cylinder was not installed.
- Sensor M4 broke during testing and was changed with M3.

DUT 2 **without** parachute cup was tested in z-axis only, with only two accelerometers placed on the outside of cylinder.

1.3 Preliminary results of post test functional checks

The post-test functional checks did not show any anomalies.

1.4 Post test status of the facility and GSE

- Accelerometer M4 was damaged. The sensor cable ripped has been ripped out of connector.
- One bandaid was used.

1.5 Confirmation of test data acquired, recorded, and archived facility side.

- CSF confirms that all Vibration data has been recorded and archived. Data will be provided to DARE mortar team.

- The DARE Mortar team confirmed that the pressure data taken during DUT1 testing was logged.

2 OVERVIEW OF POSSIBLE NON-CONFORMANCES

No no-conformances have been identified.

3 ACTION SUMMARY

Table 2 – Action Summary

Action ID	Status	Action Description	Actionee	Target Date
A1	open	CSF to provide vibration data to DARE MORTAR team	CSF	16/06/2023
A2	open	CSF to provide pictures	CSF	16/06/2023
A3	open	CSF to send MoM	CSF	16/06/2023
A4	open	Team to write test report	Team	31/07/2023
A5	open	Team to present	team	31/08/2023

4 OTHER TOPICS

No other topics.

5 PRELIMINARY CONCLUSION

Success – all objectives met

6 FEEDBACK AND LESSONS LEARNED

Lessons learned by the team are as follows:

- Testing took longer than expected. On REXUS vibration testing is much faster, but also no time is taken for in depth explanations there.
- The vibration adaptor flange size should take cable routing into account. A bigger diameter is better as it gives more options for cable routing.
- It would be good to know how sensors look beforehand and also to know about cable routing requirements.
- The team has learned a lot, in particular:
  - How to behave in a cleanroom.
  - How to determine torque levels.
  - How to understand and interpret vibration test results.

Feedback about logistics was collected.

SIGNATURE PANEL

Signatures	
(On behalf of ESA)	
(On behalf of MORTAR)	

D

Delft Aerospace Rocket Engineering

This appendix contains statistics from the DARE membership database, which is relevant to subsection 5.2.2.

DARE
Delft Aerospace Rocket Engineering

Membership Administration

Home | Members | Boards | Commissions | Projects | Functions | Safety | Profile | Statistics | Logout

Hello **Esmée Menting**

Statistics

Overview

There are currently records of a total of 1103 members in this database. Of these members, 410 are active. The members can further be divided into 192 ordinary members, 38 extraordinary members, 165 alumni and 10 members of merit. Further there are 5 honorary members and 0 donors.

The active ordinary and extraordinary members combined represent 42 countries. There are 202 Male and 28 Female members.

Institutions and Faculties

Delft University of Technology		
Aerospace Engineering	171	+71
Computer Science and Engineering	12	
Electrical Engineering	10	
Mechanical Engineering	6	
Civil Engineering	3	
Technology, Policy and Management	3	
Applied Mathematics; Applied Physics	1	
Applied Physics	1	
Industrial Design	1	
Nanobiology	1	
TU Delft		
Aerospace Engineering	11	

Computer Science and Engineering	1
Mechanical Engineering	1
Technology, Policy and Management	1
Inholland University of Applied Sciences	
Aeronautical Engineering	1
Ludwig Maximilian University Munich	
Business Mathematics	1
University of Pisa	
Aerospace Engineering	1

Study State Distribution

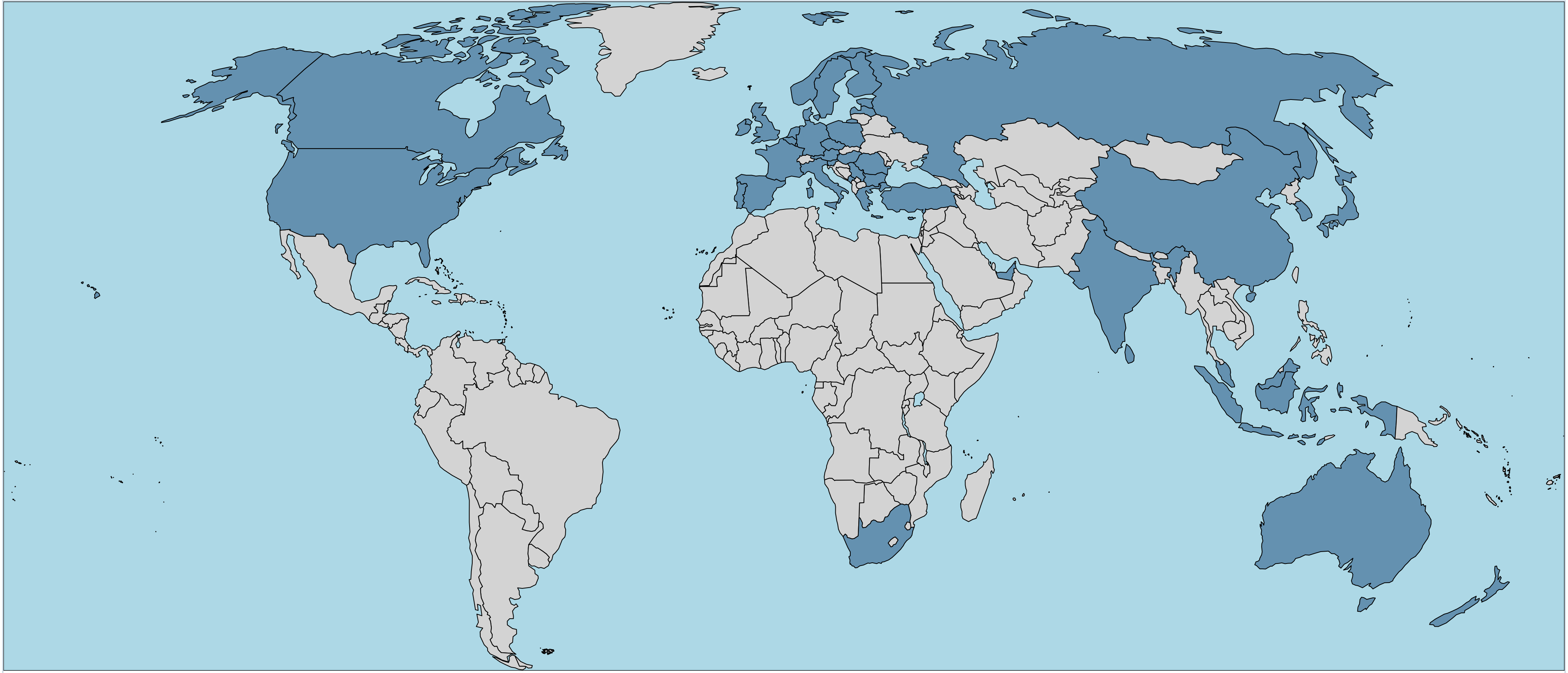
Bachelor	176	+76
Master	52	
Exchange	1	
HBO	1	

Projects, Commissions and other Organizations

Project	
Stratos V	70
SRP 2023	45
PRG	23
Dodo	13
Arc	12
Electronics	11
Chimera	11
Solids	8
Monolith	7
SHEAR	7
Vulture	7
Longboi	6
NEAR - EuRoC 22	5
Turbomachinery Development	5

Albatross	4
Universal Booster System	3
Commission	
CanSat	18
Safety Commission & Board	17
Launch Day Committee	13
Friends of DARE	12
Supervisory Board	6
Financial Committee	4
Activities	1
Function	
Server Admininstrators	7
Board	
2022-2023	6

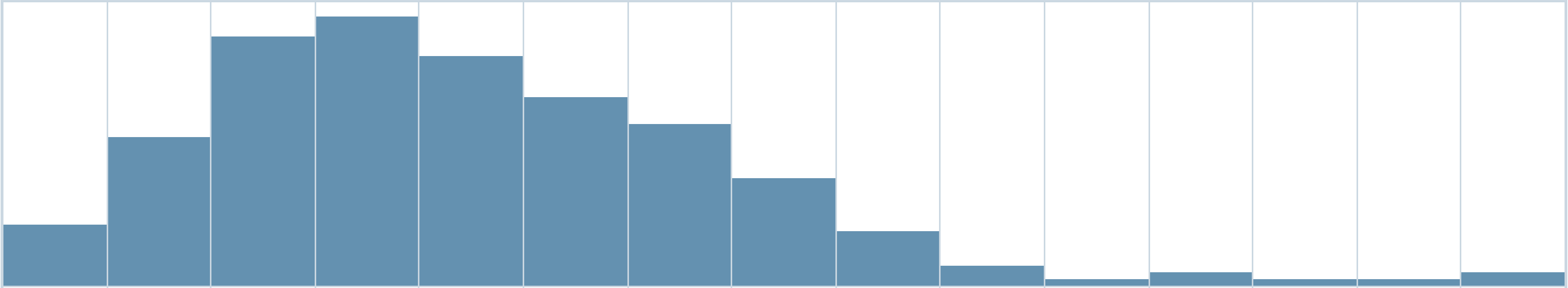
Nationalities



Netherlands	86
Germany	16
Poland	15
Belgium	15
Italy	12
Spain	10
Romania	9
United States of America	7
France	7
Greece	7
Ireland	6
United Kingdom of Great Britain and Northern Ireland	6

Portugal	6
Russian Federation	4
Hungary	4
India	4
Estonia	3
Denmark	3
Czechia	3
Bulgaria	3
Luxembourg	2
Canada	2
Finland	2
Indonesia	2
Sweden	2
China	2
South Africa	2
Cyprus	2
New Zealand	1
Malaysia	1
Austria	1
Sri Lanka	1
Serbia	1
Australia	1
Korea, Republic of	1
United Arab Emirates	1
Japan	1
Turkey	1
Norway	1
Montenegro	1
Slovenia	1
Latvia	1

Age Distribution



9	22	37	40	34	28	24	16	8	3	1	2	1	1	2
18	19	20	21	22	23	24	25	26	27	28	29	30	31	32

Beginning of Membership

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2009									2			
2010												
2011												
2012									2			
2013												
2014											1	1
2015												
2016	1	3										
2017		1					1	1		1		1
2018		6		2					5	1		1
2019		8					7		3		2	
2020		1	1			1	4	2	7	3	2	
2021		11		4		6	1	13	4			
2022	1	16	2		11	2	5	10	9	2	1	2
2023	1	36	7	1	8	6						

E

Pre-existing documentation

This appendix displays pre-existing documentation, such as:

- Space Project report, detailing the development of the SPEAR mortar between 2018-2022 (excluding appendices)
- Assembly procedures of the parachute mortar (2020)
- Assembly procedures of PIP-III (2023)

Parachute Mortar

Development and testing for the SPEAR mission

Authors:
Esmée Menting

Version:
V 1.1

Monday 22nd May, 2023

Contents

1 Introduction

Recovery systems are implemented in sounding rockets for various reasons, such as retrieving valuable flight data that cannot be sent over a telemetry downlink or recovering and refurbishing hardware for analysis, display or reuse. High altitude recovery systems generally consist of two or more parachute stages. Here a drogue parachute is deployed to stabilise and decelerate the vehicle such that the main parachute, the main decelerator, can deploy safely. The deployment of these drogue parachutes is therefore generally quite violent; it may face extremely high (supersonic) velocities, high inflation loads, or instability of the vehicle.

These conditions lead to the need for a fast drogue parachute deployment. A slow deployment from an unstable vehicle may lead to entanglement or inversion of the parachute, or lines being damaged due to a sideways deployment. A slow ejection from a vehicle travelling supersonically may mean the parachute does not deploy fully from its container or bag due to the vehicle wake. Additionally, a slow parachute deployment significantly decreases the reliability of the deployment altitude and conditions; the vehicle can easily descend for multiple kilometres during a slow parachute deployment when travelling supersonically. For these reasons, the Stratos III and Stratos IV missions both used a mortar system as high-velocity deployment device to eject the supersonic capable Hemisflo drogue parachute. The parachute mortar is essentially a short, smooth tube that is sealed at one end and attached to the rocket. Upon actuation, an explosive charge or cold gas system creates pressure which propels the parachute out of the tube and away from the rocket.

The parachute mortar is also implemented in the Supersonic Parachute Experiment Aboard REXUS (SPEAR). SPEAR is a mission specifically designed to test the aforementioned Hemisflo drogue parachute in supersonic conditions, to validate its performance in flight. The mission consists of a test vehicle or Free Falling Unit (FFU) which is ejected from the REXUS28 sounding rocket at apogee, around 95 km altitude. The vehicle speeds up throughout its descent after which it deploys the test parachute whilst travelling at supersonic speed. The pyrotechnic mortar system is selected as the deployment system as this enables a high ejection velocity which is necessary to attain successful supersonic parachute deployment and inflation. In addition to this, the SPEAR mission aimed to test the Stratos IV drogue parachute, meaning the deployment system should be as similar to the Stratos design to make the test as representative as possible.

Within the SPEAR project, it was originally planned to use the mortar system after it was fully developed by Stratos IV, a mission that aimed to launch in the summer of 2019. However, in May 2019 it was decided to postpone the Stratos IV launch by one year, resulting in a pause in the mortar development. As the SPEAR mission is a student experiment participating in the REXUS/BEXUS program, it has to comply with the program timeline where the design must be finalised in June 2019 and all hardware and testing activities must be finished by November 2019. Until the Stratos IV launch delay, the mortar system reached its first design, meaning that a significant development effort was needed within the SPEAR project to bring the system to a flight-ready level whilst complying with the REXUS timeline. The main challenges of the parachute mortar development within SPEAR are as follows:

1. The strict timeline: the team had less than one year to develop the system. The REXUS/BEXUS project has milestones that are monitored by the following reviews:
   - Preliminary Design Review (PDR) in February 2019
   - Critical Design Review (CDR) in June 2019
   - Integration Progress Review (IPR) in August 2019: first demonstration of hardware.
   - Experiment Acceptance Review (EAR) in October 2019:
     Hardware should be finalised and system tests should be completed.
   - Integration and Testing Week (ITW) in December 2019:
     Vibration test and integration tests with REXUS28 and its experiments.
   - Bench test in January 2020:
     Final integration tests with REXUS28 and all its experiments.

The little time available to develop and test the system meant the team had to select between various verification and validation activities. There was a high focus on reaching a functional system, which regularly took priority over appropriate data collection or risk reduction.

2. The SPEAR financial resources were limited, as it proved difficult to acquire sponsors and the DARE society has limited money available for team budgets. This resulted in a need to be thrifty and reuse available materials, sensors and test hardware available within DARE or the university.
3. As the SPEAR test vehicle had to fit below the REXUS28 nose cone, the available volume was extremely limited. This restricted the volume and possible attachment methods of the mortar system in addition to making safe assembly and operations more challenging.
4. The parachute deployment window of the SPEAR drogue parachute is at a high altitude (25-35 km), meaning the external pressure is low. This introduces the challenge of reliably igniting pyrotechnics in a low-pressure environment.

In the design phase of the SPEAR project, the team adapted the mortar tube developed by Stratos III and the gas generator designed in Stratos IV to its own needs and requirements. After taking up the development process in May 2019, the SPEAR team worked with a "build, test, iterate" approach due to the exacting REXUS timeline. This document describes the existing systems of Stratos III and IV as "starting point" in section 2 and the requirements for the SPEAR mission in section 3. The following sections describe the design changes made for SPEAR (section 4), early development testing (section 5), the production process (section 6) and validation tests of the flight design (section 7). Lastly, the tests during the launch campaign as well as the SPEAR launch itself are described in section 8, and a conclusion and recommendations for future development are given in section 9.

2 Background

This chapter describes the working principle of a mortar system, and the development of previous mortar systems and designs within DARE, in order to clarify the starting point of mortar development in SPEAR as well as highlight any important past challenges and design choices.
A system overview of the mortar can be seen in Figure 1. A power unit (not illustrated), connected to the plenum volume, will create or release gas upon actuation. This power unit can contain cold gas, such as CO_2, or a pyrotechnic charge, actuated by a solenoid valve or electrical matches respectively. When the gas expands it exerts pressure on the sabot, which is a sliding disk, that in turn exerts pressure on the parachute pack and the lid. The lid is constrained using shear bolts, which shear off when a predetermined pressure is reached. At this moment the lid, parachute pack and sabot will be ejected from the canister at a high velocity.

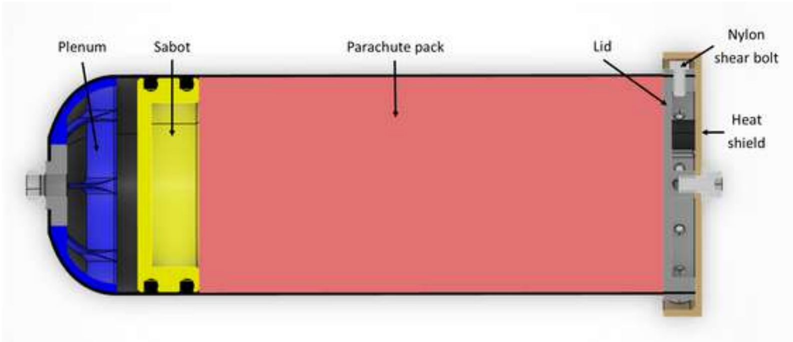


Figure 1: System overview of the Stratos III parachute mortar

The mortar is the first high-velocity parachute deployment system developed in DARE. Its development started in 2015 for the Aether mission: a technology demonstrator for the Stratos III rocket. As described in section 1, a high-velocity deployment system was deemed necessary to deploy parachutes when the vehicle descends at a high velocity or in an unstable manner - both possible scenarios for the Stratos III vehicle at the start of its design. The original mortar system had a cold gas power unit, using CO_2 to pressurise the plenum volume. The system underwent deployment tests as well as a launch on the CanSat V7M rocket, which were all successful. Unfortunately, the Aether project was postponed and eventually cancelled due to issues with engine development. Images of the first mortar test version, Aether mortar design and cold gas mortar in the CanSat V7M rocket can be seen in Figure 2.

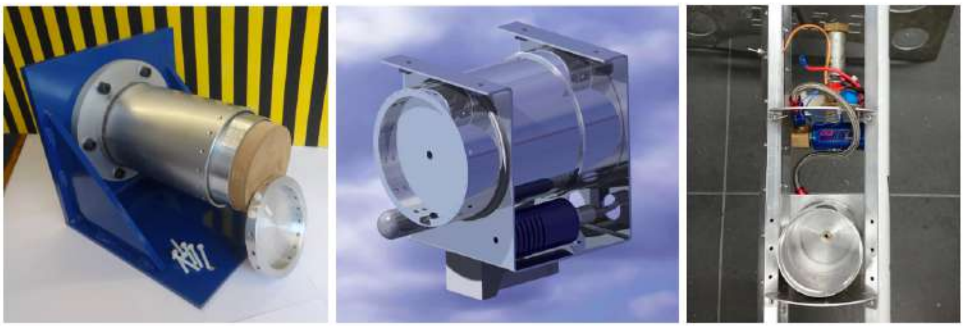


Figure 2: Test mortar (left), Aether mortar design (middle), mortar in CanSat V7M rocket (right)

The cold gas mortar system was implemented in the Stratos III mission, where two large design changes were made. Firstly, the dimensions of the canister were adjusted to fit the Stratos III drogue parachute and for the mortar to fit in the recovery section. This increased the aspect ratio (L/D) of the mortar, which leads to a higher reaction load when keeping the ejection velocity constant. Secondly, the canister was made from Carbon Fibre Reinforced Polymer (CFRP) instead of aluminium to save weight.
Throughout the Stratos III project, a simulation code was written to predict the burst pressure,

measured in the plenum volume, based on the number of shear bolts. Although a linear relation is observed in both simulation and experimental results, the slope of experimental results is higher, resulting in an increasing error with more shear bolts used. Various challenges of the cold gas mortar are described below. Midst the development phase of the Stratos III mortar, it was found that the solenoid valve clogged often during or between tests and required regular cleaning. Additionally, assembly and leak testing of the system took a lot of time. At the launch campaign, it was discovered that some of the CO_2 charge cartridges (COTS item intended for bike tire inflation) contained grease and particles which clogged the solenoid and/or valves directly upon firing. As it was not possible to identify whether a charge was clean or foul before firing, this introduced a large risk into the system. Different suppliers were consulted and their cartridges were tested, but none reliably provided a clean cartridge. Unfortunately, the Stratos III rocket broke up mid-flight during its launch in July 2018, meaning the recovery system could not be actuated or tested.

The challenges of the cold gas system mentioned above provided the prime motivator to consider a pyrotechnic mortar instead. Additionally, there is a significant volume and mass decrease possible when moving from the cold gas to a hot gas system, as can be seen in Figure 3. The main advantage of the cold gas system over the hot gas system is the ease of transport; there are significant transport restrictions on pyrotechnic charges and ignitors, and transport of pyrotechnics is expensive, which means they may have to be sourced locally. It can be debated which system has higher reliability; in low-pressure conditions ignition of pyrotechnics is unreliable, but in the cold gas system there is a high risk of leakage due to vibrations during ascent.

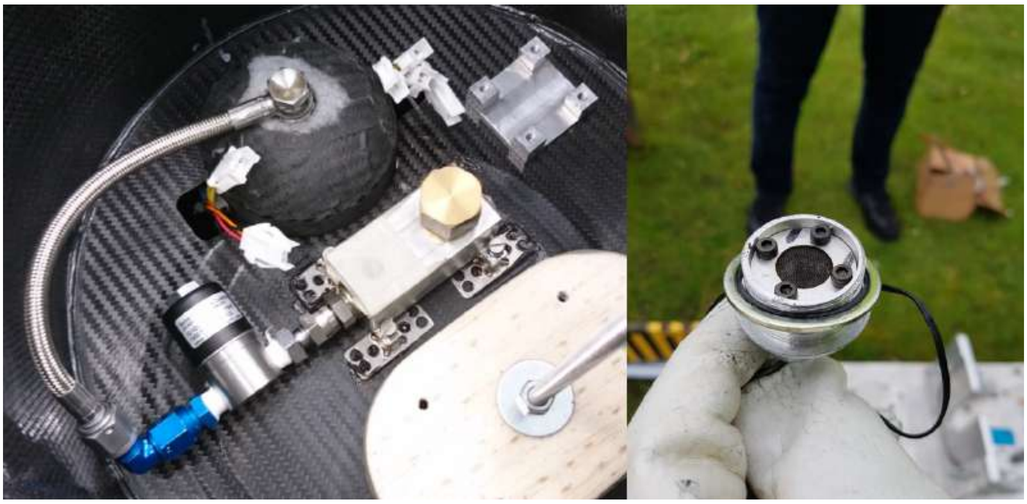


Figure 3: Cold gas feedsystem, Stratos III (left) and pyrotechnic gas generator, SPEAR (right)

To achieve mass and volume reduction, the Stratos IV mission opted for the pyrotechnic mortar system. In addition, the team ran new structural simulations on the mortar canister and adjusted its design from 6 layers of carbon fibre to 4 (orientation: 45/-45, 90/0, 90/0, 45/-45). Documentation on the simulations is unfortunately not available. All other parts in the mortar system, such as the lid and sabot, stayed identical to the Stratos III design. The Stratos IV recovery team designed and produced the first version of the gas generator, and selected Nitrocellulose (NTC) as the propellant. The team also ventured to write a new simulation code to calculate how much NTC, in combination with how many shear bolts, would generate a certain ejection velocity. Based on these simulations a design was selected of 0.1-0.2 grams NTC and 9-11 shear bolts. The documentation on the first design and this code as published in February 2019 can be found in Appendix E. A first ejection test campaign was held on the 25th of April 2019 with this design, which did not manage to eject the parachute from the mortar tube as the shear bolts did not break. Shortly afterwards in May 2019, the Stratos IV mission was delayed by one year, and the mortar system development came to a halt. From here onwards, the SPEAR team continued the mortar development as will be described in the upcoming sections.

3 Requirements

The requirements that are imposed on or relevant to the SPEAR mortar can be seen in Table 1, including their respective IDs which indicate the type of requirement (functional, performance, design, operational). In the third column, the intended verification and/or validation method is shown (Analysis, Test, Review, Inspect).

At the start of the project, the team used the approach as taught at Delft University of Technology, which has been implemented in most DARE projects. This provided an elaborate set of requirements of 8 pages. However, it was advised by the REXUS organisers to modify this and follow a more practical approach; all "obvious" requirements (such as requirements indicating compliance to the REXUS manual) or detailed requirements (mass or volume per subsystem) were to be deleted. This reduction is the main difference between the mortar system requirements in Stratos and SPEAR. It left the SPEAR team with a more concise set of requirements, keeping them manageable and promoting active use of and interaction with this document. Additionally, this allows the team to perform the selected V&V activities within the strict REXUS program timeline.

ID	Requirement	V&V
SPEAR-F-03	SPEAR shall deploy the drogue parachute	T, R
SPEAR-P-06	The drogue deployment system shall deploy the drogue parachute with a minimum velocity of 20 m/s	A, T
SPEAR-P-07	The drogue deployment device shall have a maximum mechanical deployment time uncertainty of 0.1 s	A, T
SPEAR-P-25	The drogue deployment device shall be able to deploy the drogue parachute in a pressure range from 3 to 110 kPa	T
SPEAR-D-01	The mass of the SPEAR experiment shall be at maximum 10 kg	A, T
SPEAR-D-02	The mass of the SPEAR experiment should be at maximum 8 kg	A, T
SPEAR-D-06	The SPEAR vehicle shall handle a minimum vibration of 12.7 g RMS	A, T
SPEAR-D-07	The SPEAR vehicle shall handle a minimum acceleration of 12 g	A, T
SPEAR-D-08	The first natural frequency of SPEAR shall not fall below 40 Hz	A, T
SPEAR-O-01	SPEAR shall operate autonomously	R, A, T

Table 1: SPEAR requirements relevant to the mortar system

This set of requirements is based on the following premises:

- The SPEAR mission aims to perform a supersonic parachute test. This includes the deployment of the parachute in supersonic conditions, meaning it must be stored in the vehicle until the test window opens. Resulting in: **SPEAR-F-03**.
- The SPEAR mission aims to perform a supersonic parachute test. The moment of ejection should be timed as precisely as possible to reach the desired test conditions. Resulting in: **SPEAR-P-06 and SPEAR-P-07**.
- The SPEAR mission aims to perform a supersonic parachute test. The parachute must be ejected at a high velocity to ensure line stretch, bag strip and parachute inflation before decelerating too much, in order to test the parachute in supersonic flight. Resulting in: **SPEAR-P-06**.
- The SPEAR mission aims to perform a supersonic parachute test. Simulations indicate the possible deployment window of the drogue parachute lies between 20-25 km altitude. A lower deployment does not meet test conditions but is still possible. The mortar must be able to deploy the drogue parachute at all altitudes between 0-25 km. Resulting in: **SPEAR-P-25**.
- The SPEAR mission will fly on the REXUS28 rocket. The application has been accepted for a payload mass of maximally 10 kg. A slightly lower mass is desirable to have more leeway in the final design and AIT activities. Resulting in: **SPEAR-D-01 and SPEAR-D-02**.
- The SPEAR mission will fly on the REXUS28 rocket. During ascent, the full vehicle and all systems must withstand the vibration profiles of the rocket. As SPEAR is a Free Falling

Unit (FFU), the vehicle must comply with qualification level testing of the REXUS program. Resulting in: **SPEAR-D-06, SPEAR-D-07 and SPEAR-D-08**.

- The SPEAR vehicle shall detach from REXUS at apogee. There is no uplink available or communication possible throughout its descent. Therefore the test vehicle must operate fully autonomously. Resulting in: **SPEAR-O-01**.

Compliance with the REXUS timeline in itself is a demanding constraint imposed on the development process and had the most significant influence on design and test choices. The timeline can be seen in Figure 4. As indicated in section 1 the goal was to use the mortar system developed by the Stratos IV recovery team. As there was a large overlap between members of the SPEAR and Stratos IV recovery teams, knowledge transfer went well and did not form an issue. When the SPEAR team picked up the development in May 2019, the team had roughly one month to finalise the detailed design and 5 months to conduct all test campaigns and produce the flight hardware.

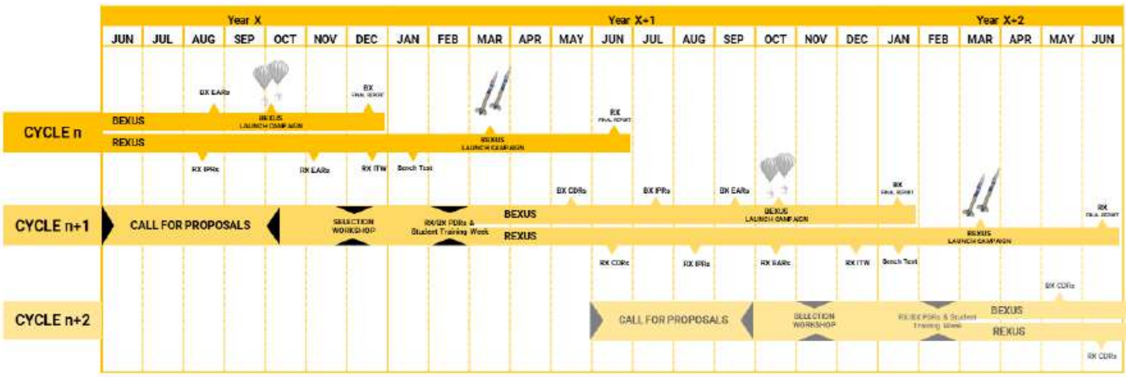


Figure 4: The REXUS/BEXUS program timeline

Due to this strict timeline, testing and analysis activities were often conducted in parallel. For the parachute mortar, this was mostly relevant to determine compliance with the ejection velocity and the vibration load requirements. Eventually, the pursuit of a detailed FEM analysis was dropped due to complexities in modelling the clamp band system, and the analysis was replaced by an additional vibration test.

4 Design of the SPEAR mortar

An exploded view of the parachute mortar can be seen in Figure 5 to illustrate the design and display all parts. This image displays the Stratos IV version of the attachment ring. The parachute mortar system consists of various manufactured parts, commercial off-the-shelf (COTS) parts, materials and fasteners, which are listed in Table 2, in a left-to-right order when looking at Figure 5.

Figure 5: Exploded render of the parachute mortar parts

Subsystem	Part	Material	Production method
Gas generator	Ignitor bolts M8x12	Stainless steel	COTS, turning
Gas generator	E-matches	Electric wire, pyrotechnic charge	COTS
Gas generator	Ignitor bolt glue	Bison Kombi epoxy lijm	COTS
Gas generator	Gas generator	Aluminium	Turning, milling
Gas generator	Teflon tape	Teflon	COTS
Gas generator	Flash paper	Paper, nitric acid	COTS
Gas generator	Vectan Ba10 powder	Nitrocellulose	COTS
Gas generator	Mesh 60	Stainless steel	Laser cutting
Gas generator	Retainer ring	Aluminium	Laser cutting
Gas generator	Retainer ring bolts (M3x6 mm)	Stainless steel	COTS
Canister	Insert	Aluminium	Turning
Canister	Insert glue	Araldite AW4858	COTS
Canister	Endstop	PLA	3D printing
Canister	O-rings	Nitrile Butadine Rubber	COTS
Canister	Sabot	POM	Turning
Canister	Canister	CFRP	Prepreg layup
Canister	Parachute pack	Various fabrics	Sewing
Canister	Lid	Aluminium	Turning, milling
Canister	Shear bolts (M4x16mm)	Nylon	COTS
Attachment	Attachment ring	Aluminium	Water cutting, turning, milling
Attachment	Attachment bolts (M4x10mm)	Stainless steel	COTS
Attachment	Attachment ring glue	Araldite AW4858	COTS

Table 2: Parts and materials list of the parachute mortar

Starting from the design of the Stratos IV mortar as described in section 2 and Appendix E, the SPEAR team made a number of design changes to the system. These are described below. The technical drawings for the SPEAR mortar can be found in Appendix D.

1. Accommodation of the Deployable Aerodynamic Stabiliser (DAS).
   Due to the limited volume of the SPEAR test vehicle, constrained by the REXUS nosecone dimensions, it was not possible to make the vehicle inherently stable. As a stable descent is needed to increase the descent velocity to supersonic conditions, a Deployable Aerodynamic Stabiliser (DAS) is implemented in the SPEAR design. Throughout the design phase, a small ballute parachute was selected as the DAS. The ballute would be stored on top of the parachute mortar lid, together with a small spring-based deployment system. As there is limited space available in SPEAR below the mortar, the mortar canister length was increased above the lid, allowing space for the DAS subsystem. This increase in the length of the canister, and thus longer stroke of the sabot and parachute pack, which might require an increased pressure and thus weight of NTC to eject at the same velocity as the Stratos IV canister. The deployment system and the attachment point of the DAS were integrated with the mortar lid, ensuring separation of the DAS upon parachute deployment in order to prevent entanglement with the drogue parachute. Later on in the SPEAR project the ballute was replaced by a drag cone due to concerns regarding inflation. The integration with the mortar changed slightly due to the addition of the DAS support, which holds a small deployment spring and drag cone itself. The DAS subsystem and integration with mortar lid can be seen in Figure 6.

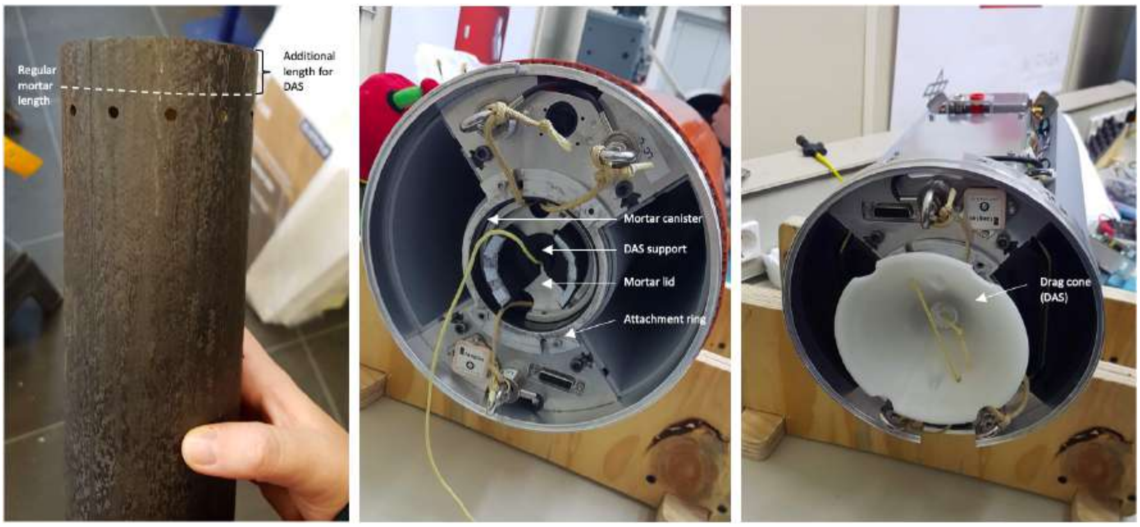


Figure 6: Mortar canister length (left), DAS support (middle), DAS assembled (right)

2. Attachment of the mortar.
   Although the attachment of the SPEAR mortar was highly similar to the Stratos mortars, the bulkhead it was fastened to was from aluminium (SPEAR) instead of CFRP (Stratos), meaning it was mounted using fasteners instead of glue. This led to a small redesign of the attachment ring, including a wider flange. The DAS system, mounted on top of the mortar lid, is kept in place by an Aramid wire running over the DAS which is clamped below the bulkhead. Slots are introduced in the attachment ring to allow for this cable. The attachment ring can also be seen in Figure 6.
3. Actuation logic.
   As the REXUS rocket has a well-known performance, it has far higher reliability in its pre-launch simulations than any DARE rocket. This allowed the SPEAR team to rely on timer windows for parachute actuation instead of sensor-based actuation which is used on other high-altitude DARE missions. The timer windows are both simpler to implement

and had a higher confidence of the team, as the sensor-based actuation was a challenging aspect of the recovery systems in Stratos III and IV and was untested. The mortar and thus drogue parachute deployment were actuated at a set time from SPEAR separation, an event recognised by two electrical break wires.

4. Mass of Nitrocellulose (NTC) and the number of shear bolts.
From the development in Stratos IV it was clear that the combination of 0.2 grams of NTC with 9-11 bolts, as determined by the simulation code, did not eject the parachute. The SPEAR team decided on an iterative testing approach over further analyses. In order to accommodate a higher amount of NTC, the gas generator length and therefore volume was increased to accommodate roughly 0.8 grams of NTC. To insure all NTC pellets are ignited, flash paper [1] wads are added to compress the NTC and fill up the volume of the gas generator. The steps of filling the gas generator can be seen in Figure 7. Tests to establish which combination of the amount of NTC and shear bolts achieves the desired ejection velocity and reaction loads are described in section 5.

Figure 7: Filling of the gas generator with flash paper and 0.5 grams of NTC

5. Electronic initiators.
Throughout the development of the parachute mortar, regular initiators were used from the DARE stock. However, these electric matches have a relatively low maximum no firing current (0.2 A) and minimum firing current (0.57 A), and concerns were raised that electrostatic discharge (ESD) at Esrange, Kiruna, might easily produce such a current, leading to undesired ignition of the gas generator. Therefore the Swedish Space Corporation (SSC), launch site operator and one of the REXUS organisers, sponsored the SPEAR team with their own initiators. These have a maximum no firing current of 1.2 A and a minimum firing current of 3.5 A. As it is difficult and expensive to transport pyrotechnics, the first test opportunity with these initiators was during the launch campaign, which is described in section 8. The DARE initiators, which had been used throughout all earlier tests, were still present at the launch campaign as back-up solution. Both initiators can be seen below in Figure 8, where the DARE initiators are already run through the ignitor bolts and the SSC initiators are covered by a rubber blast cap (light grey). The black rubber cover is removed manually to enable placement in the ignitor bolt.

Figure 8: DARE initiators (left) and SSC initiators (right)

[1]Flash paper is made from nitric acid and burns quickly.

5 Technology development test campaigns

From previous experience with the cold gas mortar system, as described in section 2, it was difficult to simulate the ejection velocity based on the pressure in the plenum volume. The first simulation written by Stratos IV for a pyrotechnic mortar also did not provide correct results, as the first testing attempt with 9-11 shear bolts and 0.2 grams of NTC did not achieve parachute ejection. Therefore, the SPEAR team executed multiple test campaigns in order to attain a functional mortar design. As the team members did not have experience manufacturing the CFRP canister, and this had a lengthy production process, it was determined to start with a battleship test mortar from aluminium. Simultaneously, a Low Pressure Ignition test campaign was initiated to evaluate the risk of underperformance at lower external pressures. Various Battleship Ejection (BE) and Low-Pressure Ignition (LPI) tests were conducted over the summer, of which a summary is presented in Table 3. The test reports as written throughout the project are added in Appendix B, however, some are of limited quality due to time constraints and/or low documentation standards in DARE.

Date	Test type	No.	Result
10-07-2019	LPI	1	Bulkhead slanted, no sealing possible anymore.
19-08-2019	LPI	0	System leaks, delay of test.
20-08-2019	BE	3	Two successful tests saw high velocity ejections. During one test a wedged sabot resulted in a low ejection velocity.
21-08-2019	LPI	4	Successful tests at desired pressures in plenum volume.
20-09-2019	BE	4	Repeated successful ejection tests achieved.

Table 3: Overview of mortar development tests

The **Low-Pressure Ignition (LPI) tests** were performed by igniting a gas generator, containing 0.5 grams of NTC, in a closed volume equal to the normal plenum volume. Through a vacuum pump, the pressure in this volume can be lowered to pressures between 0-1 bar in order to examine gas generator performance at different plenum volume pressures. The tests at LPI campaigns were performed under the following pressures, corresponding to relevant scenarios:

Pressure	Scenario
∼1.023 bar	pressure during ground ejection tests
0.5 bar	expected external pressure at deployment for Stratos IV at 5-6 km altitude
35 mbar	expected external pressure at deployment for SPEAR at 25 km altitude
0-5 mbar	minimum pressure in plenum volume

The volume was closed off on one end by the gas generator bulkhead, slid into the canister and constrained by a snap ring. On the other end a "sensor bulkhead" was placed, constrained by a snap ring as well. In order to prevent the bulkheads from sliding inward when the pressure was lowered, a 3D-printed spacer ring from PLA was placed inside. The sensor bulkhead contained a pressure sensor, temperature sensor, bleed valve, and a connection to the vacuum pump. This connection is closed off by a valve in order to prevent damage to the vacuum pump by the hot gases released by the gas generator. An image of the test setup and sensor bulkhead can be seen in Figure 9.

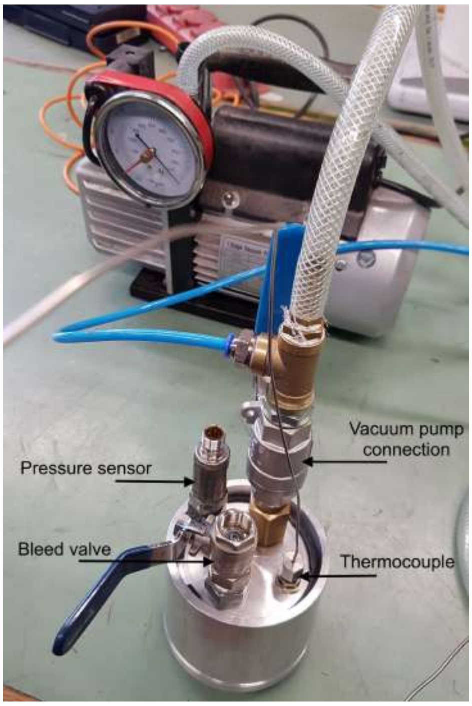


Figure 9: LPI canister configuration

The team faced a number of challenges whilst preparing for and executing the LPI test campaigns:

1. Allocation of the required valves and sensors on the sensor bulkhead. The LPI test canister made use of the same diameter as the battleship canister, in order to use available stock material and gas generator bulkheads. The sensors and valves should all be placed on one bulkhead, in order to keep the gas generator bulkhead on the other end freely accessible to ensure safe operations. The first sensor bulkhead that was produced did not succeed in accommodating all valves and sensors. Although technically they would fit in their final position, there was no way to assemble both valves without the handles colliding whilst fastening them. A redesign of the bulkhead with increased spacing, as well as dismounting the blue handle from the bleed valve and installing it after assembly of the bulkhead, enabled the final test setup to be completed.
2. The vacuum pump that was available in DARE had major leaks. The team took apart and rebuilt multiple connections of the pump and hose in the workshop in order to identify and mitigate the largest issues. Although it ended up functioning well in the lab, after transportation to the test location, new leaks were identified. These issues were only resolved by trial and error and a lot of patience, resulting in a number of test delays and even cancelled test dates (see Table 3). This was one of the major causes to cancel any future LPI tests with the purpose of gathering more data points, also with variable amounts of NTC, as LPI testing was deemed too time intensive for the project.
3. The pressure sensor used was selected from available sensors in DARE to measure pressures up to 100 bar and withstand high temperatures (300 C°). This unfortunately resulted in a low accuracy of approximately 0.5 bar, meaning the sensor did not provide reliable data on the pressure inside the plenum volume before a test (0-1 bar). This meant that, in order to establish the plenum volume pressure prior to ignition, the dial on the compressor had to be used before closing the connecting valve. This also meant it was not possible to observe any leaks in the plenum volume between closing the valve and initiating the pyrotechnic charge. In order to ensure the correct pressure was maintained and no leaks are present, the pressure was rechecked by opening/closing the connection to the vacuum pump dial twice before testing.

In the third LPI test campaign, four consecutive tests were conducted with success. For these tests the pressure in the plenum volume was brought to 0-5 mbar, 35 mbar, 0.5 bar and ∼1.023 bar (atmospheric pressure). The gas generator (GG) is mounted on the other bulkhead in the canister, as shown in Figure 10. Firing the gas generator at 0-5 mbar did not result in the ignition of the nitrocellulose charge, whilst the squibs did fire. This was double-checked by one extra test with the same result. In all other tests, the nitrocellulose charge ignited. A plot of the pressure and temperature over time during test 4 is shown in Figure 11. The curve of the pressure and temperature profiles is similar across all tests, with a different maximum value. Results of the maximum pressure and maximum temperature per test can be seen in Table 4. A significant performance drop can be observed for ignition at lower pressures, however, all nitrocellulose did burn fully. Ideally, the LPI test campaigns would be continued to research which amount of NTC will produce 36.2 bar as maximum pressure at a plenum volume pressure of 35 mbar. This would enable a comparison between ejection tests at sea level pressure with 0.5 grams of NTC and the lowered performance of [unknown] grams of NTC at 35 mbar in flight. However, it was unfeasible to continue LPI test campaigns due to the prolonged preparation and test procedures inherent to the current setup.

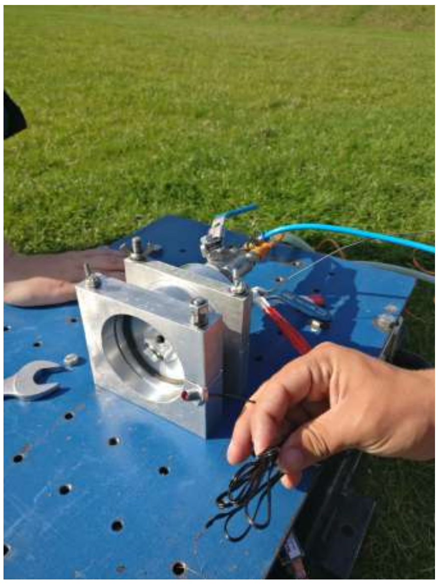


Figure 10: LPI test setup

Test No.	Pressure in plenum volume	Max. pressure after GG firing	Max. temperature
1	0-5 mbar	0 bar	25 °C
2	35 mbar	28.1 bar	109.5 °C
3	0.5 bar	32.8 bar	182 °C
4	~1.023 bar	36.2 bar	230 °C

Table 4: Results of Low-Pressure Ignition tests

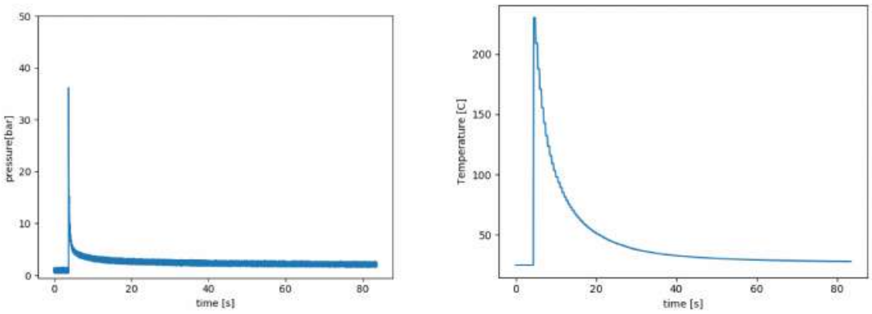


Figure 11: Graph of pressure (left) and temperature (right) over time for LPI test 4

The **Battleship Ejection tests** were performed by igniting a gas generator in a fully assembled parachute mortar, made from an aluminium casing instead of CFRP. The primary goal of the battleship tests was to achieve a successful ejection to quickly show proof of concept to the REXUS organisers, allowing the team to take more time for the production of the CFRP canisters. The secondary goal was to obtain data on the ejection velocity and kickback force of the mortar and the maximum pressure inside the plenum volume.
Unfortunately during the battleship test campaigns, there were multiple issues with the Data Acquisition system (DAQ) used: the cRIO (compact RIO), in combination with LabView as programming interface. This system is used regularly in DARE during engine tests by other DARE subteams. As the SPEAR team members were inexperienced with this system, they faced various challenges with achieving a proper connection, sensor readout, and data storage. Because the main focus of the test was on achieving a successful deployment, not enough time was spent on testing and troubleshooting the DAQ system, leading to very little measurements being done.

During the first test campaign on August 20th 2019, three battleship ejection tests were performed. In the first test the sabot got stuck in the canister. The parachute was still ejected but at a low velocity, leading to a low horizontal distance travelled (1m). The team was not able to determine the cause of this blockage, so the next tests were performed with the same setup. The second and third tests achieved a successful ejection, however no data was collected on the ejection velocity, kickback force and pressure. It was observed that in some tests the steel mesh remained intact, whilst in some tests it sheared out from the retainer ring (see Figure 12)

Figure 12: Battleship ejection tests - Result of test 1 (left), intact mesh and sheared mesh (right)

During the second test campaign on September 20th 2019, four successful ejection tests were performed. Two configurations were tried out, using four or six nylon shear bolts. A highspeed camera was used to obtain data on the ejection velocity of the parachute pack over a distance of 1.5-2 meters. The average ejection velocity per test can be seen in Table 5, and images of the system and tests can be seen in Figure 13.

Test No.	Mass of NTC [g]	Number of shear bolts	Average ejection velocity [m/s]
1	0.5	4	16.75
2	0.5	4	17.00
3	0.5	6	19.81
4	0.5	6	18.56

Table 5: Results of Battleship Ejection test campaign 2

These results lead to the selection of 0.5g NTC and 6 shear bolts as a configuration for future tests. Although the ejection velocity was slightly below the SPEAR requirements (see Table 1), further tweaking to reach the minimum ejection velocity of 20m/s would be done with the CFRP canister, as this material change could also influence the performance of the system.

Again, the team faced issues with the cRIO data acquisition system, leading to no data on the plenum volume pressure or kick-back force of the mortar. Throughout these test campaigns, the team iterated on the assembly and operational procedures of the system. As members gained more experience, the turnaround time between tests dropped to 1 hour. Examples of the test procedures can be found in Appendix C.

Figure 13: Battleship Ejection tests: Setup (left), side view (middle), front view (right)

6 Production process

Numerous SPEAR team members were very experienced with metal manufacturing (turning, milling), so these parts were regularly and quickly made throughout the mission. The production of the CFRP canisters was a larger challenge for the team. Within SPEAR only Esmée had some experience with composites manufacturing, so SPEAR collaborated with the Stratos IV recovery team to make all new canisters between October 2019 - February 2020 together. The following parts and production steps were used to manufacture a parachute mortar canister:

1. **Mould**: an aluminium positive mould is lathed from a solid cylinder of aluminium. It has a straight cylindrical shape with a dome on top, having a slight bulge where the hole for the insert needs to be. Generally in composite manufacturing, a draft angle of at least 3 degrees is implemented in any mould. This was not feasible for the mortar system, as this angle would lead to a diameter increase of 29mm over the full tube, which does not benefit a straight insertion and ejection of the sabot. The absence of a draft angle makes the CFRP canister difficult to release from the mould. The first mould used was made during Stratos III which used a plastic insert for the dome section. This mould was damaged by a different team upon release, which after an unsuccessful repair with putty (filler) meant that a new mould had to be produced. This SPEAR mould was made fully from aluminium. Both moulds can be seen in Figure 14.

Figure 14: Stratos III mould after putty repair (left) and SPEAR mould (right)

2. **Release agent**: this general composites manufacturing staple is applied to the mould, to promote easy release of the part. It is applied using blue paper to rub over the mould. A minimum of 3 layers is applied in different directions of the stroke, letting it dry 15-20 minutes per layer.
3. **Gelcoat**: the gelcoat is applied on top of the release agent, and will form the innermost layer of the finished mortar canister. It is used to make the inner canister surface as smooth as possible, to decrease friction between the sabot and canister. For SPEAR following materials were used: 7090 clear epoxy hars and 7091T epoxy verharder, in a 10:3 mixing ratio, from Resoltech. In total 65 grams of gelcoat was mixed and applied by paint brush. Later on, the gelcoat was coloured by adding orange pigment paste to increase visibility of the gelcoat. Different amounts of pigment paste were added, leading to less-more translucent colouring of the tube. The gelcoat was cured at 40 °C for 1 hour. The readiness of the gelcoat was checked by touching it (wearing a nitrile glove), it should leave a mark in the gelcoat but not wet the glove.
4. **Carbon fibre prepregs**: four layers of CFRP prepregs from Gurit were applied on top of the gelcoat. Three different shapes were cut: a square to cover the cylindrical tube section,

a circle to cover the top dome, and long strips to cover both the tube and dome. Examples of these cut shapes of prepreg can be seen in Figure 15.

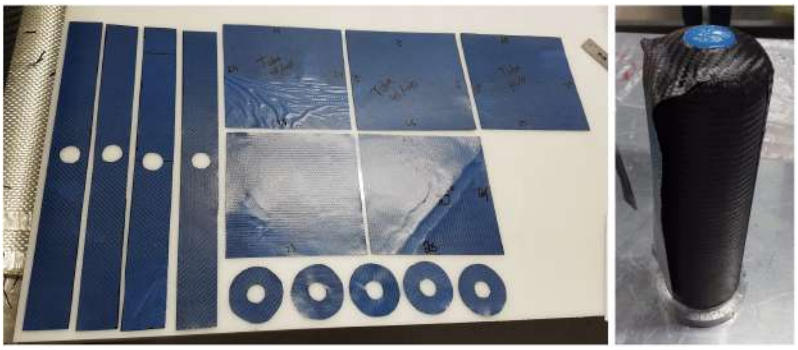


Figure 15: Cut CFRP prepreg shapes (left), canister during layup (right)

The following lay-up was used for the SPEAR canisters:

- Layer 1: 45/-45 dome + tube
- Layer 2: 90/0 4x strips
- Layer 3: 90/0 tube + dome
- Layer 4: 45/-45 tube + dome

During the layup, the layers are kneaded and manupilated into a flat layer. Cuts may be made into the dome and strips in order to fold the prepreg in a flat way. An example can be seen in Figure 15, where a strip is applied to the mould, which would need two cuts to flatten out the current bulges.

5. **Peel ply, release film, breather, vacuum bag, tacky tape**: are general composites consumables, which are applied on top of the CFRP prepregs. These enable the correct outer surface finish, release of the vacuum bag and proper resin dispersion during curing. The vacuum bag ensures that no air bubbles will remain in the part during curing.
6. **Curing**: after the vacuum bag is succesfully applied and leak tight, the part is placed in the oven for curing. The parachute mortar canister is cured for 3 hours at 100 °C.
7. **Demoulding**: after curing, the vacuum bag, release film, and peel ply are removed. Then the solid CFRP part is removed from its mould, by clamping it and hammering on the top bulge of the mould, or by placing it in a freezer for a few hours such that the mould shrinks more than the canister and it releases. The team faced many issues during this production step as the part would often not release. The main causes were the absence of the draft angle and roughness of/impurities on the mould. At two instances it was not possible to remove the part from the mould at all using the aforementioned methods. Due to this, and the high time pressure on finishing the parts, the team made use of the Liquid Nitrogen tanks at 3ME as extreme cooling method to release the canisters. It is not known what effect this process has on the part itself. The demoulding method can be seen in Figure 16.

Figure 16: Demoulding of the canisters using Liquid Nitrogen

8. **Post processing**: after the release of the canister, it needs to be shortened to the correct size, and the holes for the shear bolts must be made. In addition, any deformities or wrinkles in the tube surpassing 83.0mm in diameter needed to be sanded off in order for the canister to fit through the SPEAR bottom bulkhead. These post processing steps use a dremel, drill, and sanding paper, and are done in a specific carbon fibre sanding room whilst wearing a full body suit and full face mask as personal protection equipment (PPE).
9. **Integration**: using Araldite AW4858, the attachment ring and insert are glued onto the canister. All surfaces should be prepared by sanding them and cleaning them with acetone. It is important to adhere to the curing time of 24 hours at 21°C.

Five canisters were produced for the SPEAR mission using these methods, which can be seen in Table 6. On occasion the mould made for Stratos IV was used by SPEAR, and vice versa.

Number	Production date	Mould used	Gelcoat colour	Demoulding method
1	03-09-2019	Stratos III	Transparant	Manual
2	28-10-2019	Stratos III with putty	Transparant, spots	Liquid Nitrogen
3	15-12-2019	SPEAR	Translucent orange	Manual
4	31-01-2020	SPEAR	Bright orange	Liquid Nitrogen
5	31-01-2020	Stratos IV	Transparant	Liquid Nitrogen

Table 6: Production information of CFRP canisters

Unfortunately, there was insufficient quality control on the parts that were produced. This meant that certain sets of hardware fit better together than others. The main issues encountered during assembly were:

- The fit between the canister and the sabot & lid. After glueing the attachment ring onto the canister, it was more difficult to insert the sabot and lid. This varied per canister.
- Alignment of the radial holes between the lid and canister, as some canisters had better spacing between the shear bolt holes than others.
- Shear bolt threading into the lid. Some lids were not threaded as deep or as fully as others. The cause of this difference turned out to be that the used tap was the second part of a 3-part tapping set, and therefore did not fully thread the hole properly.

During test campaigns the full mortar system was regularly test fitted with all parts. On occasion, it happened that a select combination of hardware did not fit well together. Fortunately, the team had sufficient hardware to swap out an ill-fitting part when these situations appeared. To ensure no mismatch arose, an elaborate fit test was done before the final ejection test campaigns and the launch campaign.
The parachute mortar was assembled early on in the SPEAR vehicle during integration tests, ensuring no collisions occurred and the order of assembly worked well. These integration checks already started before any CFRP canister was manufactured by making a SPEAR mock-up from PLA and wood, as can be seen in Figure 17.

Figure 17: Early SPEAR prototype

7 System qualification test campaigns

Multiple test campaigns were executed in order to verify the flight configuration of the parachute mortar against the requirements composed in Table 1. The following will be discussed: vibration tests, (CFRP) Flight canister ejection tests, assembly tests and bench tests.

Two **vibration test campaigns** were performed during the SPEAR mission. As the SPEAR experiment is an ejectable vehicle, it had to be tested up to the REXUS qualification level, for which the test levels are specified in Figure 18.

Frequency	Level	Sweep Rate
(10-50) Hz	0.124 m/s (4.87 in/s)	4 octave per minute
(50-2000) Hz	4.0 g	4 octave per minute

Axes	Frequency	Level	PSD
Longitudinal (Z)	(20-2000) Hz	12.7 g_{RMS}	0.081 g^2/Hz
Lateral (X,Y)	(20-2000) Hz	12.7 g_{RMS}	0.081 g^2/Hz

Figure 18: REXUS Sinusoidal (left) and Random (right) qualification test levels for all axes

The first vibration test campaign, held at the NLR (Marknesse), was organised to verify the structural integrity of the clamp band separation system and the internal structure under REXUS qualification level vibration loading. This test campaign replaced the FEM analysis that was originally required in the experiment documentation for REXUS. The two main success criteria of the test were:

- There is no difference between the response curves in the resonance survey before and after the test, which could indicate a mass shift.
- There is no visible difference between the vehicle before and after the test, for example loose fasteners or damage to the structure.

All tests were completed successfully and showed no difference between the response curves or the vehicle itself. The test setup and parachute mortar within the vehicle can be seen in Figure 19.

Figure 19: Vibration test 1 [NLR]: SPEAR vehicle (left), parachute mortar in SPEAR (2x right)

The second test campaign, held at ZARM (Bremen), was the flight qualification test for the REXUS programme. This is a hard go/no-go moment for each experiment participating in REXUS, where the experiment must remain intact after the specified vibration loading. The two success criteria used during the NLR test remained the same, but one success criteria was added:

- The lowest eigenfrequency of SPEAR must be above 40 Hz.

The largest difference in the vehicle configuration between the tests at NLR and ZARM were the inclusion of the electrical subsystems (power, avionics and retrieval PCBs, cabling, sensors) and the outer shell of the vehicle. The test setup and SPEAR vehicle during the second vibration test campaign at ZARM can be seen in Figure 20. During the vibration tests, one M3x6 bolt holding the camera bracket let loose, but this was accepted after review and loctite should be applied during the launch. The lowest eigenfrequency of SPEAR was 67Hz. This is relatively low compared to other REXUS experiments, and is thought to be due to the springs and parachute subsystems in SPEAR, which allow for slight movement of roughly 2.1 kg of mass (approximately 27% of the vehicle mass). But, as it complies to the requirement set by REXUS, the test was deemed a success and the vehicle was structurally accepted for flight.

Figure 20: Vibration test 2 [ZARM]: vibration setup (left), inside SPEAR vehicle (2x right)

Numerous **Flight canister ejection tests** were performed as system qualification tests to confirm the correct performance of the CFRP canisters and that the final design configuration meets the ejection velocity requirement ($\geq 20m/s$) and remains structurally intact. However, design iterations were still needed on the attachment ring. It was possible for the team to test roughly every 2-3 weeks based on existing Fellowship field reservations and availability of DARE safety officers. Numerous test campaigns were cancelled or not completed fully due to external circumstances, as can be seen in the testing overview in Table 7.

Date	No.	Result
09-11-2019	0	Canceled due to sick safety officer.
14-11-2019	0	Canceled due to heavy rain, Fellowship field deemed unusable.
25-11-2019	1	Wedged lid, no deployment, likely due to asymmetric spacing of shear bolts.
07-12-2019	2	Canister mounting insufficient. One test with battleship tube.
15-01-2020	0	Canceled as pyrotechnic delivery was not scheduled by safety officer.
04-02-2020	1	Two ejections, failure of 5mm attachment ring during test 2.
21-02-2020	2	Delays due to no functional DARE ignition system (3 misfires), two successful ejection tests with 10mm attachment ring.
12-03-2020	1	One successful ejection test with 10mm attachment ring.
29-08-2020	5	One test without ejection (GG did fire), four successful ejection tests. Additionally, one gas generator and one ignitor bolt were fired in the open.

Table 7: Overview of CFRP canister ejection tests

The data that was collected for this report comes from various sources: test reports, slack communication channels, and personal photos. In general data collection and data management were poorly conducted throughout the full development of the parachute mortar. This leads to minimal available data for the kickback force and pressure inside the plenum volume. Camera footage was used to determine the ejection velocity, but it is not clear which cameras are used, at how many frames per second and how the data is processed. Only two generated velocity plots are stored. This also means the error on the data points is unknown. The following paragraphs describe the data and information that was collected per test campaign.

25-11-2019: although the nylon bolts had sheared off, the lid and parachute assembly had not exited the canister. The presumption is that the lid got wedged sideways due to asymmetric spacing of the shear bolts. Only 3 shear bolts were assembled due to assembly issues with the lid. The CFRP tube did withstand the pressure upon ignition of the gas generator. No pictures are available.

07-12-2019: one test was performed with a CFRP canister, clamped down between rubber sheets. This clamping method was insufficient, and the canister flew backwards upon ignition and parachute ejection. Due to this issue it was not possible to continue testing the CFRP canister, so the second test was performed with the old aluminium battleship canister. Here data was collected on the kickback force, which can be seen in Figure 21, and the average ejection velocity which was 18.5 m/s.

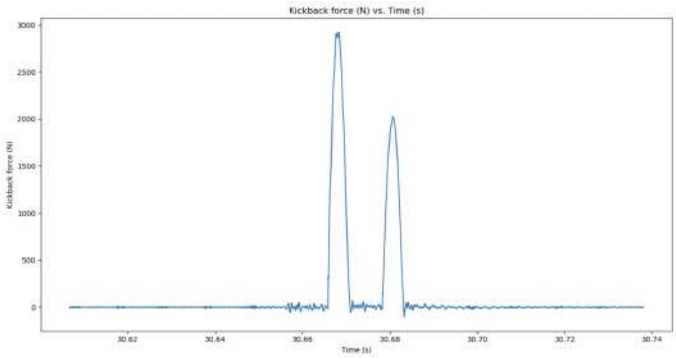


Figure 21: Kickback force over time of battleship ejection test

04-02-2020: the test report mentions a successful first test, but no data was stored due to issues with the cRIO data acquisition system. Data was collected for the second ejection test on the ejection velocity over time and the pressure over time, which can be seen in Figure 22. The pressure profile shows a maximum pressure of 17.2 bar which is significantly lower than the maximum pressure observed during the LPI tests (36.2 bar). This is attributed to the near-instant increase of the plenum volume due to sabot movement and compression of the parachute pack.

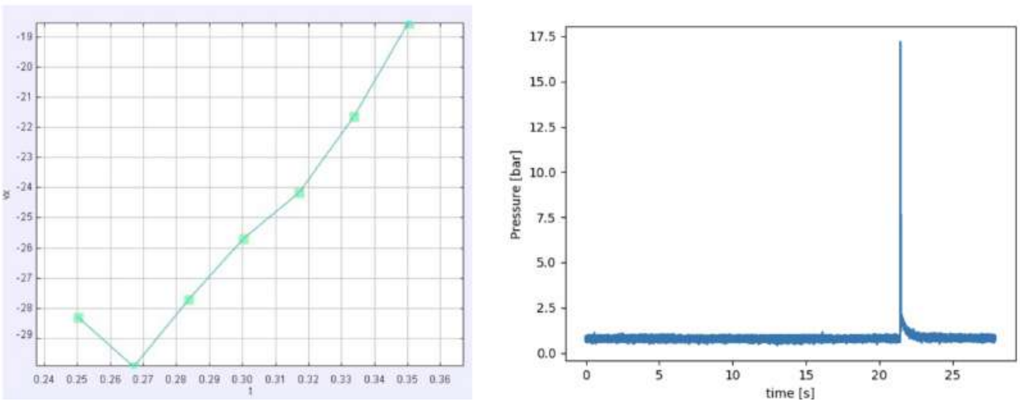


Figure 22: Velocity over time (left) and pressure over time (right) of CFRP ejection test

During the second test, the glued connection to the attachment ring failed, and the attachment ring shot upward. Due to movement of the canister the collected kickback force data of this test was not useful. Images of the attachment ring before, during, and after test 2 can be seen in Figure 23. This failure placed the team in a difficult position, as the launch campaign was less than one month away and all hardware for the flight vehicle had already been shipped to Esrange, Kiruna for a spin and balance test. Although design changes were very unwelcome at this point, after discussing this failure with the REXUS organisers, an exception was made and the ring could be redesigned.

Figure 23: Attachment ring before (left), during (middle x2) and after (right) ejection test 2

It was seen that the current area of the glue joint should have just been enough with the attachment ring height of 5mm (safety factor=1.3), but possibly the thickness of the glue joint (0.2mm) was not fully applied everywhere during manufacturing, as the attachment ring fit quite tightly around the carbon tube. As there was still very little data on the kickback force over time, it may also be that the current design load (3kN, excluding safety factor) was underestimated. The new design for the attachment ring doubled the height of the glue joint to 10mm, and saw a slight inner diameter increase to ensure a 0.2mm thickness of the glue joint was possible. However, it remained challenging to achieve a consistent surface preparation and application of the glue, leading to the remaining uncertainty of whether the connection would hold. This concern was particularly strong as this test campaign showed that a specific glued connection can still fail after having had one or more earlier successful tests, without any visual indication of damage.
21-02-2020: two tests were succesfully conducted with the new 10mm attachment ring. Videos were taken of the ejection tests, but not with a high number of frames per seconds (fps), so it could not be used to accurately determine the ejection velocity. The team also started testing with two ignitor bolts, which was the final flight configuration, to ensure this also works well. This did not allow for a pressure sensor to be assembled into the gas generator, so no further data was collected.
12-03-2020: after the REXUS launch campaign was postponed due to the COVID-19 virus, the SPEAR team joined Stratos IV on this test day to test a new canister with a 10mm attachment ring (bright orange, see Table 6), such that it could be used as a back-up part. Photos are present of the test setup on the day before, but no data is available of the test itself, except a two messages in Slack (team communication app) that the test was successful and no damage could be observed.
29-08-2020: one large test campaign was organised over summer to test all existing canisters once more. The first ejection test used an old gas generator that could only fit 0.3-0.33 grams of NTC, which did not eject the parachute. After a new gas generator was inserted, the canister did eject succesfully. The first gas generator used also had an ill-fitting retainer ring bolt which let loose, however, all NTC of the charge was fully burnt. This can be seen in Figure 26. High-speed video footage was collected of four successful ejection tests, and a graph of the ejection velocity is presented in Figure 24.

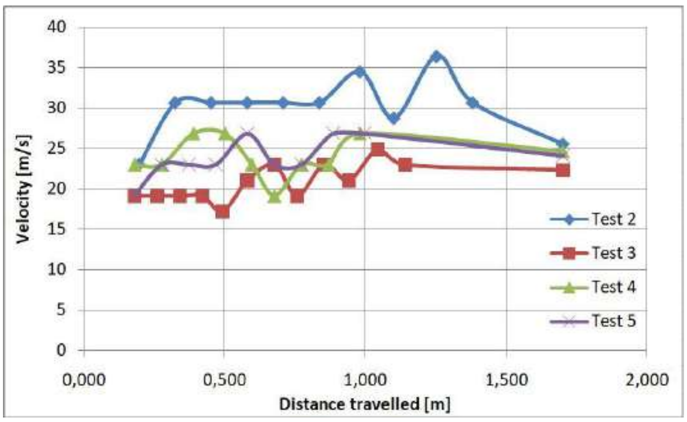


Figure 24: Velocity over distance for tests 2-5

Each test shows some fluctuations in the velocity profile due to the difficulty of processing the high speed footage. The averaged velocity per test is computed: Test 2: 30.2 m/s, Test 3: 20.9 m/s, Test 4: 24.0 m/s, Test 5: 23.9 m/s.
Test 2 shows a significant higher performance, likely due to the fact that the fired gas generator from test 1 already compressed the parachute pack significantly. Tests 3 is most representative as this canister also had a 10mm attachment ring. The ejection velocity of test 3 is just compliant with the requirement of $\geq 20m/s$ and can be accepted. The canisters without attachment ring (test 4 & 5) have a higher ejection velocity, likely as the ring constrains the tube slightly and it also requires more force to assemble the sabot and lid into a tube with attachment ring. Shots from the high-speed footage of ejection test 2 can be seen in Figure 25.

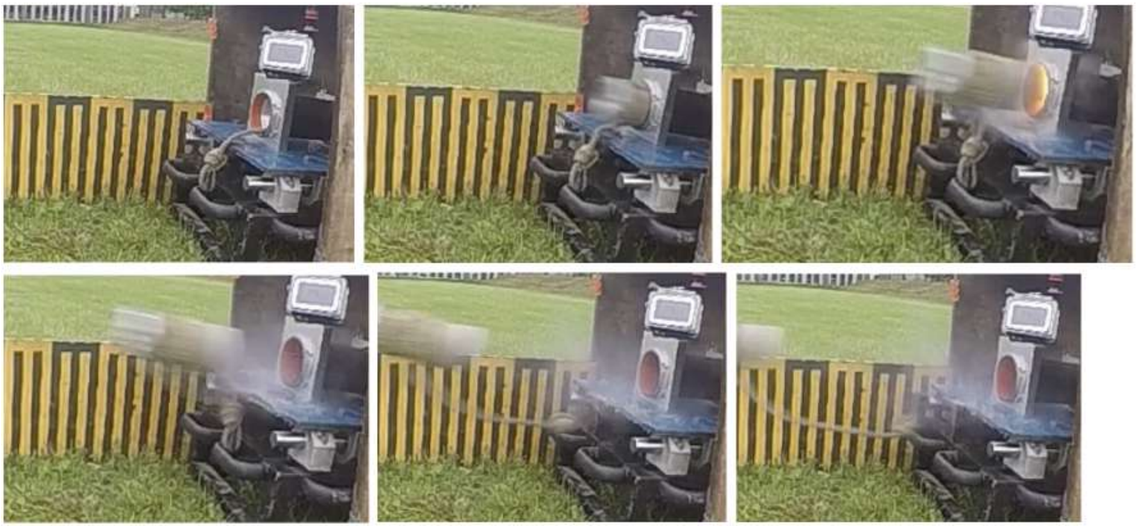


Figure 25: High-speed footage of ejection test 2

Additionally, one gas generator and one ignitor bolt were fired in the open to assess the severity of the safety risk that an ignitor bolt or gas generator fires during assembly. Images of these tests can also be seen in Figure 26.

Figure 26: Retainer bolt release (left), ignition of one ignitor bolt and one gas generator (right)

In addition to these results from individual test campaigns, general observations can be made across the full set. Firstly, the pyrotechnic charge generally ignites and fires reliably. In nearly all cases the parachute is succesfully deployed, even during the tests that saw failures in the attachment method. The final flight configuration has an ejection velocity of $\geq 20m/s$ and meets the imposed requirements. Unfortunately, it can be seen that traces of use and some damages appear after using the hardware a few times. This is most prominent in the CFRP canisters, where significant damage is visible to the shear bolt holes and cracking/chipping of the gelcoat. Secondly, the threads of the gas generator and insert degrade over time. Re-tapping these threads occasionally helps to keep the assembly process smooth. Examples of such damages can be seen in Figure 27.

Figure 27: Damages: cracked gelcoat, damaged shear bolt holes, worn out threads

Throughout the project, multiple **assembly tests** and dress rehearsals were organised to fit-check all SPEAR subsystems and achieve a working order of assembly. The final assembly procedures that were used during the launch campaign can be found in Appendix C. During the assembly tests, the following items were relevant to the parachute mortar:

- Determining the optimal way to pack the drogue parachute subsystem in the parachute mortar canister, as the volume was very tight.
- The order of subsystem assembly. Originally, the internal structure would be fully assembled, and the mortar and main parachute canisters would be mounted onto it one by one. In the new version, the mortar, DAS and sensors are fully assembled onto the base bulkhead. The main parachute canisters and electronics boxes are fully integrated in the remaining section of the internal structure (top bulkhead and stringers). These two halves of the SPEAR vehicle are only mated later on, and can both be seen in the middle image of Figure 28. This allows for far easier integration of the mortar shear bolts and DAS, as well as the holding mechanism for the main parachute deployment system. Additionally, members were able to work on the two parts simultaneously.
- The mortar lid should only be fastened when the bridle lines are connected to their respective eyebolts and the correct length of line is placed inside the mortar, to prevent slack lines.
- In the original design, the X-plate, antenna foam and cabling did not yet cover the parachute mortar. It was intended that placing the gas generator and ignitor bolts and connecting these were some of the last steps in the assembly. In the flight version multiple subsystems needed to be mounted after this was done. In order to assure safety at the launch campaign, a separate room was reserved for these operations, and the ignitor bolts were still only unshunted and connected at the last moment.

Three **Bench Tests** were performed during the SPEAR mission before attending the launch campaign. These tests focused on the integrated electrical and mechanical performance of all experiments aboard REXUS28 in combination with the REXUS Service Module (RXSM). No pyrotechnics of the mortar system (ignitor bolts or NTC) were used in these test campaigns to assure the safety of all participants and because pyrotechnic transport to Germany was difficult and expensive to arrange. The mortar actuation was simulated by LEDs to demonstrate the safety inhibits in the SPEAR electroncis system, such as the breakwire, Remove Before Flight (RBF) pin and Insert Before Flight (IBF) pin, as well as confirm the correct actuation when SPEAR goes through its different flight states.

Figure 28: Assembly of the SPEAR vehicle

8 Launch campaign

As mentioned in section 4, ideally the electric matches provided by SSC would be used in the parachute mortar for SPEAR, due to a high risk of electrostatic discharge (ESD) at Esrange, Kiruna. Additionally, it was easier to purchase the Nitrocellulose from a Swedish supplier and have it shipped to the launch site, than to ship part of the DARE stock from the Netherlands to Sweden by pyrotechnic transport. Although the same powder was ordered (Vectan Ba10), it did come from a different supplier. For these reasons it was desired to perform extra tests with these new materials during the SPEAR launch campaign. Additionally, canister 5 (see Table 6) did not undergo an ejection test yet with its attachment ring glued on. Because the other CFRP canisters had been fired more times, they started to show some damage in the gelcoat, shear bolt holes and insert, as can be seen in Figure 27. Due to this the idea of using the 'most tested canister' for the SPEAR launch was changed to using the 'most intact canister', which was the new transparent one (tested on 29-08-2020, during test 4 and 5, see Figure 24). The test at the launch campaign would serve as final validation test for the full combination of canister subsystem hardware: the CFRP canister and attachment ring, endstop, sabot and lid.

The pyrotechnic preparation on the ignitor bolts and gas generators was done simultaneously for these tests and the launch. Throughout the preparation, extra attention was paid to the risk of ESD by wearing antistatic bracelets and testing all members with an ESD checker. Images of the pyrotechnic preparation can be seen in Figure 29.

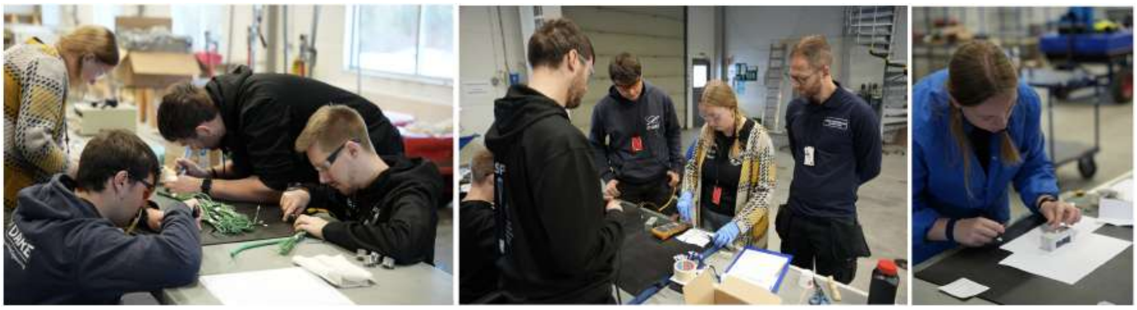


Figure 29: Preparation of ignitor bolts and gas generators on the SPEAR launch campaign

In total, five tests were performed to establish nominal functioning of the mortar system and correct integration with REXUS28 and SPEAR: a LED actuation test, an initiator ignition test, a gas generator ignition test, a flight canister ejection test, and a bench test with actuation of ignitor bolts.

- LED actuation test: this test was performed before any pyrotechnic tests, to ensure the SPEAR vehicle correctly observed all safety measures (IBF, RBF and breakwire), and to practice the full test sequence once before the initiator tests. The SPEAR electronics succesfully lighted two LEDs whilst in the drogue deployment state.
- Initiator ignition tests: the second test aimed to ignite the new initiators, provided by SSC, from the SPEAR vehicle. Upon the first attempt, the initiators did not fire. After declaring the system safe (insertion of RBF, removal of IBF, shunting of initiators) the datasheets of both the DARE and SSC initiators were reviewed. This led to the conclusion that the firing current was in order, but the duration of the firing pulse was likely too low (10ms for the DARE initiators, whilst the SSC initiators require 25ms to fire). The settings were adjusted to a conservative time of 250ms in the SPEAR software, and when the test was repeated, the initiators successfully fired. A photo of the initiators firing can be seen in Figure 30.
- Gas generator ignition test: the gas generator assembly was successfully fired from the SPEAR electronics. This also provided a second test to confirm the SPEAR electronics can ignite the SSC initiators. The Nitrocellulose burned fully and no pellets were left.
- Flight canister ejection test: the HGDD successfully ejected the parachute assembly with no delay after the ignition pulse. The gas generator had a clean burn as no pellets remained in

the system. Due to the limited cameras and test infrastructure available, it was not possible to establish the precise ejection velocity. The best estimation that can be made from the available footage indicates an ejection velocity between 20-27.5 m/s. A photo of the ejection test can be seen in Figure 30.

- Bench test: a 'hot timeline test' was performed after the first assembly during the launch campaign. The objective was to validate the integrated performance of the SPEAR vehicle together with REXUS28 and the ROACH2 experiment in a flight configuration. This includes running through the full launch sequence and testing if all systems are correctly activated, including all pyrotechnics. This is the first time that the drogue pyrotechnics (initiators only) were included in the hot timeline test, so this test also aims to confirm that this does not generate any unexpected issues. The timers used in SPEAR to switch between states were based on the last trajectory simulations, approximating the real final flight timers. The SPEAR hot timeline test was successful. The vehicle was ejected cleanly from REXUS, the DAS deployed, the parachute mortar initiators fired and the main pilot chutes were ejected from the canisters. Data and video transmission and the retrieval system also operated nominally.

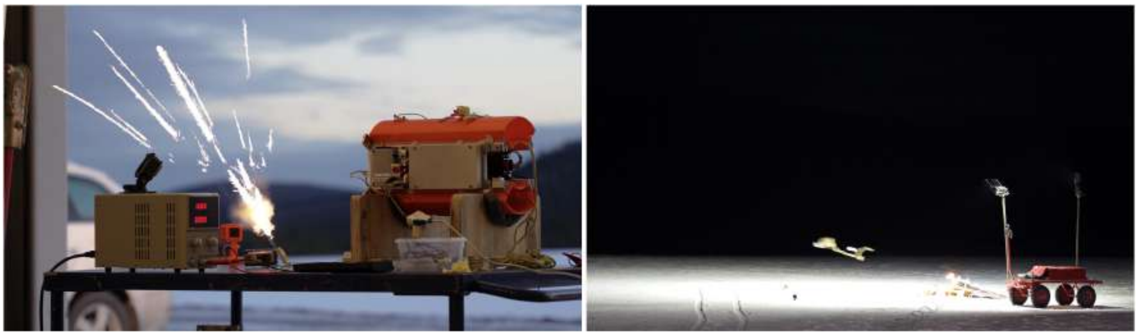


Figure 30: Initiator ignition test (left) and flight canister ejection tests (right)

The parachute mortar for the SPEAR launch was assembled according the procedures and no issues or anomalies arose. The final pyrotechnic preparation was done safely, and the gas generator and ignitor bolts were inserted fully and smoothly. Images of the final assembly of the parachute mortar for the SPEAR launch can be seen in Figure 31.

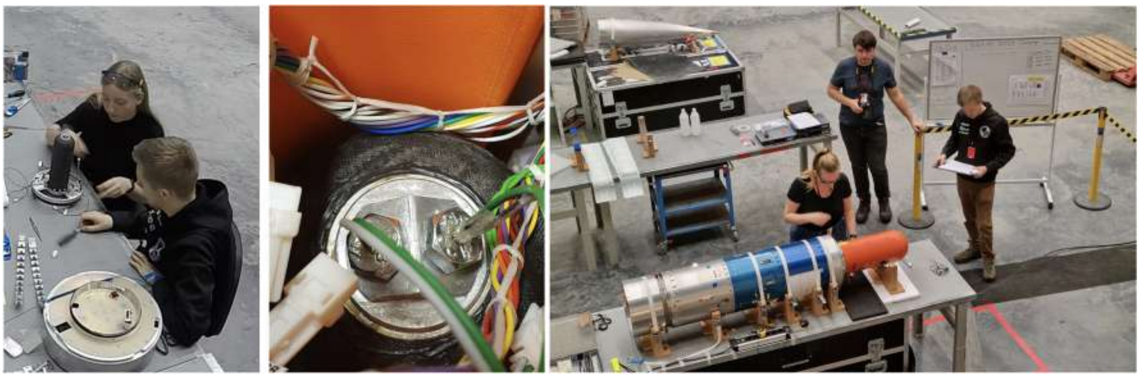


Figure 31: Assembly of the parachute mortar in SPEAR (left), insertion of the gas generator and ignitor bolts (middle), final arming of the SPEAR vehicle through IBF and RBF pins (right)

During the SPEAR launch, the mortar successfully ejected the drogue parachute when the actuation signal was given. However, as the SPEAR vehicle aims at observing the drogue parachute, there is little information available on the performance of the mortar itself. All data on mortar performance was 'nice to have'. Two main sensors in SPEAR were used for post-flight analysis: the inertial measurement unit (IMU) and the camera, looking towards the parachute. A first altitude over time plot was made from the IMU shortly after the launch, which is shown in Figure 32 as a green line. Later on, more assumptions were corrected for, such as the gravitational acceleration (g) not being constant but decreasing from 9.82488 to 9.5345 over the altitude, and incorporating weather cocking of the REXUS rocket. This data is shown in Figure 32 as a blue line, and results in an apogee of 96.1 km altitude. The REXUS organisers established the apogee at 95.7km altitude based on their onboard data of the REXUS28 rocket, which is quite in line with our model (0.417% deviation). In this scenario, deployment of the drogue parachute occurred whilst travelling at Mach 2.9, at approximately 38.5 km altitude. This event is represented by the last vertical dotted line in the graph. The data of the onboard pressure sensor does not yield a logical altitude graph, although it is interesting to see a raise in the pressure (and drop in predicted altitude) approximately 22 seconds after drogue deployment, which may indicate entering subsonic flow.

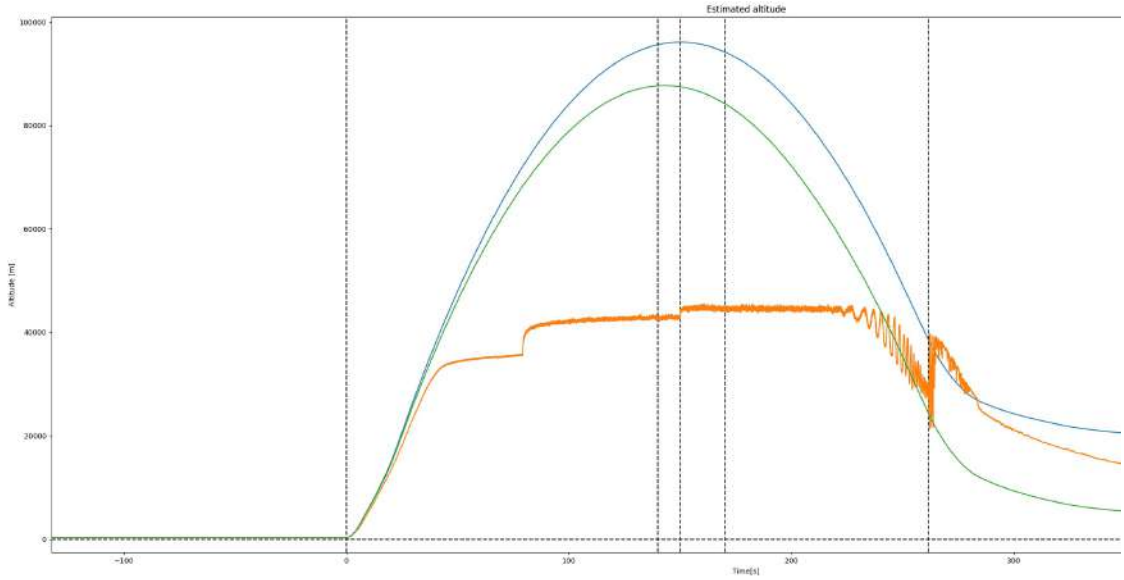


Figure 32: SPEAR altitude over time from IMU data, version 1 (green), version 2 (blue) and from pressure data (orange)

The video footage is analysed to observe the drogue parachute deployment and inflation. Six frames of the parachute deployment can be seen in Figure 33. It takes 8 frames, or 0.134 seconds, from deployment initiation to reach riser line stretch. The riser and bridle line assembly is 2.53 meters long, indicating an average ejection velocity of 18.9 m/s. However, this is based on very inaccurate measurements, thus a large error margin is applicable.

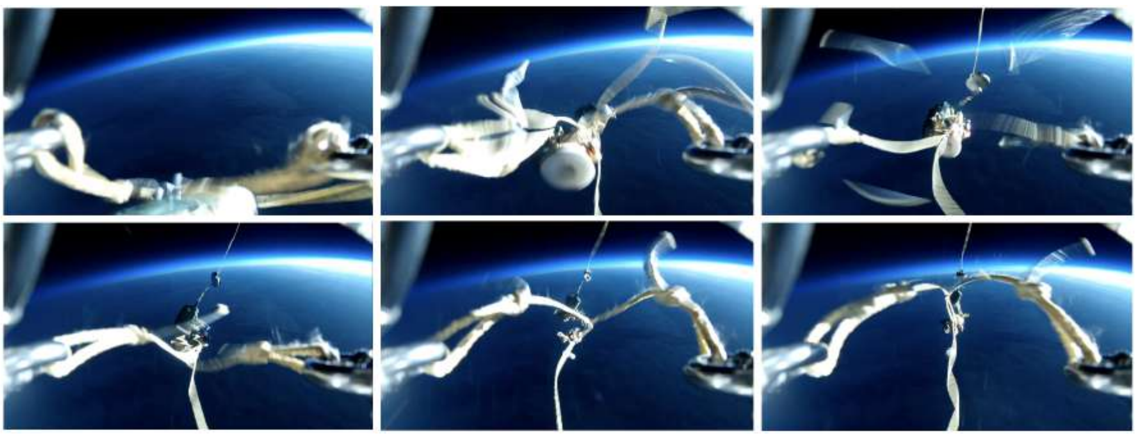


Figure 33: In-flight deployment of the Hemisflo ribbon drogue parachute from the SPEAR mortar

In case the mortar did underperform in comparison to ground based testing, this may be due to one of the following factors:

- During ground testing, the mortar was fastened rigidly to the test bench. In flight, the impulse of ejection also acts on the SPEAR body.
- Potential leaks in the plenum volume during vibrations, leading to an ignition of the NTC at ambient pressures below 1 bar. The Low-Pressure Ignition tests indicated this leads to underperformance in terms of generated pressure.
- The parachute mortar was never tested whilst fully integrated with SPEAR, which excludes any interaction with the bridle lines attachment.

Regardless of the compliance with the ejection velocity requirement of $\geq 20m/s$, the deployment of the drogue parachute in the supersonic regime was still quite violent, and drogue parachute inflation took longer than expected. It may be reconsidered whether $20m/s$ is sufficient for a successful parachute deployment, or if this requirement needs to be adjusted.

9 Conclusion & Recommendations

9.1 Conclusion

The SPEAR team participated in the development of a pyrotechnic parachute mortar in DARE. From June 2019 until March 2020 a high-paced production and testing schedule was conducted to achieve a functional system. A more organised, systematic design and testing approach would have prevented some issues. However, due to the immense time pressure on the system development, this was not feasible.
When checking the final subsystem against the requirements posed in Table 1, an overview can be made of which tests verified which requirements before launch:

ID	Requirement	Verified through
SPEAR-F-03	SPEAR shall deploy the drogue parachute	Ejection tests
SPEAR-P-06	The drogue deployment system shall deploy the drogue parachute with a minimum velocity of 20 m/s	Ejection tests
SPEAR-P-07	The drogue deployment device shall have a maximum mechanical deployment time uncertainty of 0.1 s	Not confirmed
SPEAR-P-25	The drogue deployment device shall be able to deploy the drogue parachute in a pressure range from 3 to 110 kPa	LPI tests
SPEAR-D-01	The mass of the SPEAR experiment shall be at maximum 10 kg	Assembly tests
SPEAR-D-02	The mass of the SPEAR experiment should be at maximum 8 kg	Not met
SPEAR-D-06	The SPEAR vehicle shall handle a minimum vibration of 12.7 g RMS	Vibration tests
SPEAR-D-07	The SPEAR vehicle shall handle a minimum acceleration of 12 g	Vibration tests
SPEAR-D-08	The first natural frequency of SPEAR shall not fall below 40 Hz	Vibration tests
SPEAR-O-01	SPEAR shall operate autonomously	Bench tests

Table 8: Overview of verified SPEAR requirements relevant to the mortar system

A few requirements necessitate further elaboration:

- The maximum mechanical deployment time uncertainty has not been confirmed during testing. Although test footage indicates a sufficiently low delay between the audible ignition of the charge and the ejection, this is not deemed reliable enough to pass this requirement. An additional LED could have been included in the test setup that would light up when the ignition signal is given, to measure this uncertainty accurately.
- The final mass of the SPEAR free-falling unit (FFU) was 7.89 kg.
  The total mass of the SPEAR experiment, including separation mechanism and supporting subsystems, was 9.11 kg.
- Although it is confirmed that the pyrotechnic charge will fully ignite between 3-110 kPa, a lower pressure performance has been observed. Therefore, this does not guarantee the simultaneous compliance to the performance requirement SPEAR-P-06.
- The drogue parachute deployment altitude in flight was higher than anticipated (38.5 versus 20-25 km altitude). Therefore the 3-110 kPa requirement was also inadequate to cover the deployment conditions.

Most importantly, the parachute mortar demonstrated its performance during the SPEAR launch, where it successfully deployed the drogue parachute in harsh conditions.

9.2 Lessons learnt and recommendations

The lessons learnt and recommendations can be divided into three categories; design changes, tests to be done, and potential R&D areas.

1. Design changes
   - Consider material change to aluminium for the canister. Re-evaluate mass cost versus production ease and increased reliability.
   - Improve the glue joint between the canister and attachment ring, or find a different attachment method.
   - Lower the L/D ratio of the canister to between 1.5-2, to lower the reaction load.
2. Tests to be done
   - Perform an ejection test after a vibration test, to establish whether the vibration loads influence the performance (for instance, by increasing the burn surface area by breaking up the NTC pellets).
   - Perform ejection tests with the parachute attachment (bridle lines, riser) fully integrated and mounted as in flight.
   - Perform a vacuum test that follows the flight profile, and measure the pressure in the plenum volume. Alternatively this test can be performed whilst undergoing vibrational loading.
3. Potential R&D areas
   - Replace gas generator with small grain, which allows for easier upscaling, and a lower reaction load.
   - Further research on how a different mass of NTC and/or amount of shear bolts influences the system performance, by performing closed-tank tests. These are essentially the tests performed during the LPI test campaign, but at atmospheric pressures.

Lastly, and most importantly, it is strongly recommended to increase documentation efforts on future parachute mortar development. The current documentation is heavily scattered around DARE and inaccessible to many DARE members. It is also recommended to not only document tests and/or launches, but also the production process and assembly tests, as these may influence the design choices heavily.

Delft Aerospace Rocket Engineering

HGDD Test Procedures

Test ID: HGDD-FC-05
(SPEAR and Stratos IV Recovery)

Saturday 22nd August, 2020

Test Location:
Fellowship field
Kluyverweg 5
2629 HS Delft

OSO:	TBD
TC:	Esmée Menting
TO:	TBD
CP:	Bram Koops

Version: V2.0
Author: Esmée Menting Elrawy Soliman

In case of emergency: (+31 15 27 81226)

Low risk/priority	**Medium risk/priority**	**High risk/priority**
• Test-setup is safe to approach • No safety gear required	• Only authorized personnel in test area • Wear appropriate safety gear	• Clear all personnel from test area • Do not approach the test-setup

CP	Control Post	**OSO**	Operational Safety Officer	**PT**	Pyrotechnician
DAQ	Data Acquisition	**PO**	Pad Officer	**TL**	Test Leader
NTC	Nitrocellulose	**PPE**	Personal Protective Equipment	**TO**	Test Operator

Overview of the Test

The test will consist of the firing of the battleship version of the hot gas deployment device. We would like to fire the system five times with varying amount of NTC and carrying the amount of shear bolts to see how this affects the exit velocity of the sabot.

Test number	HGDD	Amount of NTC (g)	Number of nylon bolts	Canister
1	Stratos IV	0.5	6	Composite
2	SPEAR	0.5	6	Composite
3	Stratos IV	0.5	6	Composite
4	SPEAR	0.5	6	Composite
5	SPEAR	0.5	6	Composite
6	SPEAR	0.5	6	Composite

The system works by igniting nitrocellulose in the gas generator. This builds pressure. At a certain pressure the nylon bolts holding the lid on will shear and the sabot will be ejected along with the lid and the parachute.

The deployment system will be mounted on a test bench to measure the kickback force. There will also be a striped board next to the system with a camera to measure the exit velocity of the sabot.

Safety Considerations

The maximum pressure considering a combustion temperature of 2700 K is 66 bar assuming the sabot does not move at all. Once the gas cools down to 300 K the internal pressure will be 7.4 bar.

However 0.4 grams was enough to compress the parachute 52.6 mm. So assuming the the parachute compresses the same as in the last test and that the bolts do not shear, the max pressure will be 20.1 bar and 2.2 bar after it cools down. The pressure vessel is based off of Martin's BEM casing which yields (GG shear out) at 100 bar.

Equation 1 was used with values taken from proprop. The shear pressure was calculated to be about 1 bar per bolt according to Stratos III reports.

$$P = \frac{Mgas * Rsp * Tc}{V} \tag{1}$$

1 Pre-test Operations

Prep location:	Dreamhall
Starting time:	

			A - Pre-test organisation	
ID	**Check**		**Operation**	**Remarks**
A1			Print a sufficient number of procedures and packing lists.	See packing list
A2			Ensure all required tools are available	
A3			Ensure cameras and laptop are charged and available, and that SD cards with sufficient capacity are too.	
A4			Ensure that launch boxes are available and charged.	Make sure that the there is a cover in case of rain
A5			Ensure that the RIO is available and ready to go.	Do not forget RIO laptop and dongle
A6			Make sure tube is all prepared and ready for insertion of ignitor bolt and gas generator	Tube needs to have been produced and the items that go inside should fit correctly
A7			Ensure a first aid kit and a fire extinguisher are packed.	
A8			Check packing list.	
A9			Fill out time	Time:

			B - Part preparation	
ID	**Check**		**Operation**	**Remarks**
System Status: • Gas generator x2 • Ignitor bolts x10 • Mesh x2 • Retainer ring x2 • bulkhead & tube • Acetone • Gloves • Blue paper				
B1			Check ignitor bolts for sharp metal burs	
B2			Ensure grooves of the bulkhead and tube are not sharp	
B3			Check that threads of bolts and gas generator are okay	
B4			Clean all parts using Acetone	Avoid touching parts with bare hands

C - Igniter bolt preparation x10

ID	Check		Operation	Remarks
C1			Fill out time	Time:

All personnel wear safety jackets, safety glasses, safety shoes, phones are off

ID	Check		Operation	Remarks
C2			Area is cleared of unnecessary personal	Only OSO and TO are needed.

System Status:

- Table is clear
- Box with squibs is on the table
- Igniter bolts are on table
- Two component epoxy, coffee cup and mixing spoon are on table
- Fire extinguisher & bucket of water are near by
- First aid kit readily available

ID	Check		Operation	Remarks
C3			Notify others in lab that pyrotechnic activities are being executed	
C4			Squib is unpacked	
C5			TO unshunts squib leads	Announce verbally
C6			Squibs are measured for resistivity	Should be around 1-3 ohms
C7			TO shunts squib leads, confirms when finished	
C8			Squib leads are led through hole in bolt	
C9			Two part epoxy is thoroughly mixed	Take a small bit at a time (just for 1 bolt, about 1 thick drop). It dries quickly.
C10			Epoxy is applied thoroughly to the lead below the match head	No knot is used for M8 so do not skimp on epoxy
C11			Pull squib into final position	Move back and forth slightly and wiggle to ensure good spread of epoxy. Ensure match head is mostly within ignitor bolt and does not stick out too much.
C12			Wait for epoxy to dry	Keep an eye on if the match head stays in the ignitor bolt
C13			Resistivity is measured between squib leads and bolt	Should not have electrical contact
C14			Bolt is packed into a propellant box ready for transport to the fellowship field.	

System Status:

- Igniter bolts are measured and ready for transportation

Continued

ID	Check		Operation	Remarks
C15			Fill out time	Time:

			D - Gas generator preperation x2	
ID	**Check**		**Operation**	**Remarks**
D1			Fill out time	Time:
			All personnel wear safety jackets, safety glasses, safety shoes, phones are off	

System Status:

- Table clear
- Gas generator with dummy bolts is present
- Flash paper is present
- Box of Nitrocellulose is on table
- Small scale is on table
- Sufficient sheets of A3 paper are present
- Mesh (pre-cut to size), Retainer ring and retainer bolts are on table
- Water bucket and fire extinguisher are present

D2			Cut flash paper into shape of Gas generator bottom.	Use retainer ring as template
D3			Insert dummy ignitor bolts into gas generator	Apply teflon tape on the dummy bolt that will stay during the test, if applicable. Apply a dowty seal to the dummy bolt that will be replaced by the ignitor bolt.
D4			Place flash paper in gas generator	You can put two layers to cover it better
D5			Put retainer bolts through ring and mesh	
D6			Put gas generator on scale and tare the scale	
D7			Pour in small bits of Nitrocellulose into the gas generator using a folded piece of paper	.... grams NTC depending on test
D8			Put away box of Nitrocellulose	
D9			Make little swabs of flash paper to fill up the remaining open volume	Fill up with flash paper and softly press down. Should be multiple little parts such that air can flow through.
D10			Screw retainer ring and mesh on the gas generator using bolts	The mesh should press down on the NTC slightly. Do not over-tighten.
D11			Place gas generator in plastic bag	
D12			Place generator into box	
D13			Fill out time	Time:
Continued				

ID	Check		Operation	Remarks
System Status: • Gas generators is ready for transport • Table has been cleaned				

			E - Testbench preparation	
ID	**Check**		**Operation**	**Remarks**
E1			Fill out time	Time:
			All personnel wear safety jackets, safety shoes.	
				
E2			Check load cell	See if the load cell is properly assembled on to MOAB
E3			Mount clamps to test bench near the correct end	double check if the ejection direction is in the correct orientation

2 Test Site Prep

Test location:	Fellowship field
Starting time:	

			F - Test Site Preperations	
ID	**Check**		**Operation**	**Remarks**
F1			Fill out time	Time:
			All personnel wear safety shoes and overalls	
				
F2			Determine the location of the test setup making sure path of projectiles is clear	
F3			Place and secure test bench using rebars	
F4			Place striped board parallel to the exit of the HGDD	
F5			Place cameras facing striped board.	
F6			Place the Rio and shrapnel box close to the test setup	Distance will be dictated by the length of the load cell and pressure sensor cables
F7			Place the ignition boxes in the right positions and cover against rain	lucifer at the test setup and gabriel at CP
F8			Unroll ignition cable and ensure it reaches test set-up	
F9			Test the connection between the ignition boxes	test fire with multimeter
F10			Connect cables and wires to RIO for laptop, power source, load cell and pressure sensor	
F11			Check DAQ setup on laptop is working	Name channel:
F12			Turn RIO off once DAQ checked	
F13			Place plastic cover over laptop	To protect from dirt and rain
F14			Fill out time	Time:

3 Final system prepartion

Test location:	Fellowship field
Starting time:	

		G - Gas generator and ignitor bolt installation		
ID	**Check**		**Operation**	**Remarks**
G1			Fill out time	Time:
G2			Make sure the cameras are positioned before pyro prep starts	
		All personnel wear safety jackets, safety glasses, safety shoes, phones are off		
				
G3			Unpack gas generator.	
G4			Insert gas generator it into bulkhead.	Ensure it is properly attached to the system and apply teflon tape.
G5			Remove dummy bolt(s)	Check that the NTC has not leaked or come out
G6			Screw the pressure sensor into its respective hole in the GG with dowty seal and/or teflon tape	
G7			Connect the pressure sensor to the RIO.	
G8			Unpack ignitor bolt.	Ensure squibs are still shunted
G9			Screw ignitor bolt into the gas generator.	Ensure dowty seal and/or teflon tape is present
G10			Place shrapnel box over test bench.	

4 System Fire

	H - Connecting the igniter			
ID	**Check**		**Operation**	**Remarks**
H1			Fill out time	Time:
	All personnel wear safety jackets, safety glasses, safety shoes, phones are off			
				
H2			Pad is evacuated only OSO, TL, TO are on the pad	
System Status: • HGDD is mounted and igniter is shunted. • HGDD is ready for connecting igniter to lucifer. • Test bench is covered by shrapnel box.				
H3			OSO turns Lucifer to safe	
H4			TL retreats 2 meter from the setup	
H5			TO checks multimeter by placing electrodes on skin	Nominal = few mV
H6			TO Connects multimeter to ignition line leads	
H7			TO measures Lucifer ignition line, confirms voltage	Nominal = 0 V
H8			OSO confirms that igniter can be connected to Lucifer	
H9			TO unshunts the igniter leads, connects igniter	Announce verbally
H10			TO wraps tape around igniter leads, makes sure they can not short	
H11			OSO confirms that igniters are connected properly	
System Status: • HGDD is live and ready for testing • RIO is on, DAQ is off • Cameras are off				
H12			OSO radios that the HGDD is ready for test and test setup will be evacuated	
H13			TO turns on cameras, CP press start on DAQ	
	People are present in field corners to watch for passersby			
H14			Start stop watch and high speed camera delay if applicable	T-2 min 30 sec Radio to CP while starting timer.
	T-2 min 30 sec			
H15			OSO turns Lucifer to arm	OSO brings key
System Status: • HGDD is live and ready for testing • RIO is on, DAQ is turned on • Cameras are on • High speed camera delay is active				
H16			OSO, TO and TL leave test setup, move to CP	
H17			Fill out time	Time:

	I - Firing		
ID	**Check**	**Operation**	**Remarks**
		System Status: • System is live • Everyone is clear • People are present in field corners to watch for passersby • Countdown in progress	
		Gas generator is ready to fire **Continue countdown from stop watch** **T-10 sec OSO Counts down with raised voice & Arm launch box** **T=0 sec FIRE** **HOLD DOWN ignition button until T+5 sec** **Set launch box to SAFE** **In case of** **- Success: Continue at J1** **- Misfire: Continue at K1** **- Failure: Continue at L1**	

	J - Successful fire			
ID	**Check**		**Operation**	**Remarks**
			System Status: • System is hot	
J1			Wait a given time for system to cool	Time to wait: 1 min
J2			OSO checks that the system is safe to approach	
J3			Carefully approach the system	Check for damage and take notes
J4			Turn off DAQ	

	K - Miss Fire			
ID	**Check**		**Operation**	**Remarks**
K1			Fill out time	Time:
	All personnel wear safety jackets, safety glasses, safety shoes, phones are off			

			System Status: • DO NOT STAND IN EJECTION PATH • We do not know if the system ignited or not • System could be hot and under pressure	
K2			Go back to checklist I - Firing	
K3			Redo these steps and try to reignite.	
Continued				

ID	Check		Operation	Remarks
K4			Wait until pressure drops	Check pressure data via RIO. Minimal wait time: 2 min. If no pressure data, minimal wait time: 5 min.
K5			Carefully approach system .	
K6			take shrapnel box off.	
K7			shunt the squibs.	
K8			slowly release pressure.	lightly unscrew 1 ignitor bolt and let the pressure seep out
K9			Shunt the squibs	
K10			Slowly unscrew each ignitor bolt	If hissing is heard, stop and wait for pressure to equalize and slowly continue.
K11			Remove the pressure sensor.	
K12			Unscrew gas generator	There may still be NTC present if so, give to OSO
K13			Turn off DAQ	
K14			Document with pictures and notes	

			L - Failure	
ID	**Check**		**Operation**	**Remarks**
L1			Fill out time	Time:
System Status: • Some part of the system has catastrophically failed				
L2			OSO approaches system to check if it is safe	
L3			Carefully approach system	Parts may be hot! NTC residue can be present, if so, give to OSO.
L4			Turn off DAQ	
L5			Take pictures of failure	
L6			Note ending position of parts	Sketch the layout

DARE
Delft Aerospace Rocket Engineering

PIP III Launch Procedures

Test ID:
PRG - PIP

Friday 31st March, 2023

Test Location:
ASK 't Harde

Parachute Investigation Project
A PRG Project

OSO:	________________
TC:	________________
TO:	________________
ME:	________________
EE:	________________

Version: 1.0
Author: Wim Jodehl

Printed: 11/05/2023 - TPC2.0

Changelog

Date	Version	Changes	Names
08-03-2023	V1.0	Created this document	Wim Jodehl, Nachiket Dighe

Contents

FLIGHT OPERATIONS CHECKLIST PART **A** ALPHA

Version:
Date: 00/00/0
Author:

Hot-Gas Deplpyment Device

The following steps compose pyrotechnic preparations required of the deployment device before the launch of PIP III.

Preceeded by: ________________
Followed by: ________________

Duration:

Abbreviations

CP Control Post
OSO Operational Safety Officer
RBF Remove Before Flight
TC Test Conductor
TO Test Operator

A1 - Igniter bolt preparation x2 for HGDD only

ID	Check		Operation	Remarks
A1-1			Fill out time	Time:
			All personnel wear safety jackets, safety glasses, safety shoes, phones are off	

A1-2			Area is cleared of unnecessary personal	Only OSO and TO are needed.

System Status:
- Table is clear
- Box with squibs is on the table
- Igniter bolts are on table
- Two component epoxy, coffee cup and mixing spoon are on table
- Fire extinguisher & bucket of water are near by
- First aid kit readily available

A1-3			Notify others in lab that pyrotechnic activities are being executed	

Continued

In case of emergency: 0th , 0
Test Location: PRG - PIP

ID	Check		Operation	Remarks
A1-4			Squib is unpacked	
A1-5			TO unshunts squib leads	Announce verbally
A1-6			Squibs are measured for resistance	Should be around 1-3 ohms
A1-7			TO shunts squib leads, confirms when finished	
A1-8			Squib leads are led through hole in bolt	
A1-9			Two part epoxy is thoroughly mixed	Take a small bit at a time (just for 1 bolt, about 1 thick drop). It dries quickly.
A1-10			Epoxy is applied thoroughly to the lead below the match head	No knot is used for M8 so do not skimp on epoxy
A1-11			Pull squib into final position	Move back and forth slightly and wiggle to ensure good spread of epoxy. Ensure match head is mostly within ignitor bolt and does not stick out too much.
A1-12			Wait for epoxy to dry	Keep an eye on if the match head stays in the ignitor bolt
A1-13			Resistivity is measured between squib leads and bolt	Should not have electrical contact
A1-14			Bolt is packed into a propellant box ready for transport to the fellowship field.	
System Status: • Igniter bolts are measured and ready for transportation				
A1-15			Fill out time	Time:

A2 - Gas generator preperation x1			
ID	**Check**	**Operation**	**Remarks**
All personnel wear safety jackets, safety glasses, safety shoes, phones are off			
			
A2-1		Insert dummy ignitor bolts into gas generator	Apply dowty seal to igniter bolt dummy, this will be put on the actual igniter bolt
A2-2		Place flash paper in gas generator	You can put two layers to cover it better
A2-3		Put retainer bolts through ring and mesh	
A2-4		Put gas generator on scale and tare the scale	
A2-5		Pour in small bits of Nitrocellulose into the gas generator using a folded piece of paper	0.7-0.8 grams NTC
A2-6		Put away box of Nitrocellulose	
A2-7		Screw the retainer ring and mesh on the gas generator using bolts	The mesh should press down on the NTC slightly. Do not over-tighten.
A2-8		Place gas generator in a plastic bag	
A2-9		Fill out time	Time:

System Status:

- Gas generators is ready for transport
- Table has been cleaned

FLIGHT OPERATIONS CHECKLIST	PART	B	BRAVO
Version: Date: 00/00/0 Author:	**Payload**		

The following steps compose preparations required for PIP's Payload. In case of PIP III, payload comprises of SPEAR II Wire Cutters.

Preceeded by: ________________
Followed by: ________________

Duration:

Abbreviations

CP Control Post
OSO Operational Safety Officer
RBF Remove Before Flight
TC Test Conductor
TO Test Operator

			B1 - Checklist	
ID	**Check**		**Operation**	**Remarks**
			All personnel wear safety jackets, safety glasses, safety shoes, phones are off	
B1-1			x1 wirecutter box (electronics, sabot, casing)	
B1-2			x1 machine ignitor bolt (M10)	
B1-3			x1 e-match	
B1-4			50mg NitroCellulose (NTC)	
B1-5			Acetone	
B1-6			Weighing scale (accurate to 1mg)	
B1-7			Multimeter	
B1-8			Two-part epoxy	

System Status:

Ensure the following items are available

Continued

In case of emergency:
Test Location:

0^{th}, 0
PRG - PIP

ID	Check		Operation	Remarks
B1-9			Cotton wadding	
B1-10			Wooden sticks	
B1-11			Paper cups	
B1-12			Stanley knife	
B1-13			Paper towels	
B1-14			Teflon tape	
B1-15			JST-PA Crimp tool	
B1-16			JST-PA 2 pin connector housing	
B1-17			JST-PA crimps (at least 5)	
B1-18			JST-PA shunting plug	

B2 - Wire Cutter Igniter Bolt Preparations

ID	Check		Operation	Remarks
			All personnel wear safety jackets, safety glasses, safety shoes, phones are off	

ID	Check		Operation	Remarks
B2-1			Cleaning: use acetone-soaked paper towels to clean the machined ignitor bolts (especially the inside of the plenum volume and hex-head of the bolt).	
B2-2			E-match check: Remove insulation on the shunted end of the e-match. Unshunt the e-match by untwisting. Measure resistance across the leads (1.6Ω-2.3Ω acceptable).	
B2-3			Knot the e-match near the head of the e-match.	
B2-4			Insertion: put two-part epoxy in a paper cup. Mix thoroughly with wooden sticks. Insert the e-match into the ignitor bolt. Glue it from the inside of the plenum volume. Glue wire on the bolt head.	
B2-5			Pyrocharge: accurately measure 50mg NTC. Do not directly put the pyrocharge on the scale! First put a piece of paper or cup on the scale (tare). Now measure the correct amount of pyrocharge.	
B2-6			Wait until epoxy has cured ($\approx 5 minutes$)	

Continued

ID	Check		Operation	Remarks
B2-7			Measure e-match resistance to ensure no short occured	
B2-8			Crimp JST-PA crimps to each lead of the e-match after trimming them to length.	
B2-9			Insert crimps into JST-PA 2 pin connector housing.	
B2-10			Carefully put the measured pyrocharge into the plenum volume of the ignitor bolt. Put cotton wadding to fill unused volume.	
B2-11			attach shunting plug	

			B3 - Wirecutter Assembly and Parachute Integration	
ID	**Check**		**Operation**	**Remarks**
			All personnel wear safety jackets, safety glasses, safety shoes, phones are off	
				
B3-1			Remove parachute from the deployment device.	
B3-2			Open the wirecutter box by unscrewing four bolts. Gently remove the wirecutter casing. Ensure that the parachute line running through the casing and the wirecutter assembly (with sabot and shear bolt) remains undisturbed.	
B3-3			Ensure activation Headphone jack is securely inserted.	
B3-4			Ensure electronics are unarmed	Slider switch towards mounting hole
B3-5			connect battery	
B3-6			Remove headphone jack to confirm LED Sequence is indicating correct state	Solid LED should be shown
B3-7			reconnect headphone jack	
B3-8			Put Teflon tape around the thread of the ignitor bolt.	
B3-9			Thread in the ignitor bolt into the wirecutter casing. Ensure that all pyrocharge stays in place. Tighten using appropriate wrench.	
B3-10			Plug in pyro into board	
Continued				

ID	Check		Operation	Remarks
B3-11			Remove headphone jack and confirm continuity from LED pattern	Ensure arm switch is still off (towards mounting screw). LED pattern should be 1.5s on, 0.5s off, in case of quick blinking reconnect headphone jack immediately and investigate
B3-12			reconnect headphone jack	
B3-13			Arm electronics	Slide switch away from screw. From this point onwards make sure Headphone jack will not accidentally be pulled. In case it is pulled immediately re-connect it. You have 37s time to reconnect before the pyro will be triggered.
B3-14			Close the wirecutter box's lid by screwing in the four bolts.	
B3-15			Appropriately fold the parachute.	Make sure the line connecting the plug to the parachute does not get pulled.
B3-16			Insert parachute back into the deployment device.	

Version:
Date: 00/00/0
Author:

Final Integration

The following steps compose the final integration of the PIP III rocket. At the end of the this checklist, the rocket will be ready for tower insertion.

Preceeded by: ________________
Followed by: ________________

Duration:

Abbreviations

CP	Control Post
OSO	Operational Safety Officer
RBF	Remove Before Flight
TC	Test Conductor
TO	Test Operator

C1 - System State

ID	Check	Operation	Remarks
		All personnel wear safety jackets, safety glasses, safety shoes, phones are off	

System Status:

- The parachute contains the armed reefing electronics
- The parachute is loaded into mortar tube, bridle lines hanging out, soft links on the bridle line loops
- The test section is horizontally on rocket stands
- The electronics hatch and the pyro hatch are removed
- The prepared gas generator and the prepared ignitor bolt are ready
- The Engine Section is ready on the with NEAR drogue attached, standing upright on the ground.
- The eyebolts for the parachute are present
- The Test Section Coupler is ready, with short servo extension cable guided through it, female end on Test Section side
- The Clamp Band is ready to be installed
- An M3 Allen key is ready as a clamp band lock
- Batteries on SRP electronics and Arduino are disconnected

			C2 - Mortar Integration	
ID	**Check**		**Operation**	**Remarks**
			All personnel wear safety jackets, safety glasses, safety shoes, phones are off	
				
C2-1			Ensure area clear of all non-essential personnel	
C2-2			Guide the loaded mortar tube into the rear of the Test Section	Ensure the long servo cable is guided through the rivet cut-out in the mortar bulkhead
C2-3			Apply thread locker to the M5 eyebolts	
C2-4			Install the Eye-bolts and twist until hand-tight	Ensure M5 nut is threaded all the way down the eye bolt before installation
C2-5			Twist back the eyebolt until the plane of the eye is tangent with the skin.	
C2-6			Tighten M5 nut onto the Mortar Bulkhead	Ensure the eyebolt orientation remains the same.
C2-7			Use soft links to connect one bridle line to each eyebolt	
C2-8			Place Test Section Coupler close to the rear of the Test Section	
C2-9			Connect short servo cable on the coupler to the long servo cable on the Test Section	Ensure colors match on connections, yellow on yellow, red on red, black on black.
C2-10			Remove bolt and washers from mortar lid	
Continued				

ID	Check		Operation	Remarks
C2-11			Guide coupler into test section and onto the mortar bulkhead	Ensure servo cable is guided through the rivet channel in the coupler and is not squished by the coupler.
C2-12			Secure coupler using the central M4 bolt with 3 washers	Do not tighten too much as to not shear out nylon bolts on mortar, but there should be no wiggle

System Status:

PIP III is now ready for section mating

			C3 - Section Mating	
ID	**Check**		**Operation**	**Remarks**
			All personnel wear safety jackets, safety glasses, safety shoes, phones are off	
C3-1			Pack Engine Section Parachute suspension lines and riser into the cavity around the servo on the Engine Section	Ensure no entanglement with the servo mechanism
C3-2			Bring rocket section close together	ES can be on ground upright and TS at the table edge on rocket stands
C3-3			Pack Engine Section Parachute canopy into Test Section Coupler cavity.	

Continued

ID	Check		Operation	Remarks
C3-4			Place Test Section on Engine Section	It's matin time, ooh yeah
C3-5			Gently compress Test Section onto Engine Section until gap between couplers is almost closed.	
C3-6			While continuing to push down, place clamp band around the couplers	Make sure wholes in ES coupler and clamp band arms are roughly aligned
C3-7			Confirm that the rivet seams almost align	
C3-8			Insert M3 allen key into the lower hole of the clampband	Ensure that allen key goes through clamp band AND coupler,
C3-9			place visual aid on allen key to mark as remove before flight.	
C3-10			Place mated rocket horizontally back onto rocket stands.	Ensure hatches are pointing up.

System Status:

PIP III is now ready for pyrotechnic insertion

C4 - Pyrotechnic Insertion

ID	Check	Operation	Remarks

All personnel wear safety jackets, safety glasses, safety shoes, phones are off

System Status:

The following should be presentOne PIP III rocket with hatches removed Pyro Hatch including 4x M4 bolts Electronics Hatch including 4x M4 bolt Prepared Gas Generator Prepared M8 Ignitor Bolt Dowty Seals for Ignitor bolt and Gas Generator Teflon Tape Masking Tape Tools

Continued

ID	Check		Operation	Remarks
C4-1			Ensure all non-essential personnel is removed from the closer area	
C4-2			Unpack ignitor bolt	
C4-3			Apply teflon tape to the ignitor bolt thread	
C4-4			Place dowty seal on the ignitor bolt	
C4-5			Unpack Gas Generator	
C4-6			Remove unsealed dummy bolt from Gas Generator	Ensure not spilling of NTC
C4-7			Insert the ignitor bolt into the open hole in gas generator	Tighten with 13mm wrench
C4-8			Apply teflon tape to the thread of the Gas Generator	
C4-9			Place dowty seal on gas generator	
C4-10			Insert Gas Generator into mortar	Tighten with TBD mm wrench
C4-11			Unshunt the ignitor leads	Verbally announce
C4-12			Connect one lead to the green pyro cable using WAGO clip	
C4-13			Connect other lead to the red pyro cable using WAGO clip	
C4-14			Tape WAGO clips to the inside of the skin using masking tape	
C4-15			Connect Arduino battery	
C4-16			Attach the pyro hatch using 4x M4 bolts	
C4-17			Connect the SRP Electronics battery	
C4-18			Attach electronics hatch using 4x M4	

System Status:

PIP III is now ready for motor insertion

		C5 - Motor Insertion		
ID	**Check**		**Operation**	**Remarks**
		All personnel wear safety jackets, safety glasses, safety shoes, phones are off		

System Status:

The following items are required:1x PIP III rocket 1x Loaded DX1 motor

C5-1			Guide the engine into the engine section until it is not able to move further and is flush with the end of the engine section	If the engine gets stuck early on, twist it around
C5-2			Twist the engine clockwise until the end cap of the motor is threaded onto the engine retention bolt	

FLIGHT OPERATIONS CHECKLIST PART **D** DELTA

Version:
Date: 00/00/0
Author:

Launch Tower

The following steps compose the final preparation of PIP III when the rocket is inserted into the launcher.

Preceeded by: ____________
Followed by: ____________

Duration:

Abbreviations

CP	Control Post	**OSO**	Operational Safety Officer	**RBF**	Remove Before Flight	**TC**	Test Conductor
						TO	Test Operator

D1 - Tower Insertion

ID	Check		Operation	Remarks
			All personnel wear safety jackets, safety glasses, safety shoes, phones are off	
D1-1			Ensure Clamp Band RBF locking pin (allen key) is still inserted in the clamp band	
D1-2			Ask safety if they are ready for tower insertion	
D1-3			After the okay from safety, lift the rocket by the engine section and test section	Best to lift with two people.
D1-4			Carry the rocket over to the launch tower	
D1-5			Remove the endstop from the launch rail	
D1-6			Insert the upper launch lug into the rail while the rocket is held under a approx. 45 deg angle	
D1-7			slide the rocket up and simultaneously tilt it to vertical	

System Status:

DX1 Motor is loaded into PIP III and the PIP III is ready to be loaded into the tower

Continued

In case of emergency: 0th , 0
Test Location: PRG - PIP

ID	Check		Operation	Remarks
D1-8			Insert the lower launch lug into the rail	
D1-9			Lift the rocket high enough in the rail such that the end stop can be inserted.	
D1-10			Inert the end stop	Ensure the bolt on the end stop is facing up
D1-11			Gently lower the rocket onto the endstop	

System Status:

The rocket is now inserted into the tower

			D2 - Tower Operations	
ID	**Check**		**Operation**	**Remarks**
			All personnel wear safety jackets, safety glasses, safety shoes, phones are off	
D2-1			Remove the clamp band locking pin (allen key)	
D2-2			Power on camera by pressing holding the power button	
D2-3			Start recording by pressing the power button shortly once	All the lights should switch off now
D2-4			Ensure break wire is attached to the launch tower by a rope	
D2-5			Set the power switch to ”ON”	This is the downward pointing position
D2-6			Insert the break wire	Ensure it cannot come easily loose
D2-7			Take one final look a the rocket and determine if anything is out of the ordinary	Keep special eyes to any form of RBF

	D3 - Igniter Insertion			
ID	**Check**		**Operation**	**Remarks**
	SO's only, stand well clear			

ID	Check		Operation	Remarks
D3-1			Stand well clear of the rocket	About a good 5m or so
D3-2			The SO and ST will perform the igniter insertion	
D3-3			Once completed, ensure that SO arms the rocket	
D3-4			Take a final look at PIP III and wave your goodbyes	
D3-5			Retreat to the upstairs CP and enjoy the launch.	

F

Literature search criteria

The following tables display the search criteria used during the literature review.

Search term	Papers found	Download y/n	Comment	Sources ID
Parachute mortar design	Parachute mortar design	yes		MOR-03
	system	yes		MOR-05
	Mars exploration rover parachute mortar deployer development	yes		MOR-06
	Mars exploration rover parachute decelerator system program overview	yes		MOR-07
	The Viking mortar-Design, development, and flight qualification	yes		MOR-08
	(CPAS)	yes		MOR-09
	strengthened DGB parachute	yes		MOR-10
	Mars science laboratory parachute simulation model	no	mortar design/testing	
	The Viking parachute qualification test technique	yes		MOR-11
	Overview	yes		MOR-12
	Mars smart lander parachute simulation model	no	focus on parachute simulation	
	subsystem	no	focus on parachute stability	
	Flight qualification of mortar-actuated parachute deployment systems	yes		MOR-04
	Some test results from the NASA planetary entry parachute program.	no	little information on mortar system	
	Parachute mortars; an engineering review	yes		MOR-01
	Low density supersonic decelerator parachute decelerator system	no	design alternative for mortar	
	system	no	unrelated	
	parachute test	no	10	
	Mars Exploration Rover Parachute System Performance	yes		MOR-13
	Rover Parachute Structural Tests	no	little information on mortar system	
	Parachute System	yes		MOR-14
	Probe	yes	different requirements	MOR-15
	Parachute Recovery Systems Design Manual	yes		MOR-16
	Design Overview of the Strengthened Mars 2020 Parachute Assembly	yes		MOR-17
	Reconstruction of the Mars Science Laboratory Parachute Performance	yes		MOR-18
	decelerator system	no	no focus on mortar design/tests	
	Mars science laboratory's parachute qualification approach	yes		MOR-19
	disk-gap-band parachute	no	no focus on mortar design/tests	
	Missions	no	only low-level description of tests	
	Experiment Sounding Rocket Flight Test	no	little information on mortar system	

	Overview of the Mars 2020 parachute risk reduction activity	yes	mentiones qualification activities mortar	MOR-20
	Deployment System	yes		MOR-21
Parachute mortar development	Inception	no	only short description of planned tests	
	Mars science laboratory parachute development test program	no	only low-level description of tests	
	The Stardust Sample Return Capsule Parachute Recovery System	no	little information on mortar system	
	Complex 80-by 120-foot Wind Tunnel at NASA Ames Research Center	no	little information on mortar system	
	Overview of the Crew Exploration Vehicle Parachute Assembly System (CPAS) generation I main and cluster development test results	no	no information on mortar system	
	Overview of the Crew Exploration Vehicle Parachute Assembly System (CPAS) generation I drogue and pilot development test results	no	no information on mortar system	
	A Status Report on the Parachute Development for NASA's Next Manned Spacecraft	yes	broad description on mortar usage	MOR-22
	Improved CPAS photogrammetric capabilities for engineering development unit (EDU) testing	no	no information on mortar system	
Parachute mortar requirements	Mars Science Laboratory Parachute System Performance	no	little information on mortar system	
	Opening Loads Analyses for Various Disk-Gap-Band Parachutes	no	no information on mortar system	
	Techniques for Selection and Analysis of Parachute Deployment Systems	yes		MOR-23
	Pack Density Limitations of Hybrid Parachutes	yes	for future references on pack density	MOR-24
	Parachute testing at altitudes between 30 and 90 kilometers.	no	no information on mortar system	
CPAS test risk acceptance plan nasa	Spacecraft Requirements Development and Tailoring	yes		RISK-03
Parachute mortar testing	A Review of the MLAS Parachute Systems	no	little information on mortar system	

	Parachute Testing for the NASA X-38 Crew Return Vehicle	no	Mortar was unmodified system from space shuttle orbiter	
	Overview of the Crew Exploration Vehicle Parachute Assembly System (CPAS) Generation I Main and Cluster Development Test Results	no	no information on mortar system	
	Phoenix Mars Scout parachute flight behavior and observations	no	little information on mortar system	
Parachute mortar flight performance	ASPIRE Flight Mechanics Modeling and Post Flight Analysis	no	little information on mortar system	
	Parachute Decelerator System Performance During the Low Density Supersonic Decelerator Program's First Supersonic Flight Dynamics Test	no	refers to source below on more info regarding the mortar system	
	Mortar deployment extensibility for the Low Density Supersonic Decelerator parachute	no	focuses on alternative system to mortar. Mission is interesting as mortar is relatively small	
LDSD ballute mortar	Pilot Deployment of the LDSD Parachute via a Supersonic Ballute	yes	increased relevance due to smaller size	MOR-25
(in-depth topic search after last paper found)	LDSD Supersonic Ballute Design and Packing	yes		MOR-26
Parachute mortar failure	Cluster Development Test 2 an Assessment of a Failed Test	no	Mortars functioned nominally, parachute attachment failure	
	Spacecraft Parachute Recovery System Testing from a Failure Rate Perspective	yes	Approach for determining which tests to perform	RISK-01
	Development of a high-performance ringsail parachute cluster	no	Only relevant for clustering of parachutes (presumed N/A for sounding rockets)	

	[Various articles]		Various articles found which did not relate to mortar failure, but parachute or mission failure.	
Parachute mortar risk analysis	CEV Parachute Assembly System Independent Reliability Analysis	yes	Valuable source of mortar risk asessment	MOR-27
	Progress in Payload Separation Risk Mitigation for a Deployable Venus Heat Shield	no	No specific risk methodology applied and no relevant mortar info	
	Tailoring a Parachute Recovery System for Commercial Space	no	No relevant mortar info	
	The Parachute System Recovery of the Orion Pad Abort Test 1	yes	Overview of tests for mortar system	MOR-28
	Project Management of the Capsule Parachute Assembly System (CPAS)	yes	Risk approach during CPAS project	RISK-02
	Orion Capsule Assembly System (CPAS) Test Program Summary	yes		MOR-29
	Summary of CPAS EDU Testing Analysis Results	no	elaborate parachute testing with many mortars, but no info on mortar functionality	
	Testing Strategies and Methodologies for the Max Launch Abort System	yes	1 relevant sentence (see column G) 1 relevant section on test (p.12-13)	MOR-30
	Human Rating the Orion Parachute System	no	only mentions which mortar tests were done (pneumatic & gas generator)	
	Passive vs. parachute system architecture for robotic sample return vehicles	no	no relevant mortar info	
	Stability Analysis of a mortar cover ejected at various Mach numbers and angles of attack	no	no download possible. **Indicates mitigation method through simulations**. Results unknown	
	CPAS Preflight Drop Test Analysis Process	no	no relevant mortar info	
	Forward Bay Cover Separation Modeling and Testing for the Orion Multi-Purpose Crew Vehicle	yes	1 relevant sentence (see column G)	MOR-31
Parachute mortar "risk management"	generated no new results			

Parachute mortar risk assessment	generated no new results			
Specific mission additions	generated no new (relevant) results			
Parachute deployment system PDD	generated no relevant results			
Parachute deployment device	Propellant Actuated Device for Parachute Deployment during Seat Ejection for an Aircraft Application	yes		MOR-32
	Parachute recovery for UAV systems	no	No relevant mortar info	
Pilot chute mortar	Space Shuttle Orbiter Drag Parachute System	no	no detailed mortar information	
	An Entry, Descent and Landing System for the Beagle2 Mars mission	no	no information on mortar system	
	Aerodynamic line bowing during parachute deployment	no	no information on mortar system	
	Beagle 2	no	no download possible	
Drogue parachute mortar	The COMET Recovery System	yes	3 relevant sentences (see column G)	MOR-33
	Huygens DCSS Post Flight Review	no	no information on mortar system	
	Development testing of large ram air inflated wings	no	no information on mortar system	
	Overview of the Crew Exploration Vehicle Parachute Assembly System (CPAS) Generation I Drogue and Pilot Development Test Results	no	fully focused on parachutes	
	Improved CPAS Photogrammetric Capabilities for Engineering Development Unit (EDU) Testing	yes		MOR-34
	Inflation Simulations of a Conical Ribbon Parachutes at Subsonic Conditions	no	no information on mortar system	
	An Airborne Parachute Compartment Test Bed for the Orion Parachute Test Program	no	no information on mortar system	
References listed in other sources	Drogue Mortar System Simulation Development and Performance Evaluation	yes		MOR-35
	A manual for pyrotechnic design, development and qualification	yes		MOR-36
	Proceedings of the Symposium on Explosives and Pyrotechnics (7th)	yes	impossible to search, hard to read	MOR-37

	Design Project: Improved Mortar Deployment Assembly of the Parachute Deceleration System for future planet exploration missions	yes		MOR-38
	Return to sender: lessons learned from Rocket Lab's first recovery mission	yes		MOR-39
	The system approach to spin/stall parachute recovery systems	yes		MOR-40
	Recovery systems design guide	yes		MOR-41
	Human rating the Orion parachute system	yes		MOR-42
Risk management engineering	Engineering risk management (book)	no	not accessible for TU Delft	
	Analytical methods for risk management: A systems engineering perspective	yes		RISK-05
	Project risk management in the Queensland engineering construction industry: a survey	no	not relevant	
	Safety risk management of underground engineering in China: Progress, challenges and strategies	no	not relevant	
	A risk engineering approach to project risk management	no	focuses on financial and planning risk	
	Engineering Decision Making and Risk Management (book)	no	focus on decision making process	
	Large engineering project risk management using a Bayesian belief network	yes	does focus on project risk, but describes risk identification methods in relevant (engineering) sector/context	RISK-06
	A risk register database system to aid the management of project risk	yes	concrete suggestion on risk monitoring phase	RISK-07
	Use and benefits of tools for project risk management	yes	Overview of various activities for all risk management phases	RISK-08
	Financial engineering: derivatives and risk management	no	focuses on financial risk	
	Risk Management in Engineering and Construction	no	not relevant	
	A risk management framework for software engineering practice	no	not relevant	
	An engineering approach to seismic risk management in hardrock mines	no	not relevant	
	Handbook in Monte Carlo simulation: applications in financial engineering, risk management, and economics	no	not relevant	

	Software engineering risk management: a method, improvement framework, and empirical evaluation (book)	no	not relevant	
	Engineering complex systems applied to risk management in the mining industry	no	not relevant	
	Survey of risk management in major UK companies	no	no access	
	Designing risk-management strategies for critical engineering systems	no	focus on continous operating systems	
Space flight risk management	Breast cancer and spaceflight: risk and management	no	not relevant	
	Assessing the risks: tort liability and risk management in the event of a commercial human space flight vehicle accident	no	not relevant	
	Human System Risk Management for Space Flight	no	not on topic	
	Systems integration in space flight environmental risk management	no	on space environmental health	
	NASA's Human System Risk Management Approach and Its Applicability to Commercial Spaceflight	no	on space environmental health	
	Integrating spaceflight human system risk research	no	on space environmental health	
	Human spaceflight risk management	no	on space environmental health	
	Estimating medical risk in human spaceflight	no	on space environmental health	
	An innovative Goddard Space Flight Center methodology for using FMECA as a risk assessment and communication tool	yes		RISK-09
Risk management sounding rocket	Range safety requirements and methods for sounding rocket launches	no	range safety	
	Why risk management is not rocket science	no	not relevant	
	STPA Analysis of Brazilian Sounding Rockets Launching Operations	no	range safety	
	Design of a universal flight computer for sounding rockets	no	not relevant	
	Systems Engineering for ASPIRE: A Low-Cost, High Risk Parachute Test Project	yes		RiSK-10
	A Proposal of a Life-Cycle for the Development of Sounding Rockets Missions	no	not relevant	

	Sounding Rocket Energy Management Using Cold-Gas Aerospike Thrusters	no	word 'risk' only occurs once	
	Air-Launched. Low-SWaP, Space-Capable Sounding Rocket	no	word 'risk' only occurs once	
	NASA Sounding Rockets Program	no	word 'risk' only occurs once	
Risk analysis NASA	NASA systems engineering handbook	yes		RISK-18
	NASA risk management handbook	yes		RISK-19
Quantitative risk analysis engineering	*Multiple case-specific QRA's surface, which are shortly reviewed, but not all copied here.*			
	How useful is quantitative risk analysis?	yes		RISK-20
	Validity and validation of safety-related quantitative risk analysis: A review	yes		RISK-21
"Risk matrix" of sounding rocket	A risk informed approach to reliability requirements tailoring	yes		RISK-22

Search terms

Search term	Sources ID	Title	Year	Author	Relevant content
	STS-01	systems engineering	2011	Sommerville	// Systems should have interdependent parts.
	STS-02	Philosophy of socio-technical systems	1999	Ropohl	originally based on factory work. How does the human psyche influence this?)
	STS-03	systems: some conceptual problems	2006	Kroes et al	include anything in the system that is necessary for performing its intended
spacecraft	STS-04	systems via failure logic analysis	2014	Gallina et al	Not relevant. (Heavy modelling based)
	STS-05	Architectures of Complex, Interconnected, Large-Scale	2009	Osorio	Not relevant. (Very top-level, no practical examples)
	STS-06	A Generic Framework for Structuring Configuration	2022	Martinie	technical" elements besides systems and software: procedures, organizational
spaceflight applications	STS-07	Martian colonisation and society build	2009	Braddock	Not relevant.
	STS-08	systematic review of developments, socio-technical	2021	Griffiths	development parties, the full chain of the technology is reviewed (sourcing -
	STS-09	and Strategic Perspectives of India's Human	2021	Sundararajan	model" fig. 4
	STS-10	Performance Shaping Factors for Human Reliability	2011	Mindock	failure types) of human failure.
	STS-11	human spaceflight simulators, analogs and human	2015	Doule	Communication challenges due to non-native language. --> Importance of
meaning	STS-12	Modeling infrastructures as socio-technical systems	2006	Ottens et al	Socio-technical systems with(out) actors and/or institutions.
	STS-13	research	2007	Coeira	
	STS-14	Designing Socio-Technical Systems	2009	Bauer, Herder	
	STS-15	modelling of socio-technical systems	2015	Wu et al	and software), actors (individual human beings, organisations), and social
	STS-16	– A Generic, Interdisciplinary Approach	2015	Schöttel	perception.
	STS-17	Vagueness in models of socio-technical systems	2010	Hermann, Loser	How to model STS actors etc. in graphical way.
management / analysis	STS-18	risk assessment of complex socio-technical systems:	2009	Mosleh	Case study of the mining system in Turkey as socio-technical system
	STS-19	analyses of socio-technical systems	2008	Leger	Application of bow-tie and barrier models to organizational risks (?)
Relevant references in articles					
	STS-20	The principles of sociotechnical design	1976	Cherns	social system separately, but integrate it and optimise it together.
	STS-21	Sociotechnical principles for system design	2000	Clegg	Early documentation on STS. Various design principles.
	STS-22	successes, failures and potential	2006	Mumford	