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LETECKÝ ÚSTAV

SYSTEM MANAGEMENT OF LIQUID-PROPELLANT ROCKET ENGINE FOR ROCKET MODEL

SYSTÉMOVÝ MANAGEMENT KAPALINOVÉHO RAKETOVÉHO MOTORU PRO MODEL RAKETY

BACHELOR'S THESIS

BAKALÁŘSKÁ PRÁCE

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Assignment Bachelor's Thesis

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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Bachelor's Thesis:

System management of liquid–propellant rocket engine for rocket model

Brief Description:

Liquid–propellant rocket engines are commonly used in space rockets. Their advantage is a high specific impulse and ability to throttle the thrust. Within the framework of the student´s rocket society, a new rocket engine is being designed for use in a competition model rocket. As part of this work, it is necessary to find out what types of these rocket engines exist. From the engine development point of view, the question arises, how to apply ECSS standards and how to organize the activities and management of competition project to achieve specified objectives and milestones?

Bachelor's Thesis goals:

– Get familiar with project management of space projects and implementation of systems engineering.
– Research of liquid–propellant rocket engines designed by student teams.
– Analysis of research and processing of system requirements for the engine development.
– Evaluation of success of the system engineering implementation in engine development.

Recommended bibliography:

HIRSHORN, Steven R., Linda D. VOSS a Linda K. BROMLEY. NASA Systems Engineering Handbook. Rev 2. Headquarters: NASA, 2017.

ECSS-M-ST-10C REV.1. Project planning and implementation. Rev.1. Noordwijk: ECSS, 2009.

ECSS-M-ST-60C. Cost and schedule management. Noordwijk: ECSS, 2008.

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In Brno,

L. S.

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Abstract
The bachelor's thesis deals with the study and implementation of systems engineering for the design of a student liquid rocket engine for use on a sounding rocket.

The first part of the work deals with the illustration of the principles and procedures of system engineering, as well as the study of existing similar engines and the study of the rules of competitions in which a sounding rocket with such an engine could participate in the future.

The second part then deals with the implementation of the findings from the first part into the actual solution of the project, the goal of which is the design of the given rocket engine. It also deals with the implementation of standards from the ECSS system, which are used in the European space industry.

In the end, the entire implementation and its parts are evaluated. Since the given project continues and will be followed by other projects in the future, it is possible to use this work as a basis for solving the system engineering problem.

Abstrakt
Bakalářská práce se zabývá studiem a implementací systémového inženýrství pro návrh studentského kapalinového raketového motoru pro použití na sondážní raketě.

První část práce se zabývá osvětlením principů a postupů systémového inženýrství a taktéž studia existujících podobných motorů a studia pravidel soutěží, kterých by se mohla sondážní raketa s takovýmto motorem v budoucnu účastnit.

Druhá část se poté zabývá implementací poznatků z první části do skutečného řešení projektu, jehož cílem je návrh daného raketového motoru. Taktéž se zabývá implementací norem ze systému ECSS, které se používají v evropském kosmickém průmyslu.

V závěru je provedeno vyhodnocení celé implementace i jejích jednotlivých částí. Jelikož daný projekt pokračuje a budou na něj v budoucnu navazovat i další projekty, je možno využít tuto práci jako podklad pro řešení problematiky systémového inženýrství.

keywords
Rocket propulsion, rocket, systems engineering, ECSS

klíčová slova
Raketový pohon, raketa, systémové inženýrství, ECSS

Rozšířený abstrakt

Rakety fascinovaly lidstvo tisíce let od doby svého vzniku ve východní Asii. ale d té chvíle s nástupem kosmického věku bylo zjištěno, že pohon raket na bázi pevných pohonných látek není dosatečně silný a efektivní pro pohon raket do kosmu. Proto byl v posledních desetiletích vývoj zaměřen především na vývoj raketového pohonu na bázi kapalných pohonných látek, které jsou schopny dodat větší specifický impuls. Tyto raketové motory jsou mnohem silnější, ale zároveň jsou i mnohem komplexnější z hlediska návru, výroby, testování a operačního nasazení. Z tohoto důvodu tedy vyvstává potřeba komplexnějšího projektového řízení.

Ped dvěma lety byl v Česku založen studentský raketový spolek, jehož cíle je zajistit aby studenti především vysokých škol získali více praktických zkušenosti s raketami a jejich součástmi již během studia. V rámci Czech rocket society jsme se rozhodli pokusit se postavit vlastní raketový motor na kapalné pohonné látky, který by bylo možno použít jako pohon pro raketu schopnou dosáhnout výšky alespoň 10 000 metrů. Tento raketový motor by měl být kompletně navržen studenty. Jelikož se ale jedná o velmi složiý projekt, vyvstává potřeba systémového inženýrství.

Hlavní úkoly systémového inženýrství pro tento projekt budou především identifikace možných osvědčených konceptů. Identifikace cílů, omezení apožadavků pro daný projekt a jejich neustálá úprava podle potřeby. Příprava projektových zhodnocení a implementace zpětné vazby získané při těchto zhodnoceních. Provádění integrace, verifikace a validace daného systému a pomoc s projektovým řízením z technického i netechnického hlediska.

Z důvodu dlouhého trvání tohoto projektu bude pozornost zaměřena pouze na fáze Předfáze A: *Koncepční studie*, Fáze A: *Koncepční a technologický vývoj* a Fáze B: *Předběžný navrh* ve smyslu jak jsou popsány dále.

První kapitoly se zabývají řešerší dané problematiky, konkrétně problematiky raketových motorů na kapalné pohonné látky a problematiky systémového inženýrství.

V rámci řešerše problematiky raketových motorů na kapalné pohonné látky jsou představeny základní funkční zásady raketových motorů a jejich kategorizace. Dále je pro raketové motory na kapalné látky představeno jejich dělení podle principu fungování a jsou představeny jejich kritické součásti a pohonné látky s kterými tyto raketové motory běžně operují. V závěru řešerše této problematiky je představena rešerše již existujících řešení a omezení týkajících se možného budoucího užití vyvíjeného motoru.

V rámci řešerše problematiky systémového inženýrství jsou nejprve představeny základní principy systémového inženýrství a základní procesy používané během jeho užití. Následně jsou představeny jednotlivé fáze používané během vývoje zařízení pro využití v kosmickém průmyslu, přičemž důraz je kladen především na popis fází jichž se týká tato práce, ovšem ostatní fáze jsou taktéž představeny.

V další části práce je následně řešena již implementace znalostí získaných během řešerše do provedení úkonů systémového inženýrství. Nejprve jsou představeny základní principy použité v rámci implementace, následované samostatnými kapitolami pro jednotlivé fáze, během nichž došlo k implementaci systémového inženýrství. Tyto kapitoly se zabývají hlavními úkony systémového inženýrství provedenými v dané fázi projektu.

V rámci diskuze je následně vyhodnoceno jak byly splněny nejen cíle práce, ale i jednotlivé cíle implementace, přičem jsou popsány i problémy ke kterým v rámci řešení došlo z důvodu nedostatečných pedchozích znalostí a jsou navržena doporučení pro případné použití v budoucnu.

SVOBODA, Jakub. *Systémový management kapalinového raketového motoru pro model rakety* [online]. Brno, 2023 [cit. 2023-05-25]. Dostupné z: https://www.vutbr.cz/studenti/zav-prace/detail/149240. Bakalářská práce. Vysoké učení technické v Brně, Fakulta strojního inženýrství, Letecký ústav. Vedoucí práce Jakub Černoch.

I declare that I have elaborated my bachelors thesis *System management of liquid-propellant rocket engine for rocket model* independently with the use of literature and other sources pf information, which are all quoted in the thesis and detailed in the list of literature at he end of thesis.

Jakub Svoboda

I would like to thank my family for their support. I would also like to thank my friends, members of the Czech Rocket Society, for their hard work on the project this thesis describes.

I would like to thank my supervisor Ing. Jakub Černoch, for his advice, help and guidance in writing this thesis.

Jakub Svoboda

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1 INTRODUCTION

Rockets have fascinated mankind for thousands of years since they were first invented in eastern Asia. But since then with the start of the cosmic age, it was figured out that rockets with solid rocket propulsion are not sufficient enough to be used for space travel. In the past decades, the main focus has drifted towards liquid-fed rocket engines as means of rocket propulsion. These rocket engines are more powerful and also more complex for development, manufacturing, testing and operation. Therefore more complex project management is needed.

Two years ago a student rocket society was founded in the Czech republic with the aim to get students more hands-on experience with rockets and their components. In the Czech rocket society, we decided to try to build our own liquid-fed rocket engine which could be used as a propulsion element for a model rocket that could fly to at least 10 000 meters. This rocket engine will be completely designed by students. But because this project is very complex, the need for systems engineering arises.

The main challenge of this project for systems engineering will be identifying viable and proven concepts. Identifying goals, constraints and requirements for said project and constantly updating them as needed. Preparing project reviews and implementing feedback from those reviews. Conducting integration, verification and validation of the given system. And helping with the project management of the said project from both technical and non-technical standpoints.

Because of the long duration of this project, the systems engineering will be only focused on Pre-Phase A: *Conceptual studies*, Phase A: *Concept and technology development* and Phase B: *Preliminary design* as they are described later in this thesis.

2 ROCKET ENGINES

Rocket engines are reactive engines using stored propellants to produce thrust. Because all necessary propellants are stored, the rocket engine can function independently of the surrounding environment. According to [1], rocket engines can be divided into several categories depending on the energy source. These include:

- **Chemical propulsion**, where the energy source is a chemical reaction between propellants
- **Nuclear propulsion**, where the energy source is nuclear fission or fusion
- **Electric propulsion**, where the energy source is electric energy
- **Other propulsion**, where the energy sources are all remaining options (this includes, for example, using solar energy)

As this thesis focuses on the rocket engine based on chemical propulsion, this propulsion method is described in more detail later in the thesis. As for the other propulsion methods, it is not deemed necessary for them to be described in more detail.

2.1 The function principle of chemical rocket engine

The energy source of chemical propulsion is a chemical reaction of a propellant or propellants between them or with a catalyst. This reaction creates high-pressure gas, which is then accelerated using a supersonic nozzle into supersonic velocity. The energy of the ejecting mass at high speed creates the needed thrust for the propulsion of the object.[1]

Chemical rocket engines are commonly divided into three subcategories: Solid rocket engines, Hybrid rocket engines, and Liquid rocket engines, depending on the state of the propellants. These categories are described in more detail in the following sections.[1]

2.2 Solid rocket engines

Solid rocket engines use solid fuels and oxidizers to create high-pressure gases. These rocket engines were the first to be developed, as they were the easiest to design, build, and operate for various purposes.[1]

The main benefits of solid rocket engines are their simple production, storability and low cost. The main disadvantages are low control over thrust and that after ignition of the engine, it is not possible to stop the reaction or restart the engine.[1]

The propellants for solid rocket engines can include black powder, sugar and potassium nitrate, or composite propellant, including fuel, oxidizer and binder. Composite propellants are the most used solid propellants for highly demanding purposes. The propellants' composition in relation to the time they burn can affect the pressure of the gases formed from this reaction, which is used for designing the engine to have desired thrust over time.[1]

Nowadays, solid rocket engines are mainly used for booster stages of rockets as the main propulsion for rockets designed to deliver cargo, as well as for military, educational and entertainment purposes.[1]

2.3 Hybrid rocket engines

Hybrid rocket engines have one of the propellants, either oxidizer or fuel, with the latter being used more frequently in the solid state, whether the other propellant is in the liquid state. This construction is more complex to design but typically performs slightly better than solid rocket engines.[1]

The main benefits of hybrid rocket engines are their easier construction than liquid rocket engines and greater control over thrust compared to solid rocket engines. The main disadvantages are more complex construction than solid rocket engines and usually a lower performance than liquid rocket engines.[1]

The main combination of propellants for hybrid rocket engines is a liquid oxidizer and a solid fuel. As oxidizers, liquid oxygen (LOX), nitrous oxide (N2O), and high-concentration peroxide (HTP) are used. As fuels, polyethylene (PE) and wax-paraffin are used primarily, although coal, wood, and other materials were tested.[1]

Nowadays, hybrid rocket engines are mainly used for sounding and experimental rockets. As of today, no rocket launcher capable of reaching earth orbit with a hybrid rocket engine was developed and tested, although some concepts were suggested.[1]

2.4 Liquid rocket engines

Liquid rocket engines use liquid propellant or propellants for chemical combustion, which generates high-pressure gases that propel the engine. They are often considered to be the most complex of chemical rocket engines. They are typically divided into monopropellant and bi-propellant categories based on the number of propellants used.[1]

Monopropellant liquid rocket engines

Monopropellant liquid rocket engines use only one propellant, which is injected into the combustion chamber, where it reacts with the catalyst, creating high-pressure gases. The main advantages generally are low ignition time and easier construction. The main disadvantages are lower performance compared to bi-propellant rocket engines and the use of toxic or hazardous substances.[1]

Typically high-test peroxide (HTP) or hydrazine are used as a propellant. The catalyst is usually a platinum sponge near the injector plate, but silver, iron oxide, manganese dioxide, and many more can be used.[1]

Because of their low ignition time, they are mainly used as a reaction control system (RCS) for both launch vehicles and spacecrafts and use in other than the aerospace industry is also tested.[1]

Bipropellant liquid rocket engines

Bipropellant rocket engines use separate fuel and oxidizer as means of combustion propellants. The main advantages are the highest potential performance of the chemical rockets and the ability to control the thrust in a wide range of values. The main disadvantage is the complexity of the said engine.[1]

Typical propellants for the bipropellant rocket engines are described later.

The primary use of bipropellant liquid rocket engines is as main engines for launch vehicles and spacecrafts. To this date, it is the most used type of rocket engine on launch vehicles capable of reaching orbit.[1]

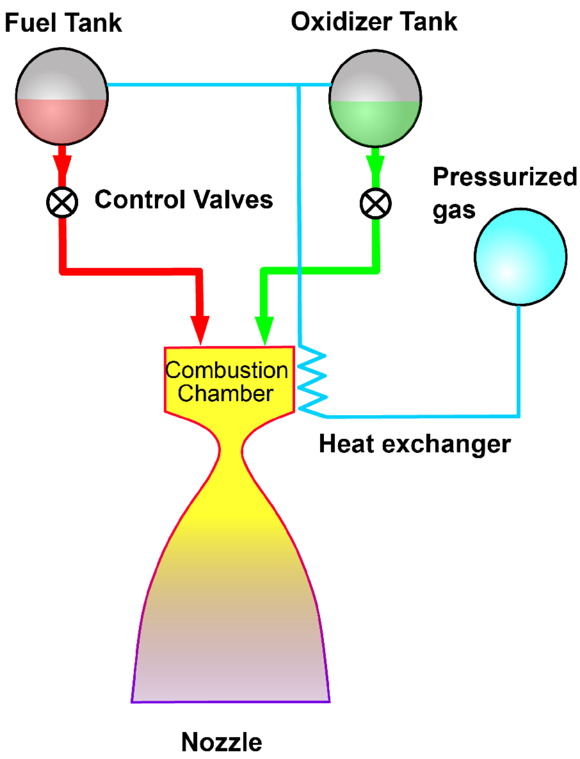
2.4.1 Engine cycles

The typical types of liquid rocket engine cycles (Figure 2.1) are pressure-fed cycle, expander cycle, gas-generator cycle (sometimes called an open cycle), and staged combustion cycle (sometimes called a closed cycle). In the last years, more engine cycles saw use, i.e. the electric pump-fed cycle used on the Electron rocket and the combustion tap-off cycle used on the New Shepard rocket.[1]

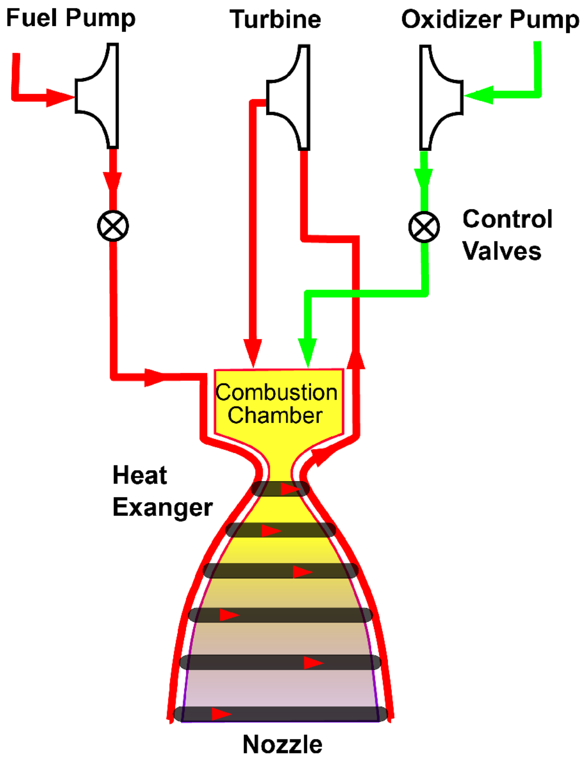
The pressure-fed cycle is considered to be the least complex of all. The propellants are fed to the combustion chamber under high pressure in the propellant tanks. The main advantages are the simplicity of the design and the low latency to achieve a full flow of propellants. The main disadvantages are the added weight of the propellant tanks to sustain the pressure, that the pressure in the combustion chamber can not exceed the pressure in the propellant tanks and the need for added pressurization equipment. The pressure-fed cycle is used mainly for small-scale rockets, launch vehicles' upper stages, and RCS.[1]

The expander cycle uses part of one propellant (typically fuel) to pass through the cooling channels of the rocket engine to change into a gaseous phase, which turns the turbine powering the turbopumps that feed the propellants into the combustion chamber. The main advantages are the simplicity of the powering of the turbine and the high performance resulting from all propellants being used in the combustion chamber. The main disadvantages are the need for the cryogenic propellant and the limited power output of gasified propellant resulting in lower possible thrust. This cycle is commonly used on launch vehicles using cryogenic propellants.[1]

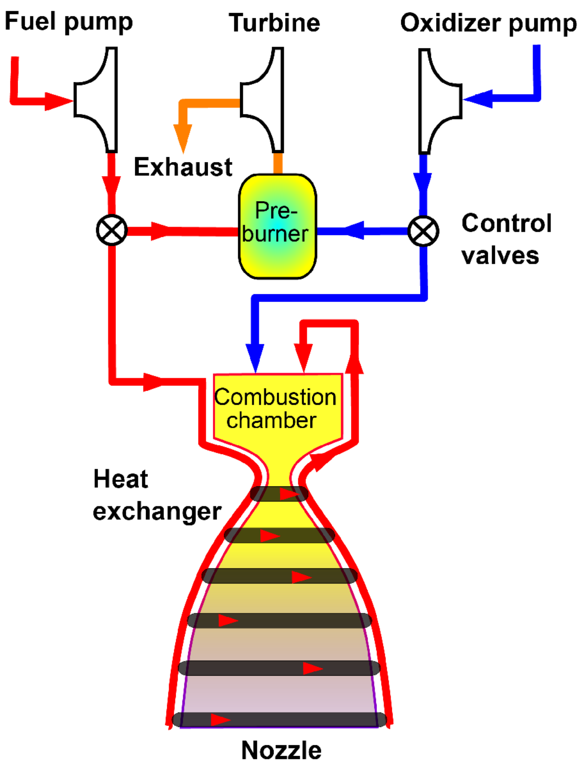
The gas generator cycle utilizes part of both propellants to mix in the pre-burner, where low-temperature gases are gained as the mix ratio is worse than ideal. These gases then power the turbine, which powers the turbopumps. The main advantages of this cycle are the design's simplicity and the system's low mass. The main disadvantage is slightly worse performance, as part of the propellants is accelerated to lower-than-ideal velocities. This cycle is currently the most widespread among launch vehicles from all countries.[1]



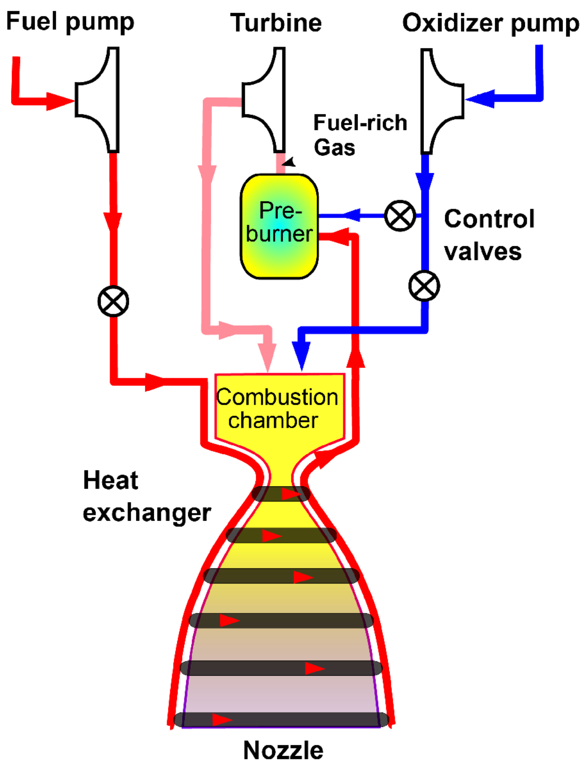
(a) Pressure-fed cycle[2]



(b) Expander cycle[3]



(c) Gas-generator cycle[4]



(d) Staged combustion cycle[5]

Figure 2.1: Typical rocket engine cycles

The staged combustion cycle uses part of both propellants to mix in the pre-burner like in the gas generator cycle, but these gases are then injected into the combustion chamber. The main advantage of this cycle is the highest performance of the described cycles. The main disadvantages are the highest complexity of the related systems, which results in a greater mass of the rocket engine. This engine cycle is commonly used on launch vehicles, although due to its complexity, it is not as widespread as the gas generator cycle.[1]

2.4.2 Propellants

Below the most common propellants in bi-liquid rocket engines are described, and the table of their advantages and disadvantages is shown.

Oxidizers

Liquid oxygen (LOX) is liquid rocket engines' most commonly used oxidizer. It is used with hydrocarbon fuels, liquid hydrogen and alcohols and provides high performance. It is non-toxic and non-corrosive but rapidly evaporates, so sufficient insulation is needed to reduce these losses. This also means that LOX is not storable. Because LOX is cryogenic, special tubing and valves are also required. It has the nature to combust with impurities, so thoroughly cleaning every part in touch with LOX is needed.[1]

Hydrogen peroxide is a powerful liquid oxidizer with clean burning. The high-concentration peroxide, also known as high-test peroxide (HTP), can cause chemical burns when in contact with human skin. It can be used as a bipropellant liquid rocket engine oxidizer and monopropellant. One of the main issues with using HTP is that to be storable, it needs to be stabilized, which rules out its use as a monopropellant. It has hypergolic[1] properties, and because of its clean burning, it is considered the primary alternative for hypergolic oxidizers in the future.[1]

Table 2.1: Selected oxidizers advantages and disadvantages

Oxidizer	Advantages	Disadvantages
LOX	High performance, non-toxic, non-corrosive, clean burning	Cryogenic, thorough cleaning needed
HTP	Hypergolic, storable (to extend), low toxicity, clean burning	Decomposition at higher temperatures, low performance
HNO3	Hypergolic, high performance, storable	Extremely high toxicity, corrosive
NTO	Hypergolic, high performance, storable	Extremely high toxicity, corrosive, tight temperature range for liquid phase
N2O	Easy to get, self-pressurizing capability, low toxicity	Low performance, cryogenic to extend, low critical point temperature

[1] Igniting spontaneously on mixing with another substance

Nitric acid (HNO_3) is a hypergolic storable oxidizer. Many variants exist of nitric acid, but for use in rocket propulsion, red fuming nitric acid (RFNA), white fuming nitric acid (WFNA) and inhibited red fuming nitric acid are mainly used. It is a corrosive and toxic oxidizer, with only some materials suitable for storage. Its fumes are toxic in small doses, so special care and equipment are needed when handling it. Due to its good storability, it is mainly used for long-term missions and military use.[1]

Nitrogen tetroxide (NTO), correctly named dinitrogen tetroxide, shares many similarities with HNO_3. It is a hypergolic storable oxidizer. Although it is slightly less toxic than HNO_3, special equipment is still needed for its handling. Its temperature range for being in the liquid state is narrow, so special additives are introduced to NTO to extend this range.[1]

Nitrous oxide is the least potent of the oxidizers listed if used in a bi-propellant rocket engine. It has some cryogenic properties, but at high pressure, these properties diminish. It is drastically less toxic than HNO_3 and NTO, but some safety precautions must be considered. It can self-pressurize itself, meaning the external pressurization system is not required.[1]

Fuels

Hydrocarbon fuels are mostly derivatives and include many different fuels that can be used as rocket propellants. The most commonly used hydrocarbon fuels are based on kerosene, with RP-1 and RP-2 (Rocket propellant 1 and 2, respectively) being the most used. Their great advantage is that they are in significant surplus and easy manipulation. They are the most widespread category of rocket fuels used nowadays.[1]

Liquid methane (LCH_4) is also considered a hydrocarbon fuel, but its properties differ vastly. It is cryogenic fuel, the main part of natural gas, with a higher specific impulse than other hydrocarbon fuels but lower than liquid hydrogen. Due to its higher density than liquid hydrogen, it has a slightly higher volumetric specific impulse, meaning smaller tanks must be constructed. It is considered the primary fuel for high-power rocket engines by many companies nowadays.[1]

Liquid hydrogen (LH_2) is one of the most used rocket fuels and has one of the highest specific impulses. However, it has very low specific gravity and a very low boiling temperature of about 20 K. Large and bulky tanks with a high amount of insulation need to be used for liquid hydrogen. All commonly used gases and liquids solidify in the liquid hydrogen and therefore pose a risk for contamination of the feed system. Mixtures of liquid oxygen with solidified air or oxygen can present a risk of explosion.[1]

Hydrazine is a chemical compound used as rocket fuel in many derivatives, the most commonly known being hydrazine, unsymmetrical dimethylhydrazine and monomethylhydrazine. Due to their many similarities, they are all encompassed in this paragraph. Hydrazine is storable hypergolic rocket fuel with very high toxicity. It can be used as a monopropellant in combination with a suitable catalyst. It is most commonly used as a bipropellant with HNO_3 and NTO. Although rocket engines with these propellants for launch vehicles exist, it is typically not used for crewed missions as the main propulsion. One of the primary uses is the reaction control system (RCS) and the propulsion of autonomous spacecrafts with long-term missions.[1]

Alcohols are not commonly used as rocket fuel nowadays, but it was the first used rocket fuel for large-scale liquid rocket engines. It has a lower specific impulse than the other fuels listed above but is easy to manipulate and get. Nowadays, it is mainly used as rocket fuel by student teams or in combination with other chemicals as new-generation green hypergolic rocket fuel.[1]

Table 2.2: Selected fuels advantages and disadvantages

Fuel	Advantages	Disadvantages
Hydrocarbon fuels	Storable, easy to get	Slightly lower performance
LCH4	High specific impulse, high specific gravity, easy to get	Cryogenic, relatively new
LH2	High specific impulse, clean burning	Low boiling point, low specific gravity
Hydrazine	Storable, hypergolic, can be used as monopropellant	Very high toxicity, not suitable for manned missions
Alcohols	Easy to get, easy to manipulate	Low performance

2.4.3 Cooling methods

Because the temperature inside the combustion chamber can exceed 3000 K, which is well above the melting point of most common materials, some cooling needs to be introduced to prevent failure of the combustion chamber and the nozzle.[1]

Regenerative cooling is done by circulating one propellant, typically fuel, around the walls of the combustion chamber and nozzle in channels. The heat transferred from the combustion chamber into the material is transferred into the propellant, which slightly raises its temperature. This cooling method is commonly used on medium to high-thrust rocket engines and is probably the most widespread for main rocket engines for launch vehicles.[1]

Radiation cooling is done by having the combustion chamber and/or nozzle made of high-temperature material, such as rhenium, niobium or carbon-carbon. This material can then radiate most of the heat into the outer environment. When the heat transfer equilibrium is reached, the wall may seem to glow red or even white. Because this method can only work with low to moderate heat fluxes, it is commonly used for combustion chambers of engines with lower thrust and pressure. The main use is probably for the parts of diverging nozzles, with an area ratio of more than 10. It is thus used on main engines for launch vehicles and spacecrafts in a vacuum, as the desired nozzles have a high area ratio, and the heat transfer by radiation also works in a vacuum.[1]

Ablative cooling is done by having the walls of the combustion chamber and the nozzle made of a material which can burn slowly burn away or evaporate, thus reducing the temperature near the walls to a safe span. Because the material gradually disappears, the cumulative burning time of a rocket engine with ablative cooling is limited to a particular time. This cooling method is used as the primary cooling method on large-scale solid rocket engines but also on liquid rocket engines.[1]

Film cooling is done by injecting a small portion of the propellant through the combustion chamber and the nozzle walls, thus creating a film of gases with a low temperature in near proximity to the walls. This method is used mainly on smaller rocket engines or with regenerative cooling to further cool the walls.[1]

Heat sink cooling is done by the material accumulating the heat from the heat transferred into the walls. This cooling method was used primarily in the past. The main problem of this cooling method is that the melting point of the selected material limits it. For all-metallic combustion chambers, the burning time of the rocket engines using this cooling method is around a few seconds at maximum. In the past years, experiments with using walls made of ceramic took place. These tests concluded that heat sink cooling can be used for smaller engines with short burning times.[1]

2.4.4 Injectors

The injectors' primary function is to deliver the propellants into the combustion chamber and atomize them there to ensure that the propellants mix properly to ensure uniform mixture composition in the combustion chamber cross-section. Over the years, many different designs of injectors have been proposed, built, and used (Figure 2.2). The most used are the impingement injectors, which are the easiest to construct. The propellant or propellants are injected as streams into the combustion chamber, colliding at calculated points, leading to propellant atomization. Some other designs, on the other hand, work with sprays of propellants which collide with themselves or with the material of the injector, thus atomizing. The most advanced injector is considered to be the so-called pintle injector, which is designed to throttle the amount of propellants into the chamber, thus throttling the engine's thrust.

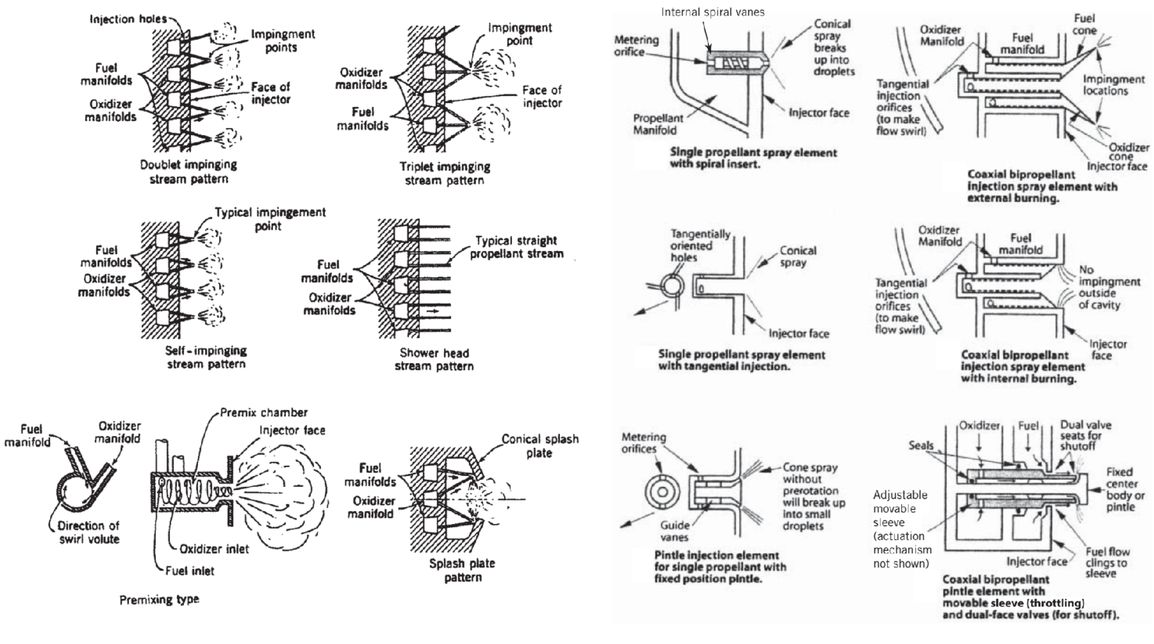


Figure 2.2: Used types of injectors in liquid rocket engines ([1] and edited)

3 RESEARCH OF STUDENT DEVELOPED LIQUID ROCKET ENGINES

In the past years, a high number of student rocketry teams attempted to develop their own liquid-fed bipropellant rocket engines that could be used as primary propulsion to their rockets. The main problem with developing rockets with liquid rocket engines is their high cost, which means typically, three purposes for these rockets are assumed:

- The rockets and rocket engines are developed for the purpose of research on a given issue. This research is mostly performed on universities with their own rocketry teams.
- The rockets and rocket engines are developed to compete in student rocketry competitions. The most prominent competitions are the European rocketry competition (EUROC), and the Spaceport America Cup.
- The rockets and rocket engines are developed to try to claim some record among student rocketry. The most prominent being the highest altitude record, but more records are to be claimed, i.e. the fastest rocket.

As stated in the list, if the rocket and the rocket engines are developed for student rocketry competition, mainly two options exist, which are EUROC, taking place each year in September/October in Portugal, and Spaceport America Cup, taking place each year in June/July in New Mexico. These competitions are the main high-powered student rocketry oriented competitions in the world, with many teams across the globe participating in them. Both these competitions share similar rules, which every team needs to fulfil to participate.

3.1 EUROC requirements

For the purpose of the project to be used in the future for any of the competitions, it was needed to get familiar with the rules concerning these competitions. Because the rules concerning the student-researched and developed (SRAD) hybrid and liquid engines and their parts are similar in both competitions listed above, it was decided that the rules as defined for EUROC shall be followed primarily due to EUROC's easier availability.

As many of the rules concern the rocket and its components, which are not directly connected to the propulsion, a table of requirements (Table 3.1), concerning the propulsion of the rocket and its components was prepared by selecting them from EUROC guidelines [6][7]. The selected requirements concern mainly the selection of the propellants, the designed total impulse of the propulsion system, and the design of the propellant tanks. They also state the selection of appropriate materials for some of the components.

Table 3.1: EUROC guidelines (selection, rewritten)

Guideline	Section	Requirement
[6]	6.1	Total impulse shall not exceed 40 960 Newton-seconds
[6]	6.4	All propellants used must be non-toxic (nitrous oxide, liquid oxygen, hydrogen peroxide, kerosene, propane, and similar substances, are all considered non-toxic)
[7]	2.6.4	Oxidizer tank venting to prevent over-pressure situations shall be implemented
[7]	2.6.5	System shall have implemented a means for remotely controlled venting or offloading of all liquid and gaseous propellants in the event of a launch abort
[7]	3.6.3	In case of propellants with a boiling point of less than -50 °C any wiring or harness passing within close proximity of a cryogenic device or a cryogenic tank shall utilize safety critical wiring with cryo-compatible insulation
[7]	4.2.2	Pressure vessels constructed entirely from isotropic materials shall be designed to a burst pressure no less than 2 times the maximum expected operating pressure
[7]	4.2.3	Pressure vessels either constructed entirely from non-isotropic materials or implementing composite overwrap of a metallic vessel, shall be designed to a burst pressure no less than 3 times the maximum expected operating pressure

3.2 Existing student-designed rocket engines

Based on the selected requirements (Table 3.1), a database of existing rocket engines with similar designs has been created. After research, 8 similar designs were found. The similarity lay mostly in the engines being developed by student teams, having a thrust of about 0.5-4 kN, and being pressure fed. The full database can be found in the annex, with its part (Table 3.2) shown below. For the purpose of Table 3.2, the name of *SDSU rocket project* was shortened as SDSU and the name of *Sun devils rocketry* was shortened as Sun devils. It is also to be noted, that P_c means pressure in the combustion chamber and F means thrust of the engine.

Table 3.2: Existing similar rocket engines

Rocket	Developed by	Propellants	Cooling method	P_c [bar]	F [kN]
Valkyrie	Danstar	IPA and N2O	regenerative	19	3.1
MIRA	TU Dresden	Ethanol and LOX	film cooling	15	0.5
LAIKA	MASA	Ethanol and N2O	ablative	28	3.78
Boomie Zoomie	Purdue	LCH4 and LOX	ablative	-	3.56
μHoubolt	TU Wien	Ethanol and N2O	ablative	-	0.5
Lady Elizabeth	SDSU	LCH4 and LOX	regenerative	-	2.27
-	Sun devils	Kerosene and LOX	regenerative	17	1.8
Project Nero	Portal space	Ethanol and LOX	regenerative	20	3.5

As can be seen in Table 3.2, the used propellants on existing similar engines are mostly alcohols, namely ethanol and IPA, as fuel and LOX or N2O as oxidizers. The main cooling method is regenerative cooling, followed by ablative cooling. The chamber pressure varies from 15 up to 28 bar, and the thrust of the engines is mostly in the 3-4 kN range.

As can be seen in the whole database in the annex, the smaller engines, namely from TU Dresden and TU Wien, are considered for rockets with a lower apogee of about 3000 meters but were entered in the database nevertheless, mainly for the pieces of information on the propellants, cooling method and the chamber pressure.

4 SYSTEMS ENGINEERING

Encyclopedia Britannica describes systems engineering (SE) as a *"technique of using knowledge from various branches of engineering and science to introduce technological innovations into the planning and development stages of a system."*[1]

Systems engineering is a multidisciplinary approach to a system's design, implementation, technical management, operations, and closeout. A system, in this sense, refers to elements that work together to achieve the desired results. These elements include all hardware, software, equipment, facilities, personnel, processes, and procedures necessary for this purpose. SE is an integrative discipline where the contributions of mechanical, electrical, chemical, and many other disciplines are evaluated and balanced against each other to create a coherent, complete system that does not favour the need for one discipline over another.[8]

Systems engineering aims to find a safe and optimized design capable of meeting given requirements in the face of often conflicting requirements and constraints. The systems engineer should develop the ability to identify and evaluate effort goals to optimize the overall design and not favour any system/subsystem at the expense of another while continuously verifying that the goals of the operational system are met.[8]

The position of a systems engineer can be diametrically different depending on the project. For larger projects, there may be one or more specialized system engineers. For significantly large projects, for example, there may be a system engineer in charge of the entire system and several system engineers in charge of particular subsystems. However, the chief engineer or a project manager may be responsible for the system engineer's duty for smaller projects.[8]

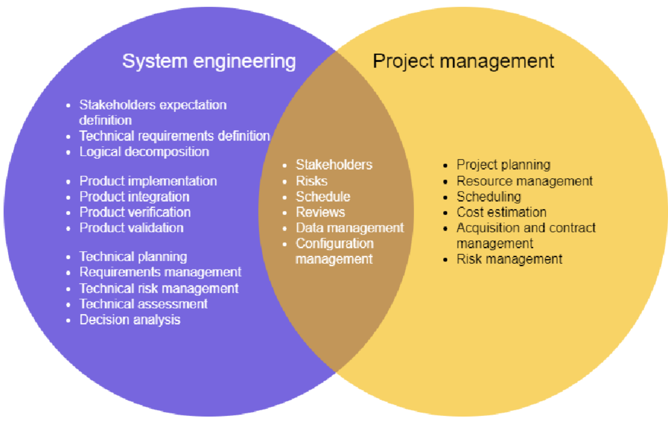


Figure 4.1: SE in context of overall project management (redrawn according to [8] and edited)

[1]Cited from https://www.britannica.com/topic/systems-engineering 22.12.2022

In Figure 4.1, the tasks of system engineering from the point of view of project management and their common area can be seen. This document further addresses the area of Systems Engineering from this diagram. All of the tasks listed are described later in more detail as needed.

4.1 The common technical processes

For the use of systems engineering in CRS, the NASA systems engineering engine was adopted to be used. The engine can be found in Figure 4.2, which shows three sets of technical processes used throughout the SE and their interactions in the form of an algorithm.

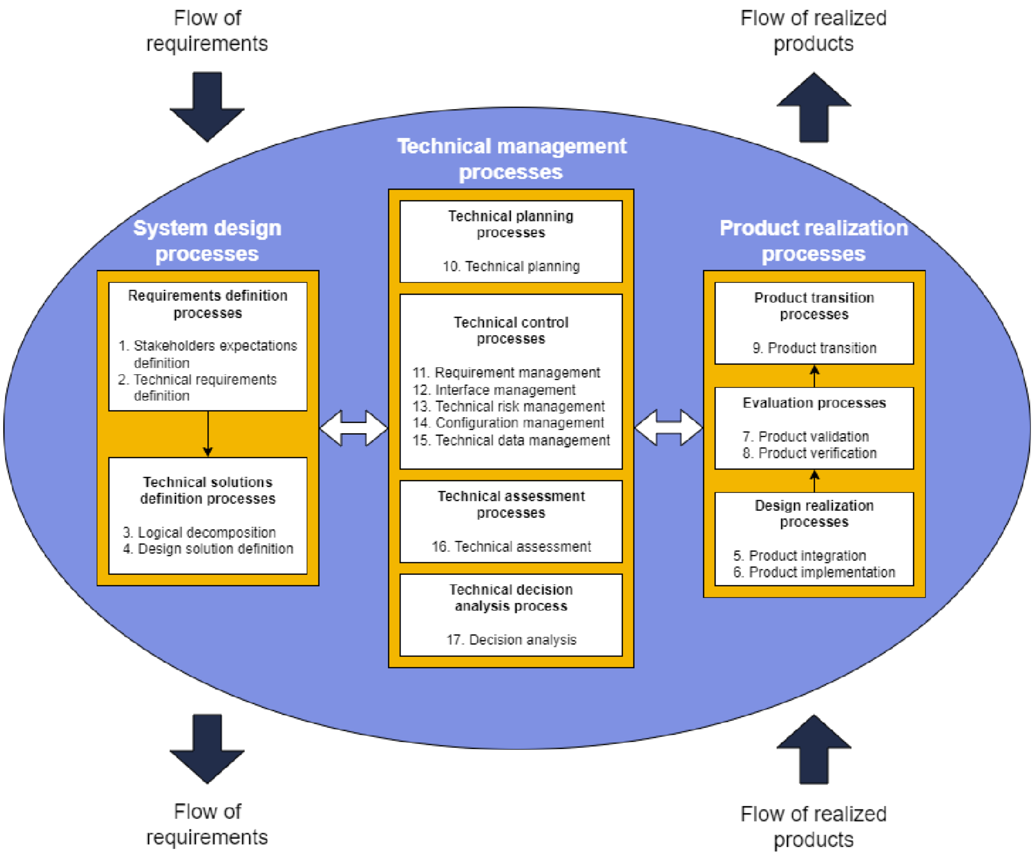


Figure 4.2: The systems engineering engine (redrawn according to [8] and edited)

System design processes

The system design processes are used primarily in the project's design phase. They are applied to take the stakeholders' expectations, define them, and transform them into technical requirements. These requirements must then be decomposed into simple enough and sufficient logical and behavioural models, which are then turned into design solutions.[8]

These solutions must fulfil the stakeholders' expectations based on the first step of these processes. If they cannot fulfil them, the processes must be repeated until the expectations can be fulfilled.[8]

These processes are applied to each product of the system structure from the top to the bottom until the lowest products in any system structure branch are defined to the point where they can be built, bought, or reused.[8]

Product realization processes

The product realization processes are used for the realization, evaluation and transition processes of the flow of the products. At first, the products from the lower levels are integrated and implemented into the resultant product of the given level. After that, the product is evaluated through validation and verification. The difference between these two is that verification is pre-requisite for validation, and it "*demonstrates through the provision of objective evidence that the product is designed and produced according to its specifications*"[9], whereas validation "*demonstrates that the product is able to accomplish its intended use in the intended operational environment*"[9]. If the final product of these processes fulfils them all, then it can be transitioned to the next level.[8]

These processes are applied to every operational product in the system structure, starting with the lowest-level product and ending with higher-level integrated products. These processes are used to execute the tasks listed above as a function of the appropriate life cycle stage.[8]

Technical management processes

The technical management processes are used to manage the project from a technical standpoint. These processes are not unique to systems engineers, as the chief engineer/architect of the project commonly executes the same processes.[8]

Unlike to system design and product realization processes, there is no order in which the individual processes shall be executed, as they usually occur simultaneously.[8]

These processes include the creation and development of the technical project plans, technical control of the project by means of requirements, interfaces, risks, configuration and data, assessment of progress against plans, control of the technical implementation and assessment in the decision-making process from the technical standpoint.[8]

These processes are applied constantly in the course of the project in cooperation with the project management processes, with which it shares many similarities. These processes must be executed jointly with System design and Product realization processes during the project duration.[8]

4.2 Cost-effectiveness consideration

One of the objectives of systems engineering is to ensure that the system is developed, manufactured and operated in the most cost-effective way possible while safely accomplishing its purpose. The most cost-effective way possible should consider performance, cost, schedule, and risk. The resultant system should show a balance between effectiveness and cost.[8]

Design trade-offs should be carried out to find designs that accomplish the best combination of effectiveness and cost. If alternatives are found that either reduce cost without reducing effectiveness or increase effectiveness without increasing costs, it is bound to be a "win-win" case, and the decision of the systems engineer is easy. The decision becomes more challenging if the alternatives reduce cost and reduce the effectiveness or increase effectiveness and increase the cost.[8]

This is sometimes called a systems engineers dilemma. The base is that:

- To reduce cost at constant risk, effectiveness must be reduced
- To reduce risk at constant cost, effectiveness must be reduced
- To reduce cost at constant effectiveness, higher risk must be accepted
- To increase effectiveness at constant cost, higher risk must be accepted
- To reduce risk at constant effectiveness, the higher costs must be accepted
- To increase effectiveness at constant risk, the higher costs must be accepted

This dilemma is shown in Figure 4.3, which represents a triangle, with each side representing cost, risk, or effectiveness. The further from any side the point is, the less emphasized its respective property. As can be seen, having the most efficient system with the lowest risk at the lowest cost is impossible, and some compromise needs to be made.

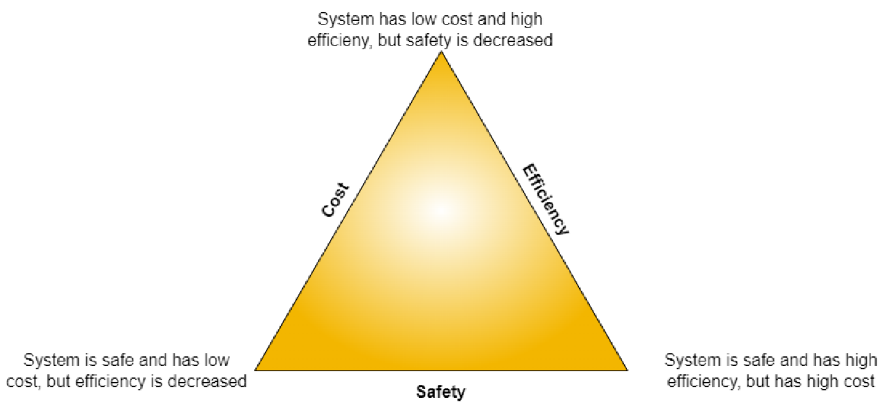


Figure 4.3: The systems engineer’s dilema

It is possible to transform the diagram into three-dimensional space by transforming it into a tetrahedron, with each face representing either cost, risk, effectiveness, or time. The further from any face the point is the less emphasized its respective property.

5 PROJECT PHASES

According to both NASA and ECSS guidelines it is recommended to divide the project into separate phases for easier project planning and project management. Therefore this division is common in the space industry in both Europe and North America.

The traditional division can be found in NASA[8] and ECSS[10] guidelines. These divisions are almost identical with only small differences, i.e. the difference in the designation of the phases. The division into phases as baselined in [8] is used for the CRS project management.

The main difference for the division into phases as used in CRS is that apart from NASA, from which it is adopted, is that according to NASA[8] each phase takes place after the previous phase was completed and concluded. On the other hand, the ECSS[10] shows that some phases may proceed simultaneously. As the project design shall be using the iterative design cycle, it is preferable to have an opportunity to proceed with more phases at the same time i.e. phases C and D as they are described later.

5.1 Division into phases

According to the division into phases as used in CRS, each project can be divided into 7 individual phases, which are:

- Pre-Phase A: Concept studies
- Phase A: Concept and technology development
- Phase B: Preliminary design
- Phase C: Final design and fabrication
- Phase D: System assembly, integration, and testing
- Phase E: Operations and sustainment
- Phase F: Closeout

Not all the phases need to be used for each project, as well as each phase can take dramatically different times to perform for different projects, depending on the need for a deeper research of the problem, the need for very high reliability, or the complexity of the final system. For very large and complex projects (i.e. manned missions) the *Pre-Phase A* alone can take years or decades to complete.

These phases can be additionally grouped into three groups for easier use, commonly known as *Pre-Formulation*, *Formulation*, and *Implementation*. In some cases, the *Pre-Formulation* and *Formulation* can be merged together and only use the *Formulation* designation.[8]

Each phase has its own purpose and typical outcomes (Figure 5.1), with each phase having its own associated reviews.[8]

PHASE		PURPOSE	TYPICAL OUTCOMES
PRE-FORMULATION	**Pre-Phase A:** Concept studies	To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility. identify potential technology needs, and scope.	Feasible system concepts in the form of simulations, analysis, study reports, models, and mock-ups
FORMULATION	**Phase A:** Concept and technology development	To determine the feasibility and desirability of a suggested new system and establish an initial baseline compatibility with CRS's strategic plans. Develop final mission concept, system-level requirements, needed system technology developments, and program/project technical management plans.	System concept definition in the form of simulations, analysis, engineering models and mock-ups, and trade study definition
	Phase B: Preliminary design	To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements and generate a preliminary design for each system structure end product.	End products in the form of mock-ups, trade study results, specification and interface documents, and prototypes
IMPLEMENTATION	**Phase C:** Final design and fabrication	To complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software. Generate final designs for each system structure end product.	End product detailed designs, end product component fabrication, and software development
	Phase D: System assembly, integration and testing	To assemble and integrate the system (hardware, software, and humans), meanwhile developing confidence that it is able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use.	Operations-ready system end product with supporting related enabling products
	Phase E: Operations and sustainment	To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.	Desired system
	Phase F: Closeout	To implement the systems decommissioning/disposal plan developed in Phase E and perform analyses of the returned data and any returned samples.	Product closeout

Figure 5.1: Project phases (redrawn according to [8] and edited)

5.2 Pre-Phase A: Concept studies

Pre-Phase A, by ECSS designation Phase 0, is generally the first phase of the project. During this phase, the project is baselined from various concepts created by the team, and preliminary plans and structure are baselined (Figure 5.2). The duration of Pre-Phase A can vary greatly, depending on the scope, size, and complexity of the project.

PRE-PHASE A: CONCEPT STUDIES

Purpose

To produce a broad spectrum of ideas and alternatives for missions from which new programs and projects can be selected. Determine feasibility of desired system; develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility, identify potential technology needs and scope

Typical activities

- Identify users and other stakeholders
    - Identify key stakeholders for each phase
    - Capture and baseline goals of the project
- Identify risk classification
- Identify initial technical risks
- Identify the roles and responsibilities in performing mission objectives
- Develop plans
    - Develop and baseline Technology Development Plan
    - Define preliminary verification and validation approach

Reviews

- MCR

Figure 5.2: Pre-Phase A (redrawn according to [8] and edited)

Pre-Phase A aims to generate a wide spectrum of mission ideas from which new programs or projects can be selected and baselined. During Pre-phase A, the team analyzes various project concepts that may fall within technical, cost, and schedule constraints and contribute to project objectives. Pre-phase A efforts may include targeted inspections of high-risk or high-tech development areas. These advanced studies and interactions with customers and other potential stakeholders help the team identify promising project concepts. Key stakeholders (including the operator and the customer) are identified, and their expectations for the project are gathered. If viable ideas are found, one or more may be selected to advance to Phase A for further development. The goal of systems engineering at this stage is to participate in developing and evaluating possible concepts.

The team develops preliminary project options as an input product for the Mission concept review, but these preliminary options are not subsequently maintained in any way.

In pre-phase A, it is important to define the exact set of stakeholders and users to ensure that the mission objectives and operational concept meet the needs and expectations of the end users. In addition, it is important to estimate the composition of the technical team and identify any unique equipment or personnel requirements.

5.3 Phase A: Concept and technology development

Phase A is generally the second phase of the project. During this phase, the final concept is established, the associated activities are performed, and the baselined plans from Pre-Phase A are reviewed and updated (Figure 5.3).

PHASE A: CONCEPT AND TECHNOLOGY DEVELOPMENT

Purpose

To determine the feasibility and desirability of a suggested new system and establish an initial baseline with CRS strategic plans. Develop final mission concept, system-level requirement, needed technology developments, and project technical management plans.

Typical activities

- Review and update documents baselined in Pre-Phase A if needed
- Monitor progress against plans
- Develop and baseline top-level requirements and constraints including internal and external interfaces, integrated logistics and maintenance support, and system software functionality
- Validate requirements
- Baseline plans
  - Systems engineering management plan
  - Control plans such as the Risk management plan
  - Other crosscutting and speciality plans such as Contamination control plan, logistics plan
- Develop preliminary verification and validation plans
- Develop and baseline mission architecture
  - Develop models, simulations etc.
  - Perform and archive trade studies
- Identify, analyze and update risks
- Perform technical management

Reviews

- SRR

Figure 5.3: Phase A (redrawn according to [8] and edited)

Phase A aims to produce a proposed system architecture that is plausible and responsive to project anticipations, requirements, and constraints. During Phase A, activities aimed at fully forming the basic project concept, commencing or carrying responsibility for developing the essential technologies, and clarifying the expected dependence on human elements in achieving full system functionality or developing an autonomous system are carried out. Along with interactions with stakeholders, this work helps mature the concept and requirements for the project. The goal of systems engineering at this stage is to participate in the development and evaluation of the architecture and assignation of requirements to the elements of the architecture.[8]

The team readdresses the preliminary project concepts conceived in Pre-phase A. The team effort concentrates on analyzation of the project requirements and establishing the project architecture. The efforts shift toward the optimization of the concept design. The goals and constraints of the projects are settled, and the requirements become defined in more depth. The risks are identified and analyzed in more detail. The preliminary verification and validation plans, as well as preliminary decommissioning and disposal plans, are developed.[8]

The effort concentrates on assigning functions to particular entities' hardware, software, and humans during Phase A. The tradeoff studies are iterated to firm the system requirements and the system architecture and design.

5.4 Phase B: Preliminary design

Phase B is generally the third phase of the project, and it is also the last phase of the Formulation phase. The emphasis is placed on defining the project to establish an initial baseline capable of reaching the mission goals and on developing a preliminary design for each end product (Figure 5.4).

Phase B aims to complete the technology development and the preliminary design. The project shall demonstrate that its technical, cost, schedule, and planning baselines developed during the Formulation phase are complete and consistent. It shall also be exhibited that the preliminary design complies with all requirements and is adequately mature to advance into Phase C. The cost and schedule should be adequate to meet the goals with acceptable risk.[8]

During this phase, systems engineering is involved in verifying and ensuring that the preliminary designs of the various systems and subsystems will work together to achieve the project goals and that they will meet all the requirements and customer expectations.[8]

The culmination of Phase B is with a series of Preliminary Design Reviews (PDR), containing system-level PDR and PDRs for lower-level end items as deemed necessary. If any design issues are uncovered in the PDR, they should e resolved so the final design can begin with exact design specifications. After this point, all the changes should be only successive refinements, not fundamental ones.[8]

PHASE B: PRELIMINARY DESIGN

Purpose

To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements and generate a preliminary design for each system structure end product.

Typical activities

- Review and update documents baselined in previous phases
- Monitor progress against plans
- Develop the preliminary design
  - Identify one or more feasible preliminary designs
  - Perform analyses of candidate designs and report results
  - Select a preliminary design solution
- Develop operations plans
- Develop appropriate level safety data package and security plan
- Update cost range estimate and schedule data
- Improve fidelity of models and prototypes used in evaluations
- Develop preliminary plans
  - Decommissioning Plan
  - Disposal Plan
- Identify and update risks
- Perform technical management

Reviews

- PDR

Figure 5.4: Phase B (redrawn according to [8] and edited)

5.5 Phase C: Final design and fabrication

Phase C aims to complete and document the detailed system design meeting the requirements and to fabricate, code, produce, or otherwise realize the products. Activities to complete the final design and realize the products are performed. The system integration, validation and verification, and operational plans are inspected and finalized for use.[8]

A Critical Design Review (CDR), with a structure similar to PDR, is performed to ensure the final design is complete and can meet all requirements and expectations with acceptable risk. Phase C culminates with a System Integration Review (SIR), after which the final product of this phase, a product ready for implementation, is prepared.[8]

5.6 Phase D: System assembly, integration, and testing

Phase D aims to assemble, integrate, validate, test, and prepare the desired system for operational use. The main activities during this phase include assembly, integration, verification and validation, and testing the system for the expected environment within the margin. Other activities include updates of the procedures, rehearsals, and training of the operating personnel and crew. The integration, verification, validation, and testing plans, as prepared in the previous phases, are used. Phase D concludes with a system capable of accomplishing its purpose.[8]

5.7 Phase E: Operations and sustainment

Phase E aims to conduct the system's prime mission to meet the identified goals and to maintain support for that need. As prepared and updated in the previous phases, operational plans are used to meet these goals. The end product of this phase is the results of the mission and performance of the system.[8]

5.8 Phase F: Closeout

Phase F aims to implement the system decommissioning and disposal planning and analyze the returned data and samples. It deals with the final closeout of the system when its mission is completed. It consists of disassembling, if needed, and archiving the system and the complete documentation, including all trade-off studies, meeting minutes, software, drawings, and all associated documents.[8]

6 SYSTEMS ENGINEERING IMPLEMENTATION

Two years ago, inspired by student rocket teams in Europe and America, the Czech rocket society was founded to help Czech university students get more hands-on experience with rockets. At the moment, the medium-term goal of the Czech rocket society (CRS) is to compete in the year 2025 at the European rocketry challenge (EUROC) with a rocket powered by a liquid-fed rocket engine that could fly to a height of up to 9 000 meters. EUROC is the biggest rocketry competition for student teams in all of Europe. The category of student-researched and designed (SRAD) rockets powered by liquid-fed rocket engines of their design, and a flight ceiling of 9 kilometres is considered the most prestigious. CRS aims to show that the Czech Republic has enough great university students to compete in such a competitive environment.

For a more manageable work organisation, the team working on this project was divided into five separate groups called departments, which will focus only on specific problems. These departments are Electronics, Feed, MTS (Mobile test stand), TCA (Thrust chamber assembly), and Management. The chief of said department supervises each of these teams. These roles serve for easier communication between various departments. Above them stands the project manager, chief engineer, and systems engineer, the prominent people running the project. Their key responsibilities are to ensure the project organisation from both technical and non-technical standpoints.

The tasks of the individual departments were chosen as follows. The Electronics department should develop an electronic system capable of running and diagnosing the whole system. They also aim to develop a graphical user interface (GUI) for easier system control. The Feed department should create the entire feed system, including tanks, valves, and sensors while developing adequate manufacturing, validation, and testing procedures. They should also create sufficient tools for the later design of an air-worthy system. MTS (Mobile test stand) should develop a mobile test stand that could be used to test said, but also future, engines while developing safety precautions for testing on such a test stand. The TCA (Thrust chamber assembly) department should develop the rocket engine's thrust chamber and nozzle, including injectors and cooling method. They should also develop sufficient tools for the later design of an air-worthy system.

Because the development of a liquid-fed rocket engine is very complex, the project started three years before the earliest intended launch date of the rocket. In case of launch in 3 years from the project beginning, the plan is as follows:

- First year: Design, build and test liquid-fed rocket engine demonstrator, learn new experience, and build sufficient tools for the future development of a flight version of said engine.
- Second year: Design, build and test an air-worthy version of said liquid-fed rocket engine. Begin with the design of the whole rocket.
- Third year: Complete work on the rocket engine and the rocket, perform tests with the whole assembly of the rocket and propulsion and finally launch the rocket.

This plan can vary depending on the system's readiness and its subsystems. Nevertheless, in all of these years, the need for systems engineering arose, as it could help coordinate efforts between stakeholders and engineers, between various departments working on a given project, help with technical management and conduction of reviews, and help in the verification and validation phase of stated project.

6.1 Phases

For this thesis, only phases *Pre-Phase A* through *Phase B* were selected due to the time and content constraints of this thesis, with *Phase B* not containing all information, as the project was delayed to accomplish the best possible results and the *Phase B* was not concluded at the time of submission of this thesis. These phases will be described more thoroughly in their respective chapters. Together, these phases are known collectively as *Formulation*. In Figure 6.1 purpose, typical activities and associated reviews of the *Formulation* can be seen.

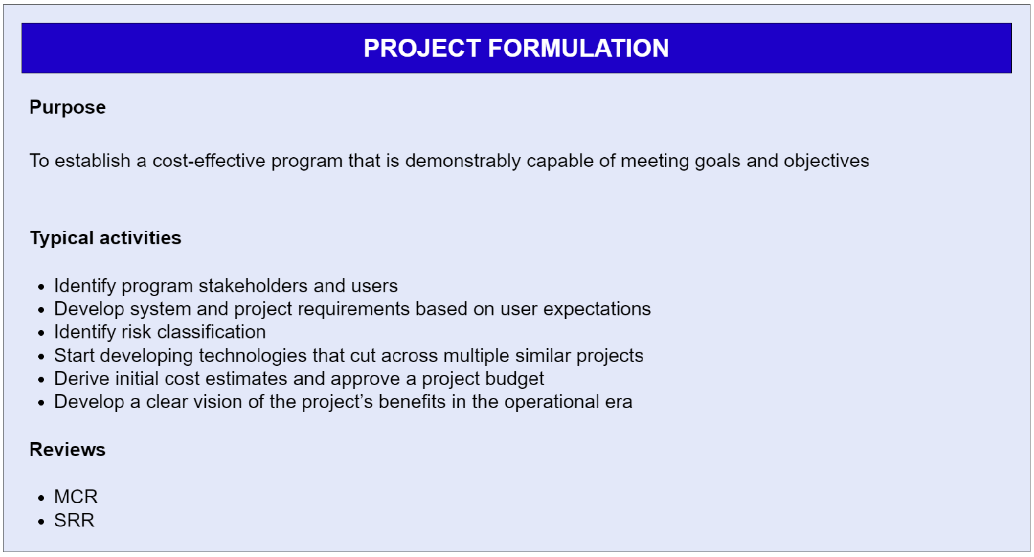


Figure 6.1: Project formulation (redrawn according to [8] and edited)

6.2 Tasks of systems engineering

As described above in the Introduction, this project's main tasks for system engineering were identifying viable and proven concepts. Identifying goals, constraints, and requirements for said project and constantly updating them as needed. Preparing project reviews and implementing feedback from those reviews. Conducting integration, verification, and validation of the given system and helping with the project management of the said project from both technical and non-technical standpoints.

As this thesis will only focus on phases *Pre-Phase A* through *Phase B*, there will be no integration, verification, and validation of the developed system, as all of these tasks are performed in the phases of Implementation of the project, which are not included.

Because of this, the first task of systems engineering will be to identify viable and proven concepts similar to the one being developed. For this, a database of similar rocket engines, preferably designed by students, will need to be established so some parameters can be chosen against existing and viable solutions. These parameters include pressure in the combustion chamber, the thrust of the engine, and the production method used.

Another task will be identifying the project's goals, constraints, and requirements and constantly updating them as needed. For this task, cooperation between various departments working on the project must be established to a greater extent. This task is described in more detail below.

There will also be a need to identify the various stakeholders of the project and the relations between them and the project, as this can help in the creation of the goals, constraints and requirements for the project, as well as the creation of the time and cost plans.

6.2.1 preparation of technical reviews

In the course of the project, the need for project reviews arises. Therefore, the NASA project life cycle, found in [8], was adopted for this project. The diagram of this life cycle can be found in Figure 6.2, whereas the life cycle was tailored to CRS needs. It shows the individual phases, their key decision points (KDP), at which the decision is made whether to proceed to the next phase and their respective reviews. The reviews shown in the diagram as red triangles are considered more important, and special attention should be kept to their conduction and results.

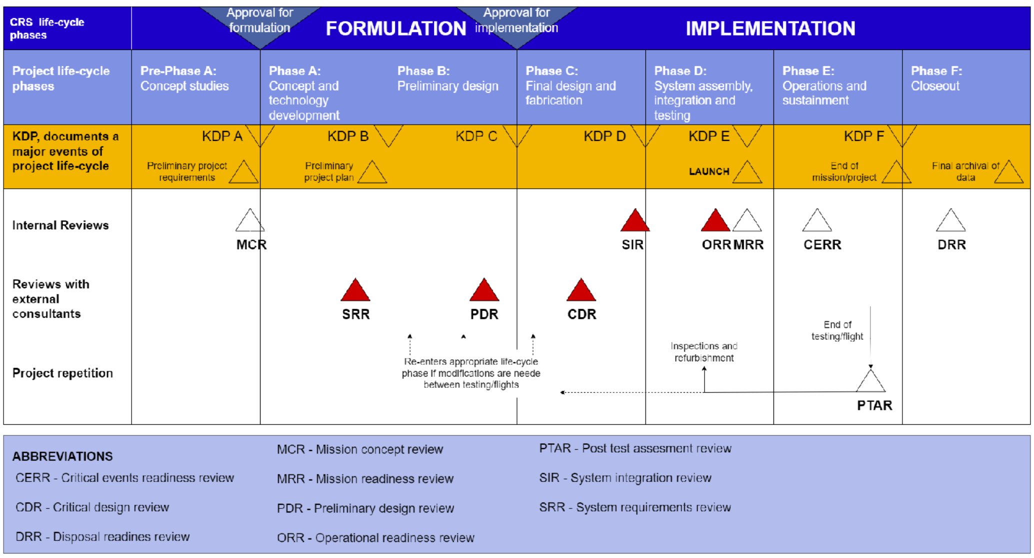


Figure 6.2: Project life cycle (redrawn according to [8] and edited)

For the reviews, the product maturity diagram (Figure 6.3) was adopted for use within the project. This diagram shows the documents and decisions needed for each major review or key decision point. The documents highlighted in red are crucial for their respective reviews, and special attention should be kept to them.

CRS Product maturity	FORMULATION			IMPLEMENTATION					
Phase of project life cycle	Pre-Phase A: Concept studies	Phase A: Concept and technology development	Phase B: Preliminary design	Phase C: Final design and fabrication		Phase D: System assembly, integration and testing		Phase E: Operations and sustainment	Phase F: Closeout
KDP and reviews of project life cycle	KDP A	KDP B	KDP C		KDP D		KDP E	KDP F	
	MCR	SRR	PDR	CDR	SIR	ORR	MRR		DRR
Stakeholders identification	**Baseline**		Update						
Concept definition	**Baseline**		Update	Update					
Cost and schedule plan	Preliminary	Update	Update	Update	Update	Update	Update	Update	Update
Requirements	Preliminary	**Baseline**	Update	Update					
Design solution definition			**Preliminary**	**Baseline**	Update	Update			
Interface definition			Baseline	Update	Update				
Implementation plans			Baseline	Update					
Integration plans			Baseline	Update	**Update**				
Verification and validation plans	Approach		Baseline	Update	Update				
Verifiaction and validation results					**Initial**	**Preliminary**	**Baseline**		
Transportation criteria				Základní	Final	Update			
Operations plans			Baseline	Update	Update	**Update**			
Operational procedures				Preliminary	Baseline	**Update**	Update		
Certification						Preliminary	**Final**		
Decomissioning plans			Preliminary	Preliminary	Preliminary	**Baseline**	Update	**Update**	
Disposal plans			Preliminary	Preliminary	Preliminary	**Baseline**	Update	Update	**Update**

ABBREVIATIONS: CDR - Critical design review; MCR - Mission concept review; PDR - Preliminary design review; PTAR - Post test assesment review; SRR - System requirements review; CERR - Critical events readiness review; DRR - Disposal readines review; MRR - Mission readiness review; ORR - Operational readiness review; SIR - System integration review

Item is required for that review/KDP

Figure 6.3: Product maturity (redrawn according to [8] and edited)

6.2.2 preparation of system requirements

One of the other goals of a systems engineer is the definition of technical requirements. This shall be executed through close cooperation between the systems engineer and the chiefs of individual departments. This is mainly due to individual chiefs having the most knowledge about their respective subsystems. The systems engineer should ensure coordination between them so that one subsystem is not favoured.

These requirements should be formed primarily using a flow-down architecture, where the entire system's goals, constraints, and requirements are first defined. Then they are shifted to a lower level where goals, constraints, and requirements are defined for individual subsystems, and they can eventually shift to a lower level for their subsystems. During the subsequent assessment and evaluation, the flow-up architecture should be used when the given goals, restrictions, and requirements are first checked at the level where they were written. Then the assessment is moved to a higher level until they reach the highest level, where goals, constraints, and requirements for the whole system can be assessed. If deficiencies are found, this cycle can be repeated as needed. This requirements definition process is described in more detail later in section 8.1.

6.2.3 ECSS standards

Since this will be the first CRS project which will include the role of a systems engineer, emphasis will also be placed on implementing existing ECSS and NASA standards. This implementation consists in selecting suitable standards and modifying them for CRS needs. Table 6.1 shows the list of ECSS standards deemed helpful for this project, which were used or will be used in future phases.

The task of a systems engineer is to choose the correct standards to be used for the project and then adopt them for use on the project as needed. Tailoring was used as described in ECSS standard ECSS-S-ST-00C[11].

Table 6.1: Selected ECSS standards

Standard	Reference	Name
ECSS-S-ST-00C	[11]	Description, implementation and general requirements
ECSS-S-ST-00-01C	[9]	Glossary of terms
ECSS-M-ST-10C	[10]	Project planning and implementation
ECSS-M-ST-10-01C	[12]	Organization and conduct of reviews
ECSS-M-ST-40C	[13]	Configuration and information management
ECSS-M-ST-60C	[14]	Cost and schedule management
ECSS-M-ST-80C	[15]	Risk management
ECSS-Q-ST-20C	[16]	Quality assurance
ECSS-Q-ST-40C	[17]	Safety
ECSS-Q-ST-70C	[18]	Materials, mechanical parts, and processes
ECSS-Q-ST-70-01C	[19]	Cleanliness and contamination control
ECSS-E-ST-10C	[20]	System engineering general requirements
ECSS-E-ST-10-03C	[21]	Testing
ECSS-E-ST-10-06C	[22]	Technical requirements specification

6.3 Cooperation between systems engineering and other departments

For the ideal conduction of project management, close cooperation between systems engineers and individual departments is needed. This is mainly to ensure that the system will be coherent and that it will be possible to integrate it, as with any other methods, as needed.

For this reason, weekly meetings were held between chiefs of all departments, the chief engineer, the systems engineer, and the project manager. The purpose of these meetings was to compare the development against plans, monitor that the interface between separate departments is kept in mind and ensure that the needs of all departments are fulfilled.

As needed, special meetings were held to address more significant issues. These included the definition of system requirements, the definition of system architecture and the main interfaces present in the system, or the definition of technical risks related to the project. Special meetings were held before each review and its parts (i.e. before sending the documentation) and after each review to assess the feedback and implement it into the system.

7 PRE-PHASE A

As described in chapter 5 Pre-Phase A is the first phase of the project and the only phase in the pre-formulation phase. During this phase, a broad spectrum of ideas and concepts are prepared and presented, and the project baseline can then be created from these ideas. The output of this phase is the Mission concept review, after which the project baseline shall be defined.

7.1 Identification of the stakeholders

One of the main problems for systems engineering in this phase was identifying the project's main stakeholders. For this project, the system's customer, user and primary stakeholder is the Czech rocket society. Other stakeholders include mainly the partners of the CRS, the suppliers, the test site, and CRS members, who are the ones working on the project. All of these stakeholders are described in more detail below.

For more accessible work, relations between all stakeholders of the StarFox project were then defined (Figure 7.1). The Financial connection considers direct financial support. The Goods and Services consider the flow of goods and services and non-direct financial support (i.e. the partners paying directly for some of the needed equipment). The knowledge relation considers the exchange of knowledge and know-how. The political relation considers the political and PR support of the project and vice-versa and the power of some stakeholders on the project goals, constraints, requirements etc. and vice-versa.

7.1.1 Czech Rocket Society

The Czech rocket society is the main stakeholder of the StarFox project, as the CRS covers it. The CRS is a student society unifying students from Czech universities and high schools, as well as Czech students studying abroad. CRS helps its members realize their projects if they gain sufficient support at the meeting of the CRS members, where all projects are submitted for approval. CRS also helps the projects gain needed support as it finds partners and directs their support to individual projects.

7.1.2 Czech Rocket Society members

The members of CRS are considered crucial stakeholders in all CRS projects, as they manage the projects and do the complete engineering part of the projects. All the CRS members are volunteers participating in the project of their own will. From the around 70 members of the CRS at the time of the StarFox project, about 30 of them are actively participating in the project on a regular basis, with many more helping as needed.

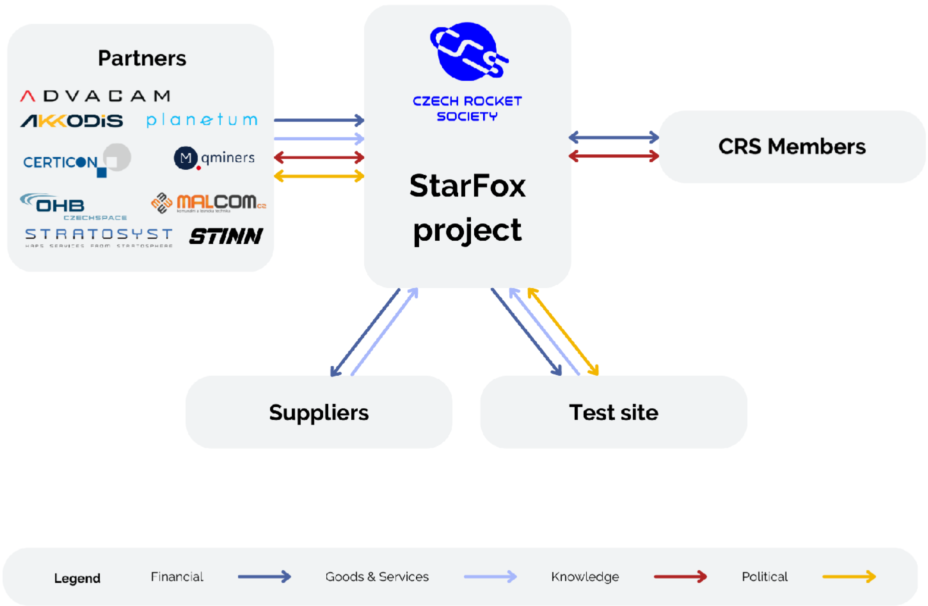


Figure 7.1: StarFox project stakeholders

7.1.3 Partners

The partners of the CRS are one of the main stakeholders for all CRS projects. They provide needed support in terms of finances, goods & services, knowledge transfer, and political support. All partners of the CRS can willingly choose in which ways they would like to support the CRS and also if they would like to focus more on some projects, even though they are still considered to be partners of all the other CRS projects. They also may have political influence on the projects in terms of requirements and/or constraints.

7.1.4 Suppliers

The suppliers are other contractors not listed above who deliver goods & services for financial payment. These goods include intermediate goods for the products to be manufactured by the members of the Starfox project and goods which, if developed and manufactured by the members of the Starfox project, would prove to be more expensive and less reliable.

7.1.5 Test site

The test site is considered one of the key stakeholders in terms of finishing the project in full, as it is needed to test the final system. The main contribution of the test site is in services, as it allows for testing of the Starfox project. It also has a political influence on the project, as it has a political influence on the testing of the system. The test site has yet to be chosen, but a close selection of potential candidates for it has been chosen, and the decision should be made soon.

7.1.6 Stakeholders' expectations

The expectations and requirements from the stakeholders different from CRS can be divided into the following categories.

- The project shall be successful, and there shall be enough documentation (photos, videos) of the manufacturing and testing phase that it can be used for further propagation.
- The project shall be conducted safely so that nobody and nothing shall come to harm so that the stakeholders can continue with their support of CRS without the risk of being associated with accidents.
- The stakeholders will provide manufacturing for some parts. Therefore manufacturability of some parts using stakeholder capabilities must be considered.

The first project goals, constraints and requirements can be defined from the list above.

7.2 Rocket engine sizing

From the requirements stated in section 3.1, some parameters of the developed rocket engine began to take shape.For example, designing an engine with higher thrust would not make sense, as the total impulse is limited. At the same time, some propellants are not possible to be used for the flight version of the said engine if it should compete in EUROC. There will also be a need for a venting system on the tanks, and the tanks will need to have a certain factor of safety, which will be different for entirely metallic and composite tanks. And at last, the need for insulation of wiring in case of the use of cryogenic propellants will be needed.

After this, the parameters of the existing student-developed rockets, as found in section 3.2, were taken, and the basic parameters of the developed rocket engine were chosen against them. The parameters were also checked against the EUROC guidelines listed in section 3.1. These parameters include that:

- Nitrous oxide was chosen as the oxidizer. It is easier to handle than liquid oxygen, has a lower specific impulse, and lacks its cryogenic property. This means easier construction of valves and tubing can be used.[1]
- Isopropyl alcohol was chosen as the fuel. It has slightly better properties than ethanol, is not cryogenic like liquid methane and has easier maintenance for its propellant delivery system than kerosene.[1]
- The cooling method was chosen as regenerative. In the project's first year, only simple cooling by water will be used. This will allow data to be obtained to develop proper regenerative cooling in the subsequent iterations.
- The chamber pressure was chosen as 25 bar. This value is almost at the upper limit of the values found in Table 3.2, but higher chamber pressure also translates into higher exhaust velocity, thus, higher thrust.[1]
- The thrust of the engine was chosen as 3 kN, a value that could be sufficient enough to fly the rocket to 9 000 meters.

7.3 Cost and schedule plan baseline

The initial cost and schedule plans were created in this phase. As for the schedule plan, as this project was not to be done as a commission for another subject, there was not thereby set fixed end date for the project. The following constraints had to be nevertheless adhered to:

- Most of the members working on the said project are students of universities. Therefore during the exam period, there will be low to no activity on the project.
- The project will need to be presented at the meeting of members in November in enough detail, so the project and its budget can be approved.

From these constraints, the initial project schedule plan that can be found in Figure 7.2 was formed. As for the cost plan, the initial estimate of the project cost was performed.

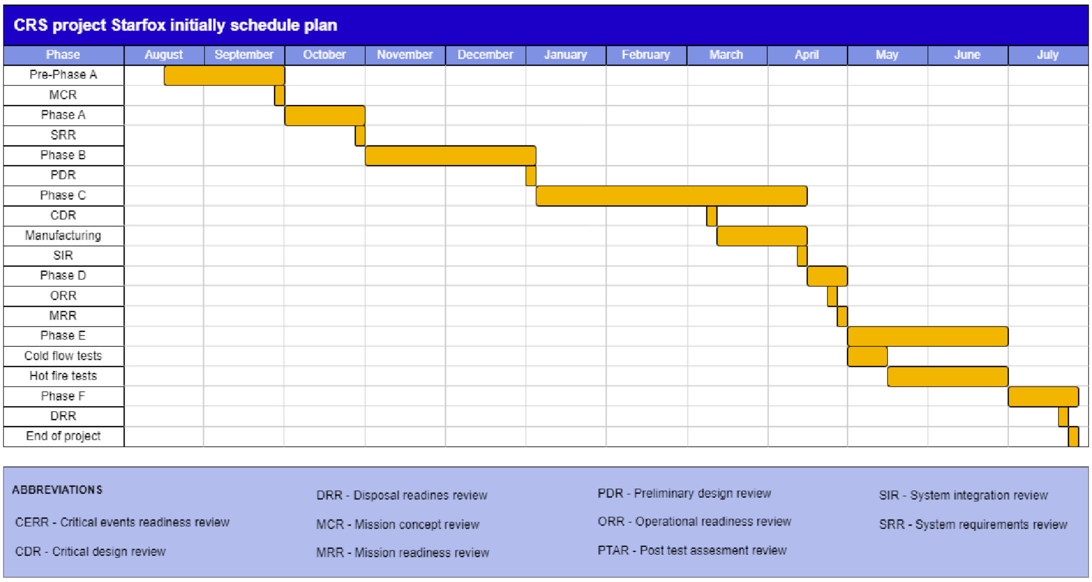


Figure 7.2: Initial project schedule plan

7.4 Mission concept review

The mission concept review is the first of the series of reviews conducted as part of the Starfox project. The main goal of the said review is to affirm the mission need and to evaluate the proposed objectives and the concepts for meeting those objectives. This review was conducted not fully to the requirements listed in [12] as it was deemed unnecessary at the time to assemble review authority for this review.

Due to a smaller team working on this project than what is probably common in the industry, a meeting with all CRS members willing to participate in the project was held, where the various concepts were presented. These concepts were evaluated against the requirements for the EUROC and existing similar designs.

The output of this review was that promising concepts were chosen, on which work will continue in phases A and B, where the final design choices will be selected. The annex contains the presentation for this meeting and the transcript of the said meeting.

8 PHASE A

As described in chapter 5, Phase A is the project's second phase. During this phase, the final concept is established, the associated activities are performed, and the baselined plans from Pre-Phase A are reviewed and updated.

8.1 Goals, constraints and requirements of the project

As part of the work in Phase A, the set of goals, constraints and requirements was established. All goals, constraints and requirements were divided into two subcategories:

- project goals, constraints and requirements
- system goals, constraints and requirements

The project goals, constraints and requirements, sometimes called the top-level instead of the project, are intended for the whole project, which in this case means for every department. These goals, constraints and requirements are the most important, and their scope is cross-cutting across different departments working on the project. One of their main reasons is to prevent the multiplication of the same goals, constraints and requirements. The system goals, constraints and requirements are more focused on individual departments and are mainly intended to be used solely for a given department.

As some of the goals, constraints and requirements depend on designs which will be developed in later phases, the abbreviation TBD (to be determined) was adopted for the use of these goals, constraints and requirements. The need for this arises mainly from these goals, constraints and requirements being deemed important enough to be listed even though their exact values were not known at the given time.

For the purpose of establishing goals, constraints and requirements, the process for establishing a technical requirements specification (Figure 8.1) similar to that found in [22] in section 5.2 for Phase 0 was used.

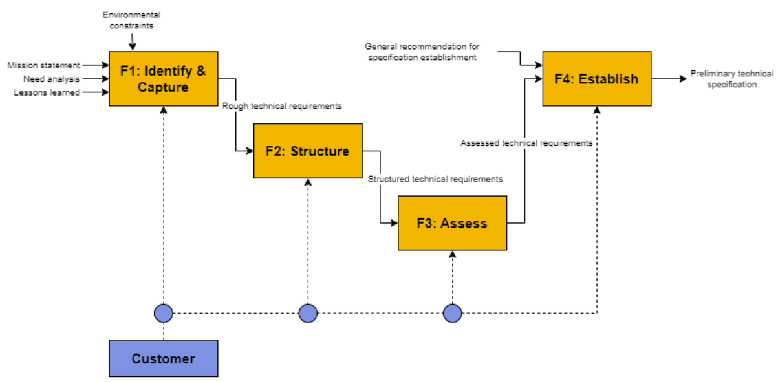


Figure 8.1: Process for establishing a technical requirements specification (redrawn according to [22] and edited)

Where:

- The F1 task: The customer identifies and captures the user's needs or mission statements, associated environments and constraints. He expresses these in terms of goals, constraints and requirements.
- The F2 task: The customer structures, classifies and justifies individual goals, constraints and requirements.
- The F3 task: The customer assesses the entire set of technical requirements for correctness, consistency and suitability for the intended use;
- The F4 task: The customer establishes and releases the preliminary technical requirements specification.

For this project, the customer and the user is the Czech rocket society, as stated in section 7.1.

8.1.1 Formulation of the goals, constraints and requirements

For the formulation of the individual goals, constraints and requirements chapter 8 of [22] was used. This standard was then tailored for project use in accordance with [11]. The main difference was that "technical requirements" was changed to "goals, constraints and requirements". For example, it was stated that all goals, constraints and requirements:

- "*shall be described in quantifiable terms*" ([22] 8.2.1 a)
- "*should be justified*" ([22] 8.2.2 a)
- "*shall be backwards-traceable*" ([22] 8.2.3 b)
- "*shall be forward-traceable*" ([22] 8.2.3 c)
- "*shall be self-contained*" ([22] 8.2.8 a)
- "*shall be verifiable*" ([22] 8.2.9 a)

The used wording of the requirements was used as defined in section 8.3 of [22]. For example, it was stated that all goals, constraints and requirements:

- "*should be expressed as a complete sentence with a verb and a noun*" ([22] 8.3.1 b)
- "*shall use the verbal form "shall" whenever a provision is a requirement*" ([22] 8.3.2 a)
- "*shall use the verbal form "should" whenever a provision is a recommendation*" ([22] 8.3.2 b)
- "*shall use the verbal form "may" whenever a provision is a permission*" ([22] 8.3.2 c)
- "*shall use the verbal form "can" to indicate possibility or capability*" ([22] 8.3.2 d)

For the wording of the goals, constraints and requirements, a debate was held within the management of this project, whether the individual wordings shall be ended with a full stop or not. After a thorough discussion, an arrangement was made that the individual wordings would **not** be ended with a full stop. If any wording consists of more than one sentence, the individual sentences shall be separated with semicolons.

8.1.2 Identification system

For the purpose of easy identification, all goals, constraints, and requirements have an assigned ID, which is unique to every goal, constraint, and requirement, to prevent confusion of requirements. The major demand for this identification system was to be easy to use and read.

Each ID starts with three letters **LIQ** marking the project as a liquid-fed rocket engine. Then follows the dash followed by either **PRO** (for project goals, constraints, and requirements) or **SYS** (for system goals, constraints, and requirements) followed by another dash. After that, **GOA** (for goals), **CON** (for constraints), or **REQ** (for requirements) is used, followed by another dash and three-number ID of every specific goal, constraint, or requirement based on the relevant department. The numbering is as follows:

- Electronics department has reserved numbers 100 to 299
- Feed department has reserved numbers 300 to 499
- MTS department has reserved numbers 500 to 699
- TCA department has reserved numbers 700 to 899
- Management department has reserved numbers 900 to 999
- Numbers 000 to 099 are being kept in reserve as needed

8.1.3 Goals

The goals are the main results that the project shall achieve. In addition to the results, they can define the means by which they shall achieve these results.[9]

8.1.4 Constraints

The constraints are characteristics, results or design features which are either prohibited or made compulsory for any reason. Generally, two kinds of constraints exist, those which concern the solution and those which concern the use of the system.[9]

8.1.5 Requirements

The requirements can be defined as documented demands to be complied with. These demands shall be defined, as well as the identification method by which it shall be evaluated if the project complied with them. They can be further identified by defining their area for easier manipulation.[9]

8.2 Identification of the risks

The first identification of the risks was supposed to occur at the time, but due to limited time and resources, it was mainly postponed into Phase B. Nevertheless, it was defined that a risk matrix for the project will be created in accordance with the ECSS system, and all of the risks will be assigned a rank in this matrix for easier decision-making in the case of whether to accept the risk, or it is needed to lower the risk.

8.3 Cost and schedule plan update

The schedule and cost plans were updated against reality in development.

As for the schedule plan, it was revealed that the research of the topics necessary for the advancement in the next phase was to take more time than was anticipated. This was caused mainly by the project being the first large-scale liquid rocket engine for every member, and the people in charge of the project management, namely the chief engineer, systems engineer, project manager, and chiefs of the departments, had no prior experience with project management of large projects. Due to this, it was deemed that the schedule plan would be moved.

The main constraints that needed to be taken into consideration during the update of the schedule plan were:

- Most of the members working on the said project are students of universities, therefore during the exam period, there will be low to no activity on the project.
- As the project and its budget was approved by the meeting of the members in November 2022 and the budget will be possible to draw for the duration of up to 1 year from its approval, the project should conclude in this period.
- For the reviews with external consultants, the documentation shall be internally reviewed and changed as needed before it is sent to external consultants. The internal review should last one week with an additional week for the implementation of feedback. The documentation shall be sent to external consultants at least 1 week before the review proceedings.
- After each review with external consultants there shall be a period of at least 2 weeks for feedback implementation. For internal reviews, this period shall be at least 1 week.

The schedule plan was then updated to accommodate all constraints written above. The updated schedule plan can be seen on Figure 8.2.

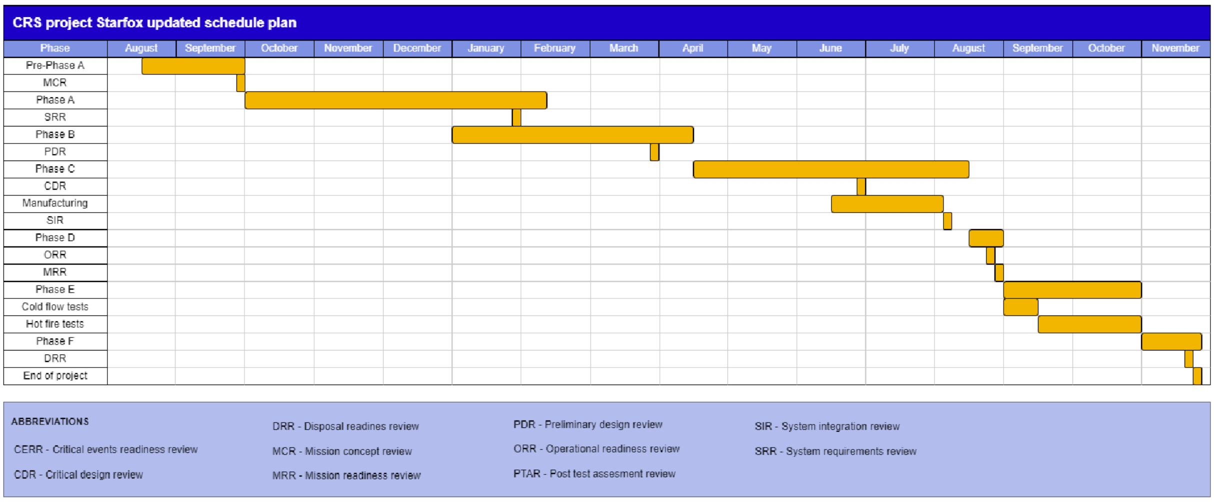


Figure 8.2: Updated project schedule plan

As for the cost plan, it was deemed that although the CRS has sufficient finances to fund the whole project, this would cause significant problems shall the project be unsuccessful. Therefore it was decided the cost of the whole system would be divided into five packages. These packages should follow after each other and at the end of each package, the resulting system shall be complete and functional. After each package, the evaluation will be carried out to determine if finances will be put towards the next package. In case the management of the project will acquire additional funds or the benefits of carrying more packages at the same time will be found useful, more than one package can be carried out at the same time. These five packages are:

- **Package A**: This package includes 1 branch of the feed system, parts of electronics and a test injector manufactured using additive manufacturing. By using some parts from the previous CRS project Thundercat[23],[24], at least partial tests of the injector and testing of the feed system can be concluded. A small amount of fuel and oxidizer shall be also purchased.
- **Package B**: This package includes the second branch of the feed system and control board for electronics. With this package, thorough testing of the whole feed system and detailed tests of the engine injector can be concluded.
- **Package C**: This package includes material for the mobile test stand and material for manufacturing the thrust chamber and the nozzle. After this, thorough cold flow tests can be concluded.
- **Package D**: This package mainly includes preparation for hot fire tests, mainly material for blast shield, fire extinguishers, some sensors and material for cooling the thrust chamber and the nozzle. After this, hot fire tests can be concluded.
- **Package E**: This package includes the rest of the sensors, which are not crucial for previous testing, funds for the acquisition of a larger amount of fuel and oxidizer and funds for testing. After this package, the testing of the whole complete system can be concluded.

As new sponsors and stakeholders of the project may arise during the duration of the project, some items can be moved to different packages if, for example, a sponsor of CRS will offers to manufacture some items as a gift. Although this cost plan should not drastically change during the duration of the project, some challenges may arise. For example, the price of electronic parts may rise due to a shortage of them, which can substantially change the cost of the project. Therefore this plan shall be updated in each phase of the project and at the end of each package.

8.4 ECSS implementation

As written above, the ECSS standards ECSS-S-ST-00C [11], ECSS-M-ST-10C [10], ECSS-M-ST-10-01C [12], ECSS-E-ST-10C [20], and ECSS-E-ST-10-06C [22] were used during this phase of the project. Other standards from Table 6.1 were used by various departments to define their goals, constraints and requirements. As one of the main activities of this phase for systems engineering was to validate the requirements and prepare a cohesive technical requirements specification document, the main emphasis was kept on the ECSS-E-ST-10-06C [22] thorough this phase by all departments.

From the evaluation standpoint, the implementation of ECSS-E-ST-10-06C during this phase can be marked as a partial success. Although the wording of all goals, constraints and requirements were attempted to be written according to rules baselined in the subsection 8.1.1, the wording of some of them contained the terms, which can be found in section 8.3.3 of [22] and which are supposed to not be used in the wording of goals, constraints and requirements. Among these are:

- **LIQ-PRO-GOA-003** Project shall be *sufficiently* financed
- **LIQ-SYS-REQ-102** GUI shall be *easy* to use for non-technical person
- **LIQ-SYS-GOA-301** Provide a *sufficient* amount of oxidizer and propellant to the injector
- **LIQ-SYS-REQ-522** The test stand design shall offer *easy* access to important features for the operating personnel

- **LIQ-SYS-REQ-736** The entire system shall be designed to allow for *easy* maintenance and inspection

The main problems that arose during the wording of these goals and requirements were, that some technical properties, for which these goals and requirements are aimed were not yet known. Therefore this wording was deemed suitable for the time being, with a view to overwriting in future phases.

8.5 System requirements review

At the end of Phase A, a Systems requirement review (SRR) was held. This review was carried out by preparing the technical requirements specification document, which can be found in the Annex. This document was then sent to both members of the Czech rocket society, for internal review, and external consultants. The external consultants included:

- External consultants from academia
- External consultants from the industry
- Other rocketry teams

No meetings were held for this review, but the reviewers were asked to send back their feedback. More than 15 responses were received from various people. This feedback was then incorporated into the wording of individual goals, constraints and requirements.

It was concluded from the feedback, that although all important goals, constraints and requirements were written down, for people not working on the project some of them were not giving sense at first look. For example:

- **LIQ-SYS-REQ-103** Sample rate shall be 100-200 samples per second

It was not clear what shall be sampled. It was decided, that the requirement should have been concerning the sample rate of thermocouples therefore the wording was changed to:

- **LIQ-SYS-REQ-103** Sample rate shall be minimally 80 sps for thermocouples

This process was subsequently repeated for every received feedback.

Another major issue was, that although in standard project management, the project phases are strictly defined and there are clear boundaries where it is possible to proceed to the next phase, for student teams it is normal that this is not strictly adhered to. Therefore by the time the SRR was proceeding, there was already work in progress intended for Phase B. This is described in more detail in section 10.1. Therefore some of the requirements more resembled design choices. This was then transferred as work to the next phase, to determine if those design choices actually make sense in the overall design, and to explain the need behind them if they are deemed important.

In the annex, a document containing all feedback on the technical requirements specification document and its implementation can be found.

9 PHASE B

As described in chapter 5, Phase B is generally the third phase of the project, and it is also the last phase of the Formulation phase. The emphasis is placed on defining the project to establish an initial baseline capable of reaching the mission goals and on developing a preliminary design for each end product.

9.1 Update of documents and plans

As the project moved forward some of the documents and plans prepared and baselined in the previous phases needed to be updated to be in accordance with the actual development.

9.1.1 Update of documents

During Phase B, some of the ongoing documents were updated, primarily the technical requirements specification document, as the requirements were still slightly changing. The main difference was the addition of the means by which the requirements will be qualified in the future. These means were:

- **Design** - for all the requirements which shall be qualified by control of the design.
- **Simulation and analysis** - for all the requirements which shall be qualified by executing simulations or providing analytical solutions.
- **Measurement** - for all the requirements which shall be qualified by measurement of the given parameter.
- **Testing** - for all the requirements that shall be qualified by testing the necessary components.
- **Visual confirmation** - for all the requirements that shall be qualified by visual control of the components.
- **Undefined** - for all the requirements that shall be qualified using different approaches.

9.1.2 Update of plans

As of the beginning of Phase B, only Cost and Schedule plans existed, as the risk management plan development was postponed into this phase. The cost plan did not need an update, but the schedule needed to be updated as new problems arose during this phase. Thus the timeline of the project needed to be edited, as all of the major events needed to be postponed. The same constraints that were taken into consideration in the section 8.3 were then applied, and an updated project schedule plan was created (Figure 9.1).

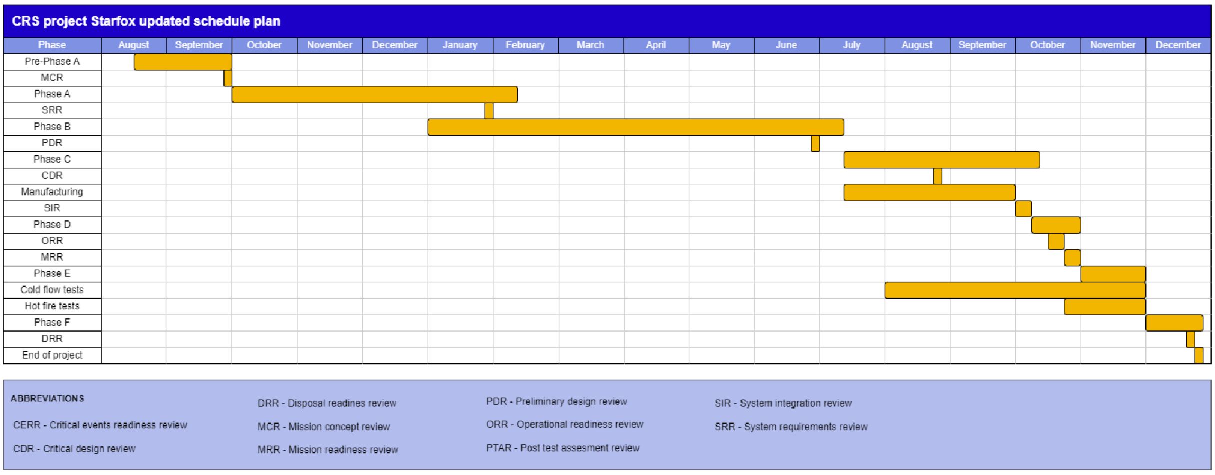


Figure 9.1: Updated project schedule plan

9.2 Preliminary design

To prepare preliminary designs, it was crucial to identify, analyze, and asses the concepts introduced in Phase A and if they could safely meet the project goals under the project's technological, cost, and schedule constraints. One or more were chosen from these concepts to begin preliminary design on them. Sometimes more designs were selected to do a preliminary design on them, with the decision which to choose to be postponed into the future after more information arises.

9.2.1 Identification of feasible designs

As described above, at least one concept was selected for each department. These concepts were as follows.

The electronis department

The main computer will be placed directly on the test stand with a wire connection to the control station at a safe distance. As the main computer, myRIO will be used due to its modularity, relatively high precision, and relatively low price for student applications. The control computer will have both virtual and physical buttons to control the system with the possibility to input the commands directly into the command prompt. The control computer will also need to be portable, preferably in one piece, i.e. in a designated case.

The feed department

The feed delivery system will consist of two separate branches, one for fuel and one for oxidizer. External pressurizing using high-pressure gaseous nitrogen (GN2) bottles will be used. A manual procedure will be used for the filling of the fuel, whereas for the filling of the oxidizer, a remote filling will need to be used. The feed delivery system must be operatable from a safe distance from the start of the oxidizer tank filling up to the oxidizer tank draining. The number of elements creating a drag should be kept as low as possible.

The MTS department

A test stand that can be used for both the horizontal and the vertical testing of this and future engines will be designed. The test stand shall use the existing CRS launch ramp components to lower the overall cost. The test stand shall feature places to fasten the feed delivery system and the main computer. The test stand shall also feature a load cell for the measurement of the engine thrust, a deflector plate to diverge the hot gases in case of vertical testing, and a blast shield between the engine and the rest of the system to protect it in case of rapid unscheduled disassembly (RUD). In the case of RUD, a remotely operated extinguishing system should be present.

The TCA department

A set of injectors that will be first tested on the water to choose the optimal one for use in the engine shall be designed. The battleship (the overall design with a significantly higher safety factor [9]) and the cooled chamber and nozzle shall be developed, and simulation & analyses shall be performed. A safe igniter system consisting of a spark torch igniter or a pyrotechnic element shall be designed and incorporated into the injector plate design.

9.2.2 System architecture

A system architecture was established for easier cooperation between various departments and to lower the risk of incompatibility of interfaces between multiple departments. A special meeting was held where all chiefs were present and where the system architecture was defined. From this definition, a system architecture diagram (Figure 9.2) was prepared for more manageable navigation.

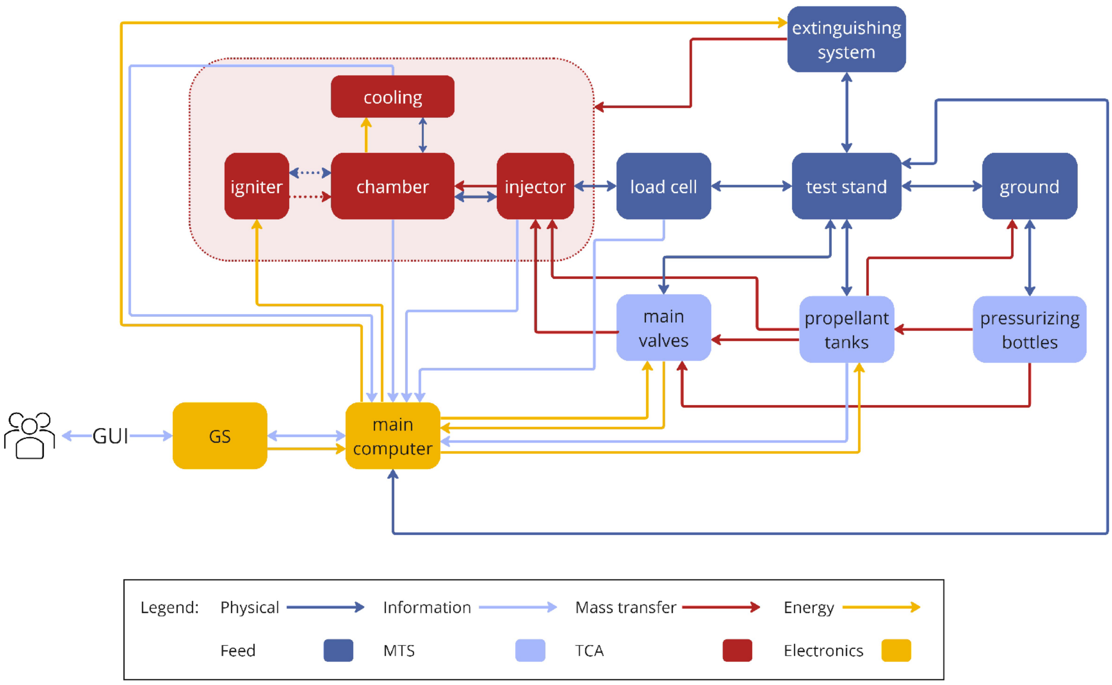


Figure 9.2: System architecture diagram

The diagram shows each subsystem's main parts and their relations. These relations are:

- Physical; connecting the components.
- Information; data transfer.
- Mass transfer; transfer of the propellants, pressurizing gas, combustion gases, or extinguishing agents.
- Energy; transfer of energy/electricity.

Based on the orientation of the arrow, it either means a one-way flow in the direction of the arrow or a two-way flow. The different colours of the arrows and the blocks represent the type of relation or the department to which the block belongs. The system architecture diagram shall feature all the cross-department interfaces, which should help with the concerned departments' exact definition in the future.

9.3 Safety plan

Although the preliminary design was developed during this phase, as described in section 9.2, it kept changing frequently. It was therefore decided that from the safety plan, only the risks would be prepared, as they are not expected to be changed drastically and will be updated in the future. It was also decided to perform risk management at this point because the risk management plan was postponed from the previous phase. The rest of the safety plan is to be developed shortly after PDR.

For the risks, the ECSS standard concerning risk management[15] was used. From this standard, the procedures for risk management were tailored and implemented for use within the project. The risk matrix was also tailored and implemented from this standard to be used with the procedures.

9.3.1 Risk matrix

Likelihood						
5	4	5	6	8	9	
4	3	4	5	6	8	
3	2	3	4	5	7	
2	1	2	3	4	5	
1	1	1	1	2	4	
	1	2	3	4	5	Severity

Figure 9.3: Risk matrix

A risk matrix was developed for a more manageable classification of the risks. The risk matrix from ECSS-M-ST-80C[15] was used, tailored and adopted. The risk matrix uses five classes for both risk severity and risk likelihood (Table 9.1).

The individual cells of the risk matrix have their "score" ranging from 1 to 9 for better differentiation of each risk's total weight. Each score then provides what actions to perform when accepting a risk with that specific score (Table 9.2). The final risk matrix with the legend can then be used to classify every risk and the actions to lower the risk's total weight.

Table 9.1: Risk severity and likelihood values meaning

Value	Risk severity	Risk likelihood
1	Negligible	Every time
2	Significant	1 in 10 cases
3	Major	1 in 100 cases
4	Critical	1 in 1000 cases
5	Catastrophic	1 in 10000 cases

Table 9.2: Risk score meaning

Value	Acceptability	Proposed actions
1	Acceptable	Control and monitor the risk
2	Acceptable	Control and monitor the risk
3	Acceptable with control	Control and monitor the risk
4	Acceptable with control	Closely control and monitor the risk, seek attention
5	Acceptable with control	Very closely control and monitor the risk, seek attention
6	Non-acceptable	Aggressively manage, seek new approach
7	Non-acceptable	Aggressively manage, seek new approach
8	Non-acceptable	Seek new approach
9	Non-acceptable	Seek new approach

9.3.2 Risk identification

For the risk definition, with coordination from the chief engineer, each department put together a list of all the risks concerning their respective departments, with project-level risks being identified by the management department. On joint meetings of chiefs of the departments and top-level project management, these risks were then checked to see if all the risks were identified.

After that, each risk was evaluated to assign its severity and likelihood as defined in subsection 9.3.1, after which the score of the risk was given by using the risk matrix. Depending on the score of the risk, an appropriate action was suggested. These actions can be divided into the following categories:

- Accept the risk; this can be used for risks with a low score.
- Lower the likelihood; i.e. by testing or by increasing redundancy.
- Lower the severity; i.e. by adding protective equipment.
- Lower both likelihood and severity.

A special meeting of all the chiefs of the departments and the project's top-level management was then conducted with the following aims. To check if all the risks were evaluated based on the same metrics, for example, if one department evaluated the risk severity as catastrophic, at the same time, another department did not assess similar risk severity as major. This can be caused by the risk severity not having any measurable properties, thus being bequeathed to a person's knowledge and intuition. Another aim was to check if the suggested actions could be performed under the project's technical, schedule, and cost constraints and if the proposed measures were complete. And lastly, to evaluate the suggested actions' severities and likelihoods. After this, a score was assigned to each risk's suggested action, which is considered accepted at the moment. These scores will be used in the future to help in the preparation of appropriate procedures and safety and operational plans.

9.4 Development of preliminary plans

A decision was made to postpone the development of the preliminary plans to the beginning of Phase C, as it is yet to be determined that the system architecture will not change after the conduction of PDR due to recommendations received from individual consultants. The development of the preliminary plans must begin as quickly as possible, as some of these plans (e.g. safety plans, system integration plan) will need to be used during Phase C.

9.5 ECSS implementation

In addition to the ECSS standards already used in the previous phase (section 8.4), which were used again, mainly the ECSS-M-ST-80C[15] standard concerning risk management was used for the whole project. This standard was used to help define the risk management processes and was used in creating the CRS risk matrix, which was used to score the risks of the project so that appropriate action could be suggested. Other than that, the ECSS-M-ST-40C[13] standard concerning configuration and information management was used to help create the documentation in accordance with the ECSS system.

9.6 Preliminary design review

The culmination of Phase B is the preliminary design review. Because as stated above, as the customer and operator of the StarFox project is the CRS and almost all people with knowledge of the problematics are working on said project, a typical structure of PDR, where the supplier presents the PDR to the customer, would not be viable. Thus an approach used by other rocketry student teams was chosen.

This consists of inviting external consultants from industry, academics, and other rocketry teams, to whom the documentation is sent beforehand to familiarize themselves with the design. Then, a presentation is conducted so that any questions can be answered in real-time and all can contribute to the discussion.

Because of the project's problems that arose during its conduction and which needed additional time to be solved, the PDR was not yet conducted at the time of submission of this thesis. Nevertheless, it can be stated that the PDR will have two parts, internal and external. Firstly the internal one will be conducted, and only the CRS members will be invited to these. The reason for its holding is to discover the remaining errors in the documentation that were overlooked by the team that worked on it until then, and at the same time, for the given team to test the presentation of the given issue. After this, any major errors will be corrected in the documentation, and the documentation will be sent to external consultants, after which a presentation will be held. After the external PDR, a special meeting, or more if needed, will be held where all feedback will be incorporated.

10 DISCUSSION

The main goals of this thesis as stated in its assignment were the following:

- Get familiar with project management of space projects and implementation of systems engineering.
- Research of liquid–propellant rocket engines designed by student teams.
- Analysis of research and processing of system requirements for the engine development.
- Evaluation of success of the system engineering implementation in engine development.

These goals can be considered fulfilled from their point of view. The research of the given issue was carried out according to the objectives as can be found in chapter 2 through chapter 5 and then the knowledge gained during this research was implemented into the actual proposal. Since the evaluation of the success of the implementation of systems engineering principles in the design is subject to discussion, this goal is evaluated below.

For the research of project management of space projects and implementation of systems engineering, research was conducted on NASA and ECSS guidelines which are similar in many ways. The main principles of project management and systems engineering were described. Even though the research was sufficient for the safe conduction of the project, a more thorough analysis would be needed for larger projects, and more people should work on it to lower the chance of distortion.

For the analysis of existing similar student-designed rocket engines, research of existing concepts and rules to which most of these engines adhere was conducted. The regulations concerning the rocket engine and its components were selected, and a database of existing rocket engines was established. The database size was limited by the number of now-existing rocket engines which were flown, if possible. Even though this database was sufficient to design the primary parameters, in future projects, a discussion on which parameters should be selected for the database should be held to help establish a better baseline.

Analysis of research and processing of system requirements was conducted as part of the implementation. Analysis of recommendations issued by both NASA and ECSS concerning the creation and the wording of the requirements was conducted. By its results, a set of requirements for the system was defined. More strict compliance with the recommendations is recommended for future projects, as it could lower the number of steps needed for the final set definition.

As for the evaluation of success of the systems engineering implementation, due to the high number of areas whose implementation could be evaluated, evaluations of the life cycle, the ECSS implementation, and the project reviews were chosen, as they were deemed the most important and the most representative. They were also chosen, as their implementations are described in the thesis assignment.

As this was the first CRS project using systems engineering, many of the activities associated with systems engineering were performed for the first time. Thus, previous know-how was minimal to non-existent. Therefore many of the activities were not performed to their full potential as the knowledge of how to do them is yet to be established.

10.1 Evaluation of life cycle implementation

For the StarFox project, a life cycle based on the NASA life cycle as found in [8] was used. Due to the project's long-term duration and the time and content restrictions of this thesis, only phases *Pre-Phase A* through *Phase B* were described. Regardless, the project will continue with this life cycle implementation, and the final evaluation may be published in the future.

From the evaluation of the phases distinction, it should be noted that the project phases distinction was not completely adhered to as described in [8]. It was common during the project duration that the distinction between the separate phases was blending together. In many cases, work on tasks that were supposed to be carried out in the next phase began before the previous phase's disclosure. This is fairly common to student rocketry teams, as following the life cycle exactly requires a considerable amount of resources, which the student teams do not possess.

Even though the project was adhering to the life cycle as it was defined in the beginning, with the tasks to be carried out in individual phases and the definition of important events, reviews, and key decision points. In the future, better task distribution and more thorough planning will need to be carried out before the project starts to ensure more proper compliance with the life cycle.

10.2 Evaluation of ECSS implementation

The StarFox project is the first CRS project to use the ECSS standards. The main problem with the implementation of the ECSS standards was that at the beginning of the project, no one working on the project was introduced to the ECSS system in more detail. Thus some of the tasks were not performed to the ECSS system requirements, i.e. the definition of the requirements from the ECSS system.

The main parts of the ECSS system that were implemented consisted of the project life cycle, project management, risk management, and information management. Their implementation was only partial, as only some parts from these disciplines were implemented. Nevertheless, this implementation can be considered successful in its scope. The Engineering and Product assurance disciplines of the ECSS system will be used in the future phases of the StarFox project, as well as other parts of the Management discipline.

Even though the ECSS system of standards was established in only small and sometimes individual cases, it can be considered at least a partial success. This is mainly because, thanks to it, the know-how of how to use ECSS standards was established in the CRS. It is important for future CRS projects to establish the ECSS implementation early in the project to ensure the biggest benefits from using it.

10.3 Evaluation of project reviews

As of this date, only the Mission concept review and System requirements review have been conducted, with the Preliminary design review prepared for conduction in the foreseeable future.

The main difference between the project reviews of this project compared to the reviews of usual projects in the industry is that, as with many other student projects, the customer is the student team overarching the given project. Because usually, all the people with knowledge of the given problem from the team are usually working on that project, it is meaningless to prepare the project review for the customer of the project as in the industry. It is, therefore, common among the student teams that the reviews are conducted by inviting external consultants from other student teams, from the industry, and from the universities to give their opinion on the project and help direct the effort.

For the Mission concept review, it can be noted that its preparation was hasted. Thus some of the important points were overlooked. For example, the concept studies were prepared in less detail than it was later revealed to be needed. Although at the time of the conduction of the review, it was deemed that the preparation was satisfactory, in later phases, it was revealed to be wrong. This increased the costs needed for the project, especially in terms of time and human resources.

The System requirements review was the first project review that was also sent to external consultants. The first step in its conduction was the preparation of a document with all goals, constraints, and requirements, which was then sent to the CRS members. They had time to send their feedback, which was then incorporated, and the updated document was then sent to the external consultants. In contrast to the Mission concept review, it was overseen that the review would be conducted as best as possible. This meant that it was delayed for a long period of time, meaning that at the time of sending the documentation, the preliminary design was taking place for several months. The main problem that caused this was the inexperience in the preparation of the requirements among the leadership of the project.

11 CONCLUSION

The StarFox project began in the summer of 2022 with the goal to design, build, and test a demonstrator of a pressure-fed liquid rocket engine, which could be in future used as a baseline for the development of an airworthy engine that could power a sounding rocket for high power student rocketry competition.

The basic principles and ley parts of liquid propellant rocket engines were described. At the same time, already existing solutions were examined so that it was possible to choose the initial parameter settings for the developed engine. Furthermore, the basic principles and procedures of system engineering of space projects were described.

Based on this knowledge, the implementation of systems engineering for the StarFox project was concluded. Although this implementation had many problems, it can be considered a success. First of all, this is the first CRS project in which system engineering is implemented, and one of its main goals is to bring the people working on the project closer to the procedures used in the industry. Furthermore, the experience gained from this implementation will be able to be used in the future for other projects that will be more complex. Therefore the correct implementation of system engineering at the beginning of the project will be more needed.

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NOMENCLATURE

Abbreviation

CRS	Czech Rocket Society
ECSS	European cooperation for space standardization
ESA	European space agency
EUROC	European Rocketry Competition
GN2	Gaseous nitrogen
IPA	Isopropyl alcohol
LCH4	Liquid methane
LOX	Liquid oxygen
MCR	Mission concept review
MTS	Mobile test stand
NASA	National Aeronautics and Space Administration
PDR	Preliminary design review
RBFP	Remove before flight pin
RUD	Rapid unscheduled disassembly
SE	Systems engineering
SRR	System requirements review
TCA	Thrust chamber assembly

Roman symbols

F	Thrust
P_c	Pressure in the combustion chamber

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