2022

A Systems Engineering approach for developing a Mars In Situ Propellant Production System

Rafael E. Martinez Paruta

A Systems Engineering approach for developing a Mars In Situ Propellant Production System

by

Rafael Martinez Paruta

A thesis research paper presented to the
Faculty of the Department of
Systems Engineering
Frank R. Seaver College of Science and Engineering
Loyola Marymount University

In partial fulfillment of the
Requirements for the Degree
Master of Science in Systems Engineering

April 27, 2022

A Systems Engineering approach for developing a Mars In Situ Propellant Production System

SYEG 696: Capstone Project

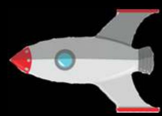
Rafael Martinez Paruta, B.S. Materials Engineering

Advisor: Dr. Elham Ghashghai

April 27, 2022

Loyola Marymount University Systems Engineering

Agenda



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MoEs: Measures of Effectiveness

Acknowledgements

LMU Systems Engineering Graduate Program
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- Gerald Sanders – Johnson Space Center
- David W Beaty – JPL
- Mary Magilligan

SpaceX
- Brandon Kan
- Eric Dymkoski

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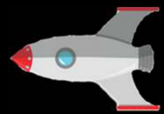

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Executive Summary

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- **Background:** In order to succeed in the short-term exploration and colonization of Mars, the transfer vehicles need to be fully reusable, and in order to achieve this, they need to be able to make return trips to Earth.

- **Problem Statement:** Making trips back to Earth from Mars is unfeasible in the short term due to the nonexistence of fuel or oxygen on Mars.

- **Objective:** Build a roadmap and foundation for students pursuing Mars exploration internships or capstone projects to develop a systems engineering analysis and model, of a solution to the problem. detailed

- **Summary:** Performed a high-level analysis of the problem, using system engineering methodology to reach a potential solution, and created a system model using Cameo.

- **Conclusion:** In situ, propellant production has a high potential to increase the short-term feasibility of the Mars exploration missions and based on my research, it's the best alternative for a mission taking place before 2030.

- **Clients:** LMU students, Mars City Design, SAM at Biosphere 2.

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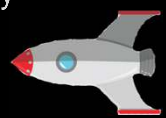

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MoEs: Measures of Effectiveness

Methodology

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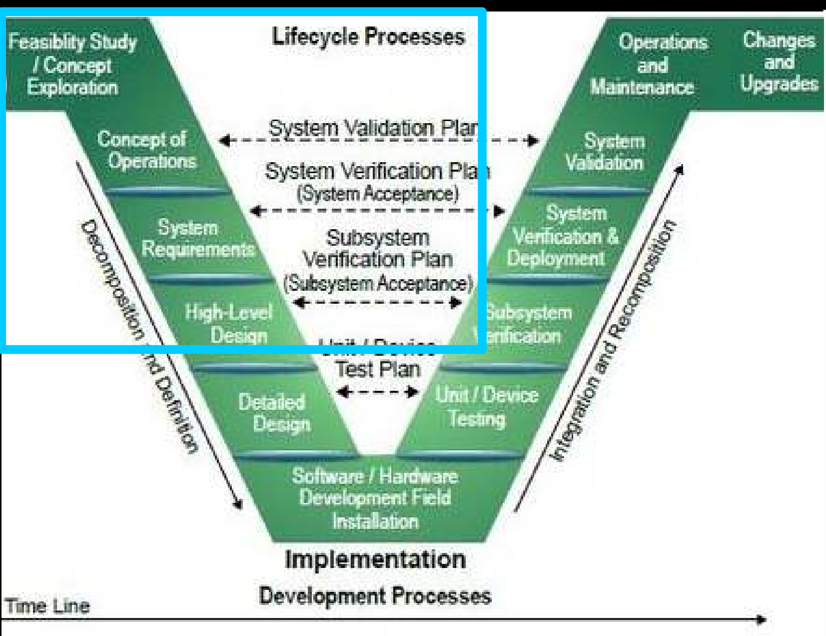

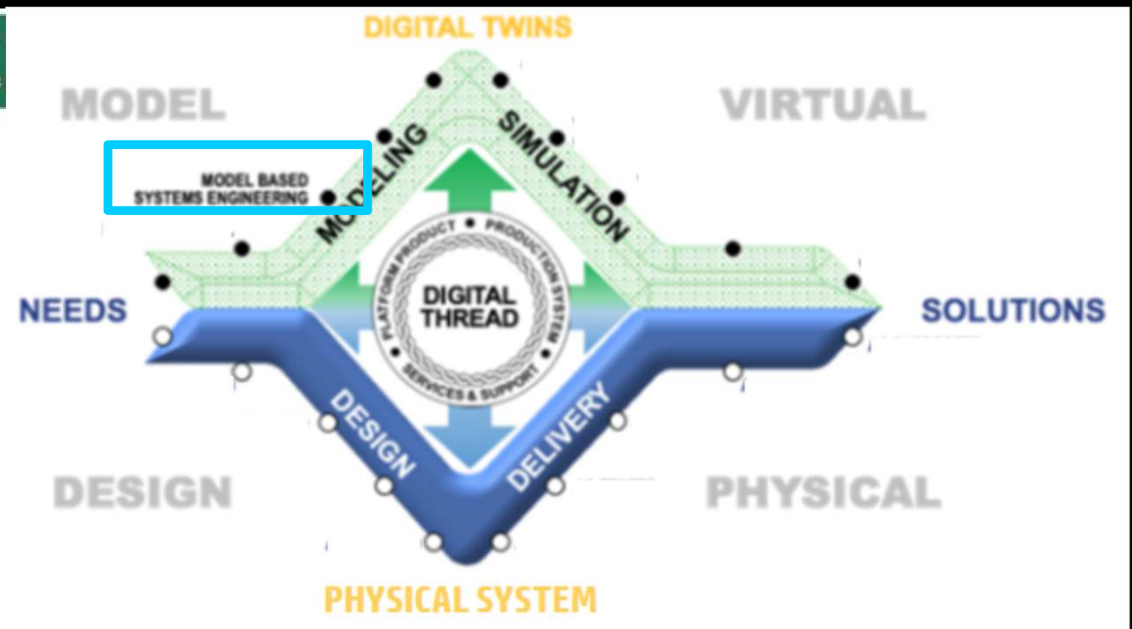

Traditional Systems Engineering "V" and Model Based Engineering Diamond

Methodology

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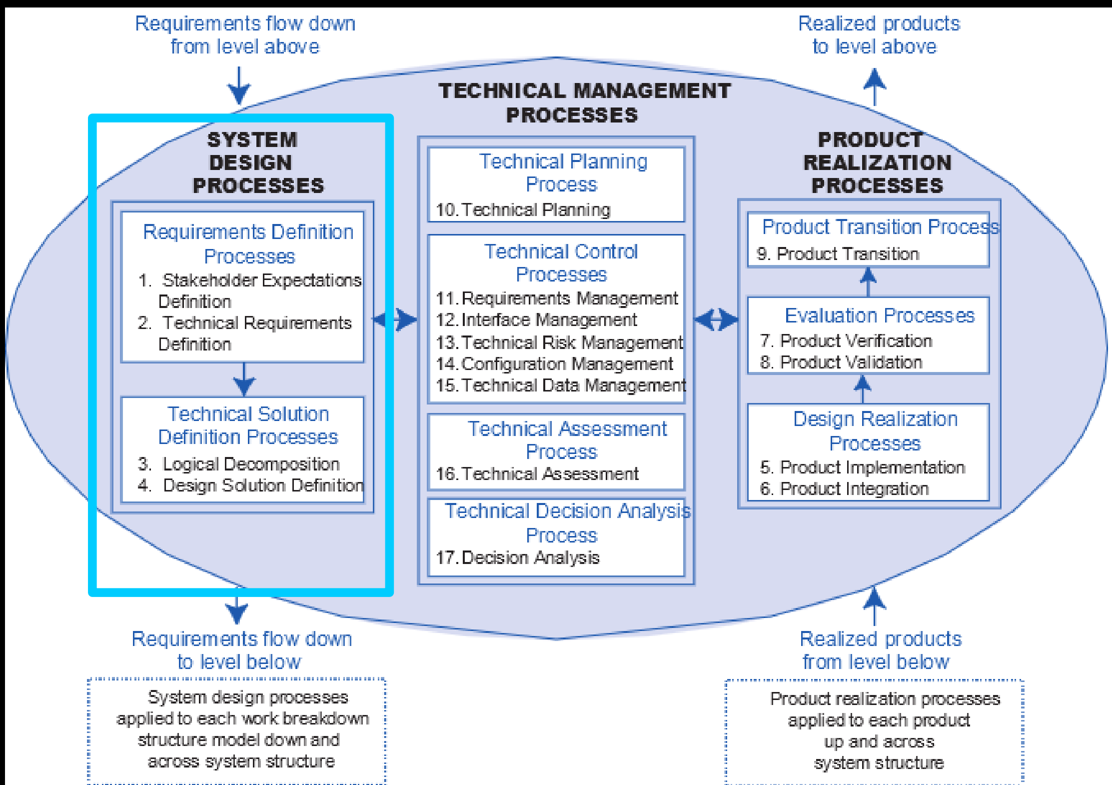

The Common Technical Process and the SE Engine

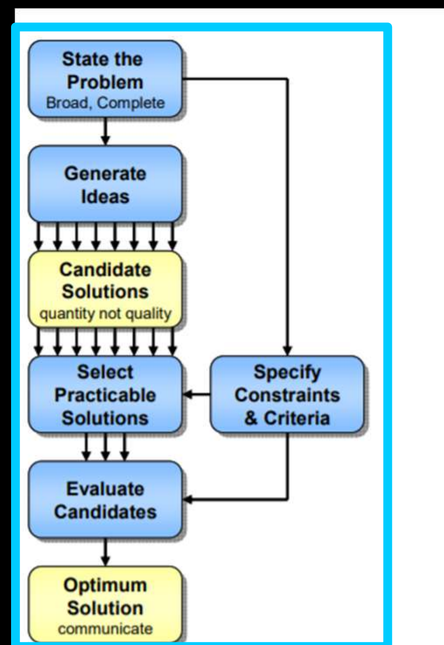

Figure 10: Concept Exploration Uses Basic Trade Study Techniques

Basic trade study technique

SE: Systems Engineering

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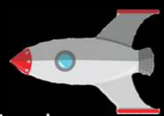

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MoEs: Measures of Effectiveness

About me

- **Previous Studies:**
  - B. S. Materials Engineering and Manufacturing. Universidad Simon Bolivar, Venezuela.
- **Latest work experience:**
  - Systems Engineering Contractor for the USSF Launch Enterprise (now AATS)
  - Systems Engineer for Space Programs at Raytheon Intelligence and Space
- **Hobbies:**
  - Snowboarding, surfing, climbing, hiking, traveling.
- **Where I have lived:**
  - Venezuela, The Netherlands, USA.

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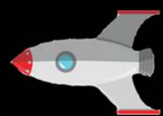

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MoEs: Measures of Effectiveness

Inspiration and Motivation

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- Curiosity about space from an early age.
- Interest in space exploration and, most recently, SpaceX's Mars mission campaign.
- LMU's Occupy Mars class.
- Desire to inspire and motivate students.
- New knowledge on Mars exploration.
- Potential connections with NASA and SpaceX.

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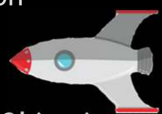

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MoEs: Measures of Effectiveness

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Background

Why venture out of Earth?

- Overpopulation
- Increased energy consumption
- Overexploitation
- Pollution
- Extreme Climate change
- Epidemics
- Nuclear wars
- Asteroid strikes
- Growth of the Sun

“We are running out of space and the only places to go to are other worlds. It is time to explore other solar systems. Spreading out may be the only thing that saves us from ourselves. I am convinced that humans need to leave Earth.”

Stephen Hawking

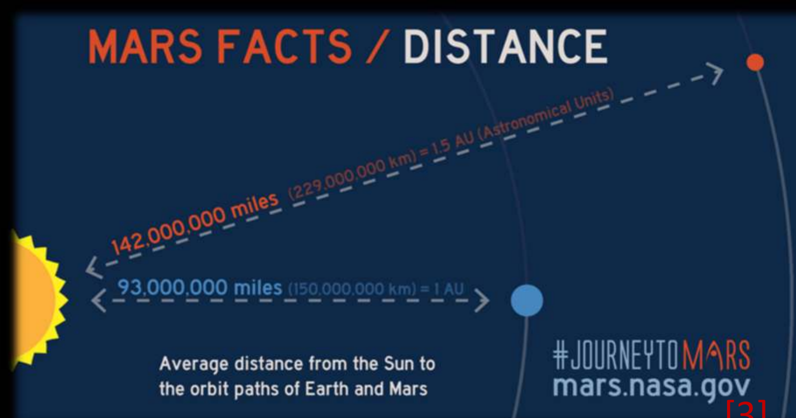
[1, 2]

Why Mars?

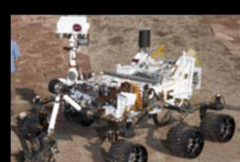
- Distance
- Similarities with Earth
- Resources
- Available data
- Can serve as a starting point to go to other places in the galaxy

“Mars is a fixer-upper of a planet, but I think one day we can make it a planet like Earth, and I think we should.”

Elon Musk



[3]



Why Starship?

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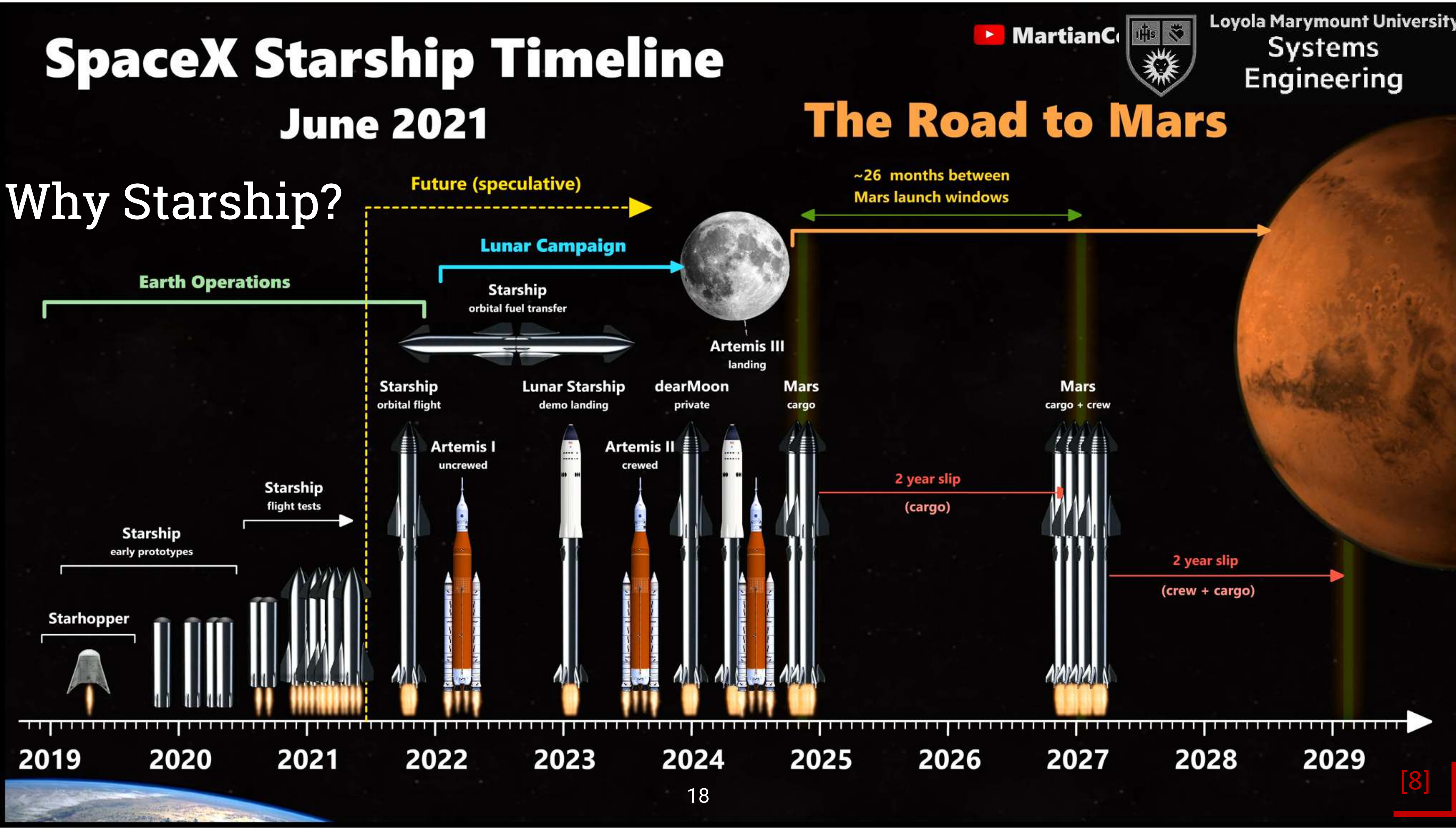
- Lower cost
- High reusability
- Capability to deliver 1 M ton
  to the surface of Mars in 10 years
- Future Oxygen orbital refilling capability
  (to be tested in 2 years)
- It’s In the final stage of development
- Picked by NASA for the Lunar mission

“The total mass to orbit per Starship after one year would be the equivalent of the total mass to orbit today worldwide (15,500 tons).”
Elon Musk

[3-7]

Why Starship?



[8]

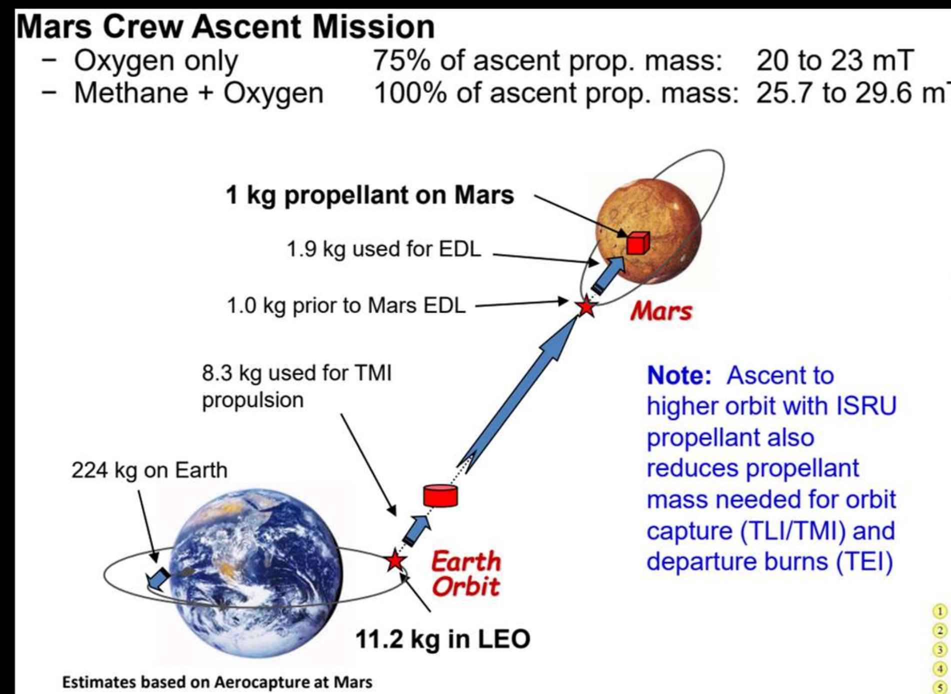
Why use Mars Resources?

- **Reduce mission and architecture mass and costs**
  - Launch mass savings.
  - Reduce launch numbers.
  - Supports reuse of mission transportation assets.

- **Enhance or enable mission capabilities not possible without them**
  - Mission life extensions and enhancements.
  - Increased surface mobility and access.
  - Increased science.

- **Learn to use Space Resources can help us on Earth**
  - Renewable Energy/CO2 Reduction, Recycling/Repurposing, Water cleanup, Environmentally-friendly mining and construction

Every 1 kg of propellant made on the Moon or Mars saves 7.4 to 11.2 kg in LEO



ISRU: In Situ Resource Utilization
EDL: Entry, Descent and Landing
TMI: Trans-Mars Injection
TEI: Trans-Earth Injection
TLI: Trans-Lunar Injection

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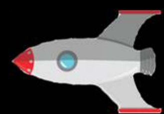

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MoEs: Measures of Effectiveness

Problem Statement & Objective

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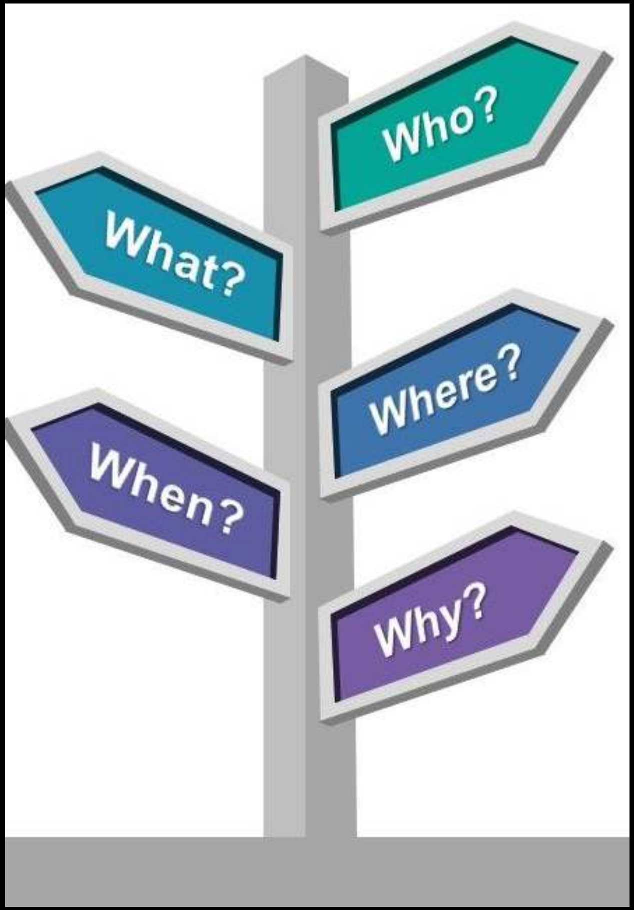
- Making return trips from Earth to Mars in the short term is unfeasible due to the nonexistence of fuel or oxygen on Mars.

- Build a roadmap and foundation for students pursuing Mars exploration internships or capstone projects to develop a detailed systems engineering analysis and model of a solution to the problem.



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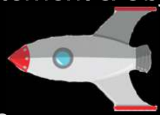

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MoEs: Measures of Effectiveness

Scope

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Out of Scope

- Chinese or Russian missions
- Missions to other planets
- Missions after 2034
- Classified technologies

In Scope

- American led Mars Missions
- Missions launched up to 2034
- Publicly available technologies

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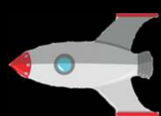

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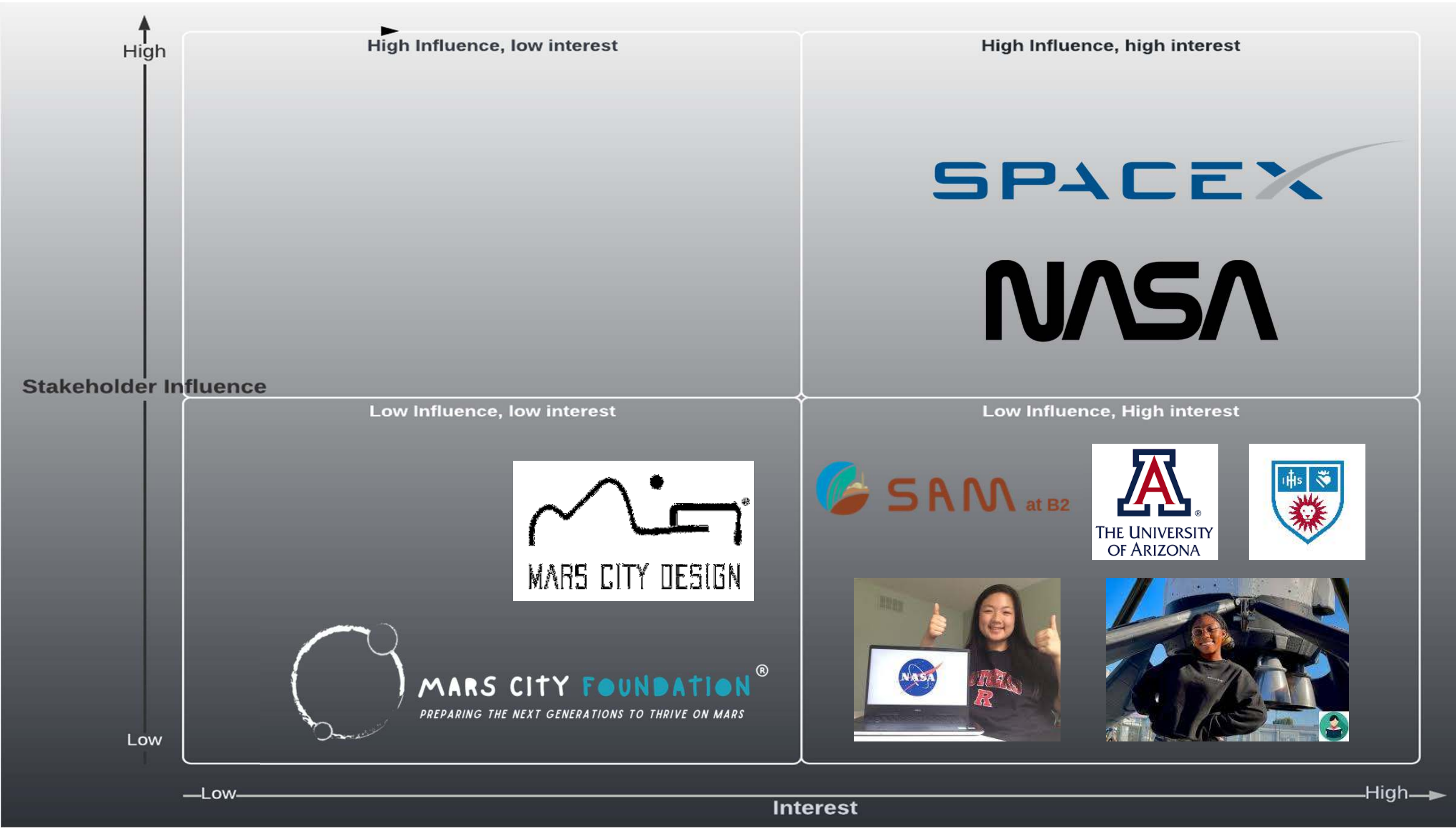
High
Low
Stakeholder Influence
High Influence, low interest
High Influence, high interest
SPACEX
NASA
Low Influence, low interest
MARS CITY DESIGN
MARS CITY FOUNDATION®
PREPARING THE NEXT GENERATIONS TO THRIVE ON MARS
Low Influence, High interest
SAM at B2
THE UNIVERSITY OF ARIZONA
Low
High
Interest

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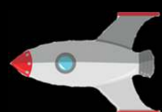

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MoEs: Measures of Effectiveness

Primary Stakeholders Needs

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NASA & SpaceX

- All equipment taken to Mars need to fit within starship's fairing and not exceed cargo load capacity.
- Low cost
- High reliability and operational life
- Space Resource Utilization
- First launch in 2029 (At the latest)
- Mission elements to be scalable to allow the creation of Mars cities.
- Rapid, safe & efficient transportation to Mars
- Minimize Exposure to the in-space environment (Radiation & 0G)
- Ability to return to Earth every 26 months
- Autonomous operations on Mars

[4,5, 10-12]

Secondary Stakeholders Needs

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Students
- The project must provide students with sufficient data and guidance

Mars City Design/Foundation
- The project needs to be aligned with MCD & MCF conferences' audience

LMU's Occupy Mars Class
- The presentation content must satisfy the instructors' program content needs.

SAM at Biosphere 2
- The verification plan must include SAM as a test facility
- The system prototype needs to have interfaces that can be connected to their test systems
- The system prototype needs to be able to fit inside the Mars Analog

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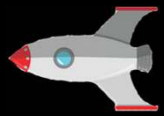

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MoEs: Measures of Effectiveness

High-Level Requirements

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	Requirement	Verification Method
HR1	➢ The systems forming the Mars mission architecture shall be fully reusable.	➢ Design analysis ➢ Early integration and verification via digital twin model demonstration ➢ Functional testing ➢ Stress testing simulation
HR2	➢ The limiting technology for the mission shall be readily available before year 1 of the project.	➢ Demonstration of the capabilities and functionalities of the technologies
HR3	➢ The cost of the system shall be less than $10B.	➢ Financial analysis
HR4	➢ The Mars transfer vehicle shall be capable of reaching Mars in 180 days.	➢ Analysis of propulsive capabilities and orbital mechanics ➢ Demonstration using digital twin
HR5	➢ The system shall be designed to be expandable.	➢ Design analysis
HR6	➢ The system shall be capable of making trips from Mars to Earth every 26 months.	➢ Demonstration via digital twin ➢ Analysis of simulation data

[28-45]

ISPP: In Situ Propellant Production

Agenda

MoEs: Measures of Effectiveness

Measures of Effectiveness

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- Technology Readiness Level (TRL)
- Earth-Mars Transfer Time
- Reusability
- Cost
- Scalability

Additional information in Appendix B

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MoEs: Measures of Effectiveness

Alternatives

- In situ production of propellant (fuel and oxygen)
- Importing resources to Mars from other solar bodies
- Alternative propulsion systems
- Hybrid propulsion systems
- Mega spaceships (capable of going to Mars and returning to earth without refilling)
- Orbital propellant and oxygen depots (in Mars orbit)

Additional information in Appendix C

Alternatives

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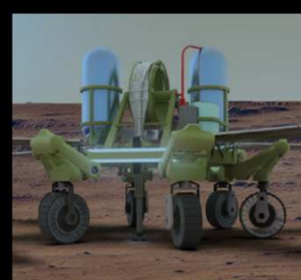
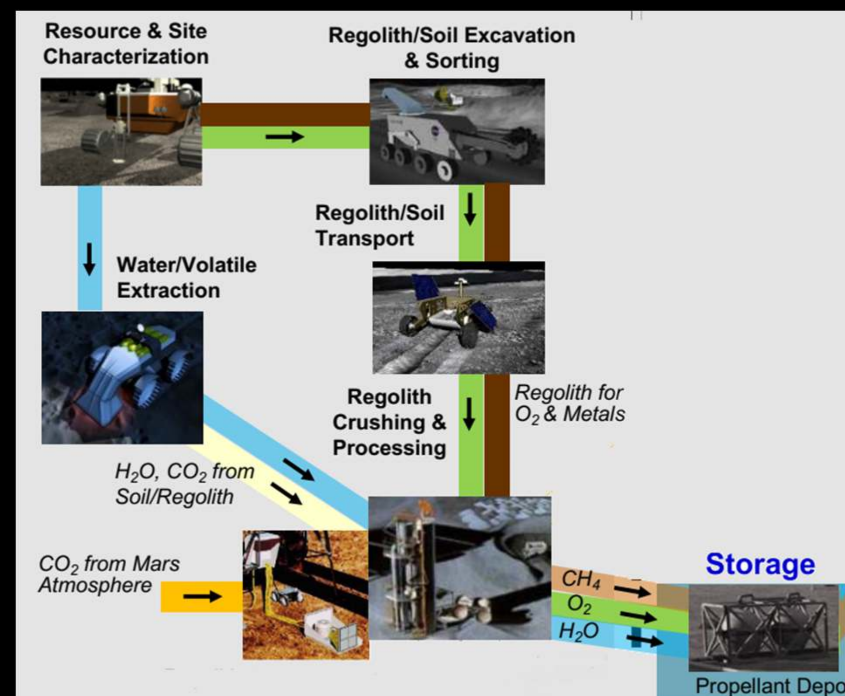
Mars In Situ Production of Fuel and oxygen

Atmosphere Processing – Oxygen/Methane Liquefaction & Storage

Excavation & Soil Processing for Water

Mars Ice Drilling & Extraction





[16-20]

Alternatives

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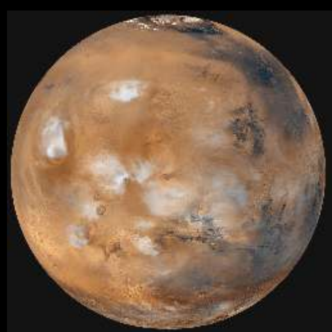
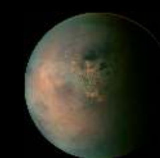
Importing resources to Mars from other solar bodies



Hydrocarbons
Hydrogen
Nitrogen
Minerals
Oxygen



[21]

Alternatives

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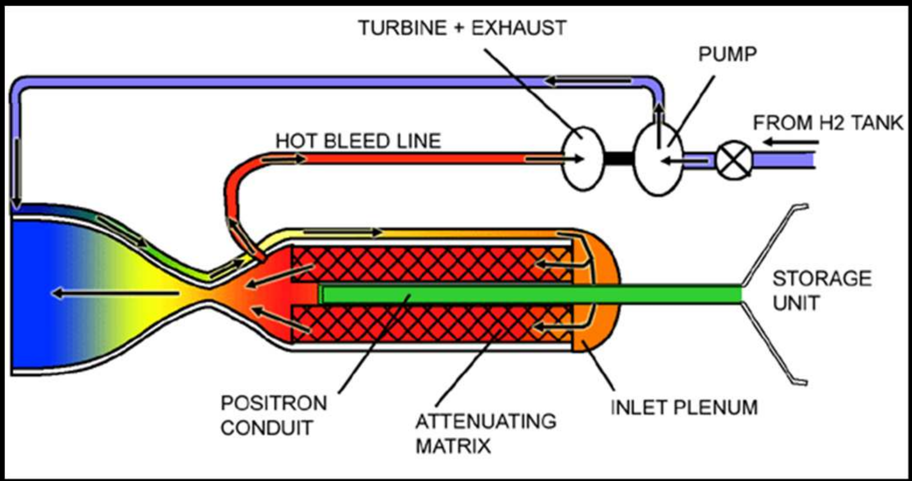
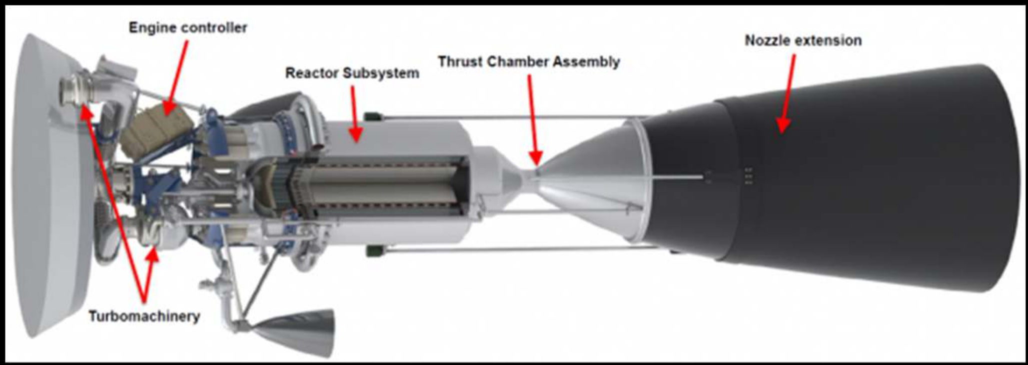
Alternative propulsion systems (Non-chemical, Advanced Propulsion)



Antimatter Propulsion



Nuclear Fission Propulsion

[22-25]

Alternatives

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Hybrid propulsion systems (Chemical + non-Chemical or Advanced)

- Two or more propulsion technologies, at least one chemical and one non-chemical.
- This system combines the high thrust benefit of chemical propulsion needed to launch from Earth with the efficiency of the non-chemical propulsion (reduces the total mission propellant mass requirements).

[22-25]

Alternatives

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Mega Spaceships

[26]

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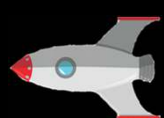

MoEs: Measures of Effectiveness

AoA (Trade Study)

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On a scale of 1-5 (1=worst, 5=best) at satisfying the MoEs.

		Alternatives				
		Import Propellant	Non-Chemical Propulsion	Hybrid Propulsion	Mars ISPP	Mega Spaceships
		SCORE				
MoEs	TRL	1	3	3	4	1
	Transit Time	5	2	3	5	4
	Reusability	5	4	4	5	4
	Cost	1	4	4	3	1
	Scalability	5	5	5	5	5
Totals		17	18	19	22	15

AoA: Analysis of Alternatives
TRL: Technology Readiness Level
ISPP: In Situ Propellant Production

[3,4,16-26]

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Loyola Marymount University
Systems Engineering

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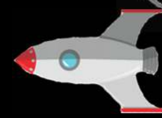

MoEs: Measures of Effectiveness

Alternative Recommendation

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Mars In Situ Production of Fuel and oxygen

- Enables the spaceships to return to Earth (reusability) in the short term
- Decreases the cost of the mission
- The technology can be applied on earth to help reduce pollution and global warming.
- Potentially scalable to enable the exploration of other planets

[16-20, 27]

AoA: Analysis of Alternatives

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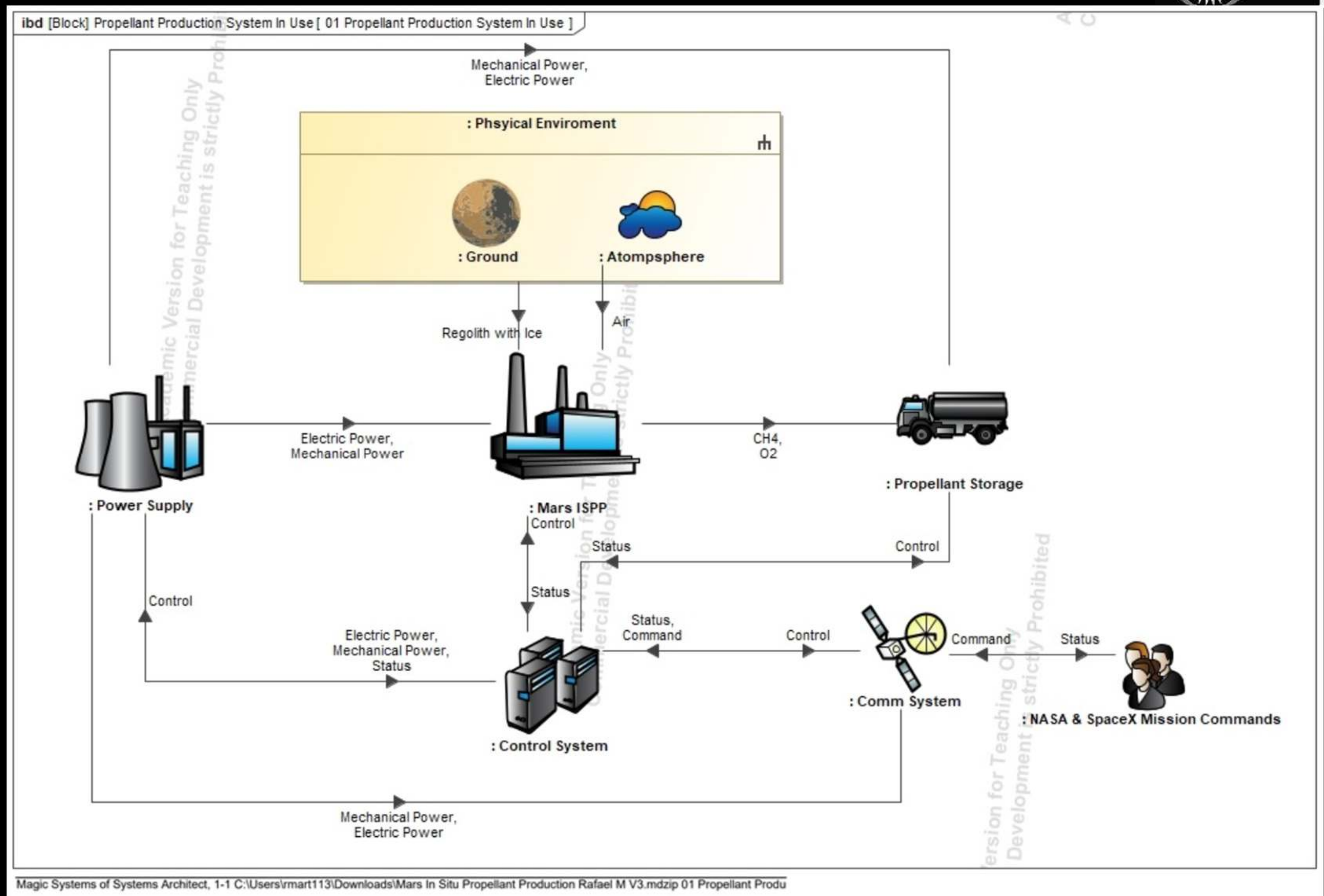
MoEs: Measures of Effectiveness

Solution Architecture – CONOPS



CONOPS: Concept of Operations

Solution Architecture – CONOPS

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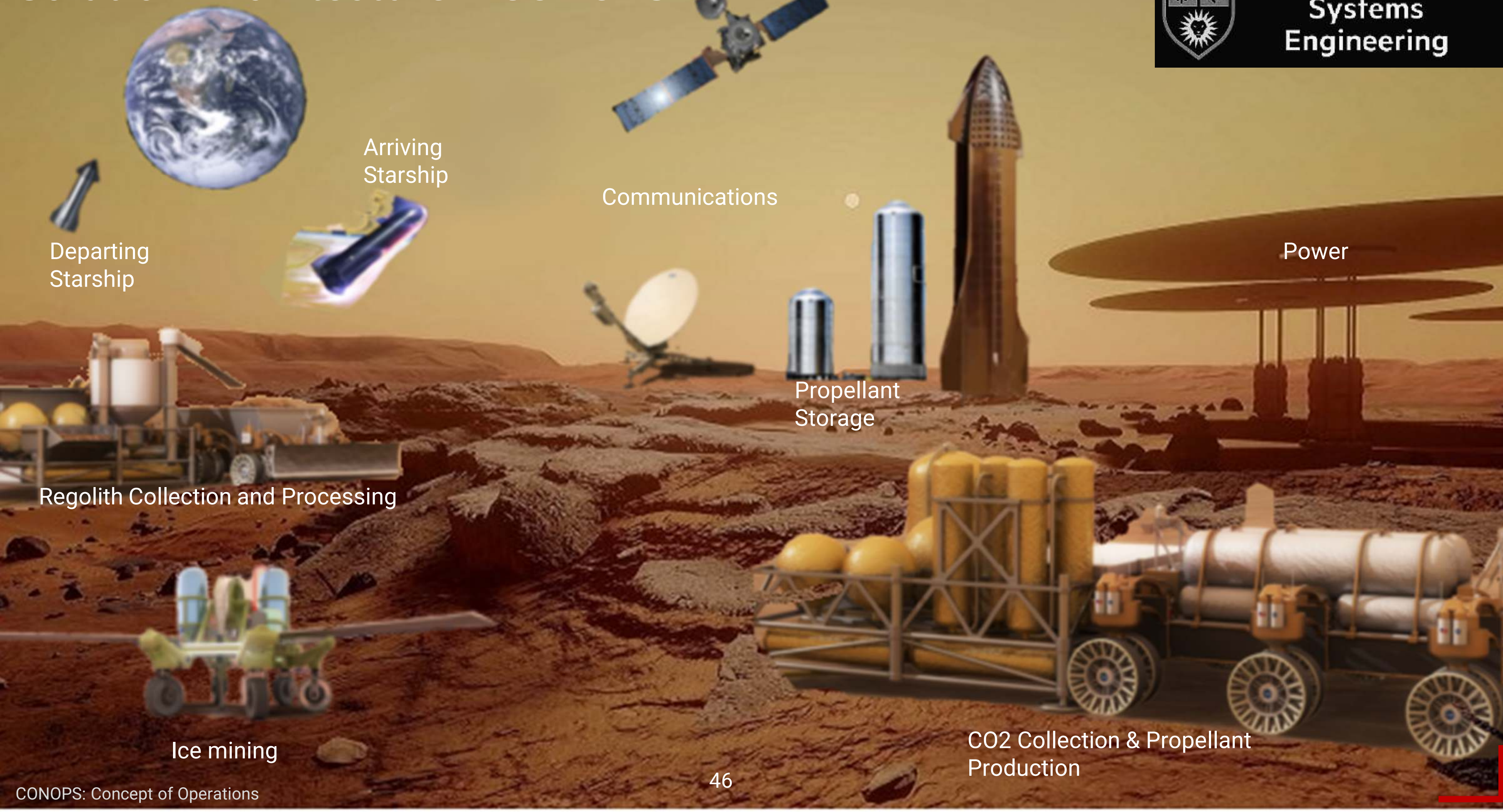

CONOPS: Concept of Operations

Solution Architecture – Internal Block Diagram

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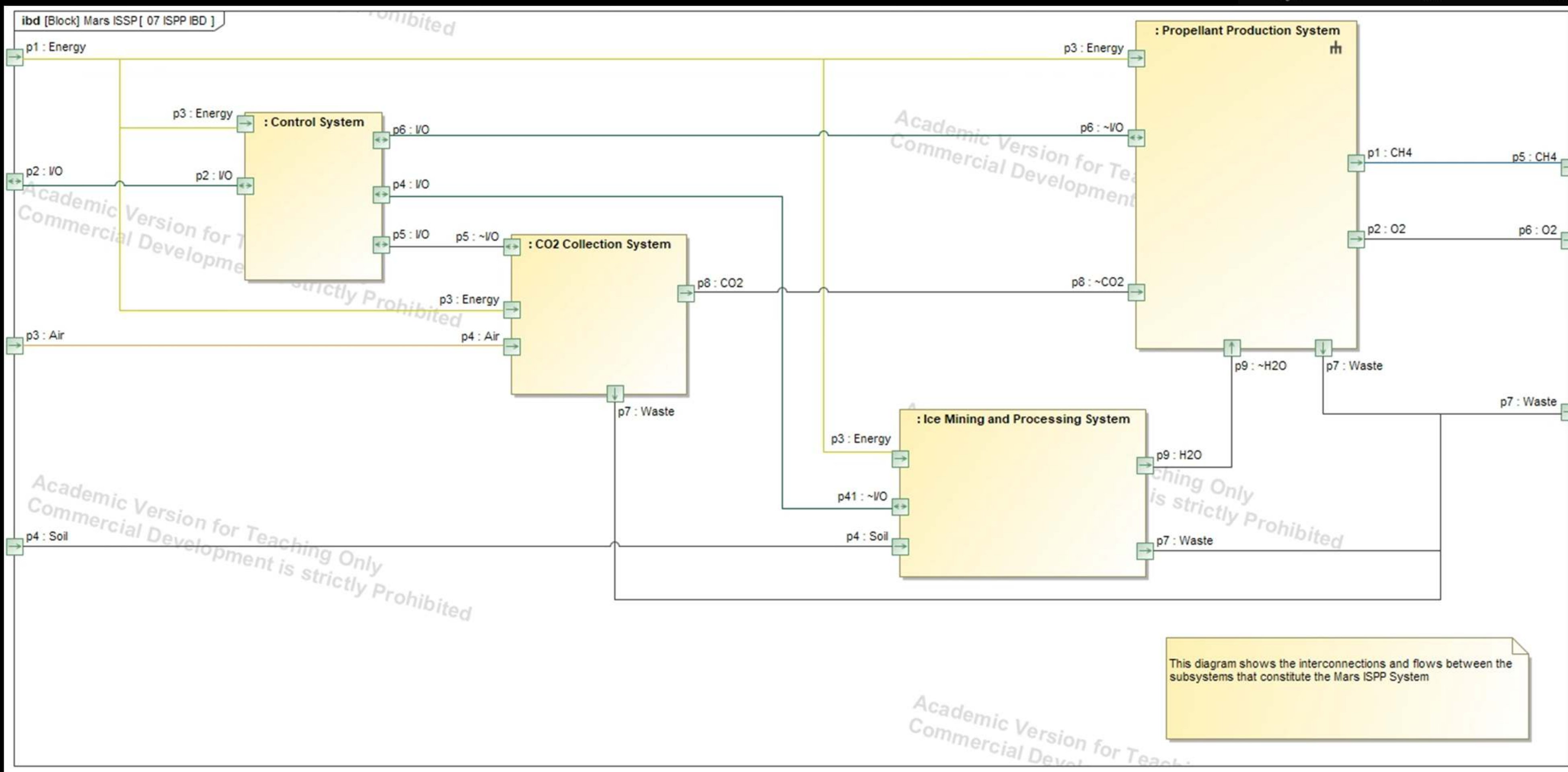

Solution Architecture - Internal Block Diagram 2

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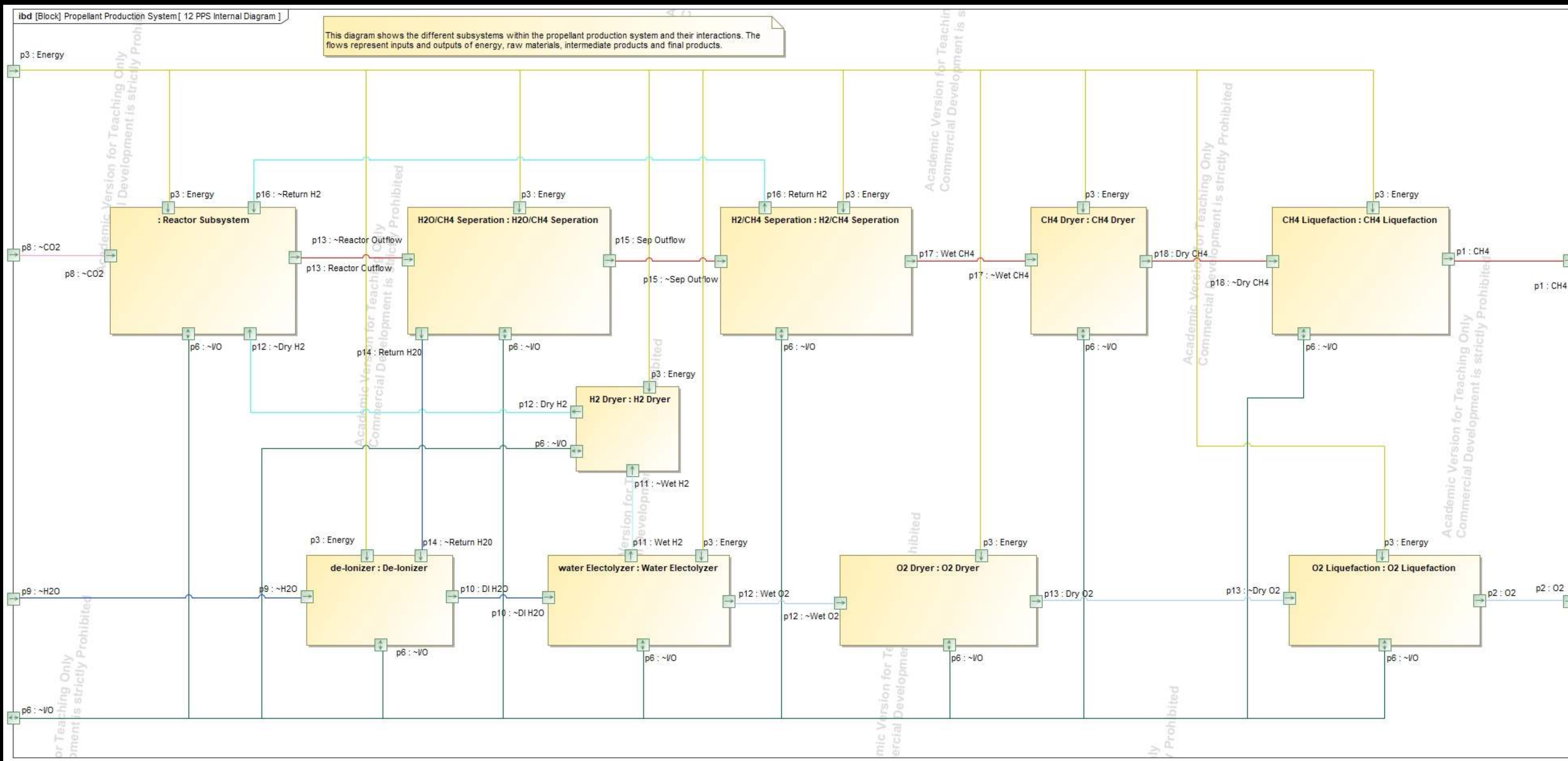

Solution Architecture - System View

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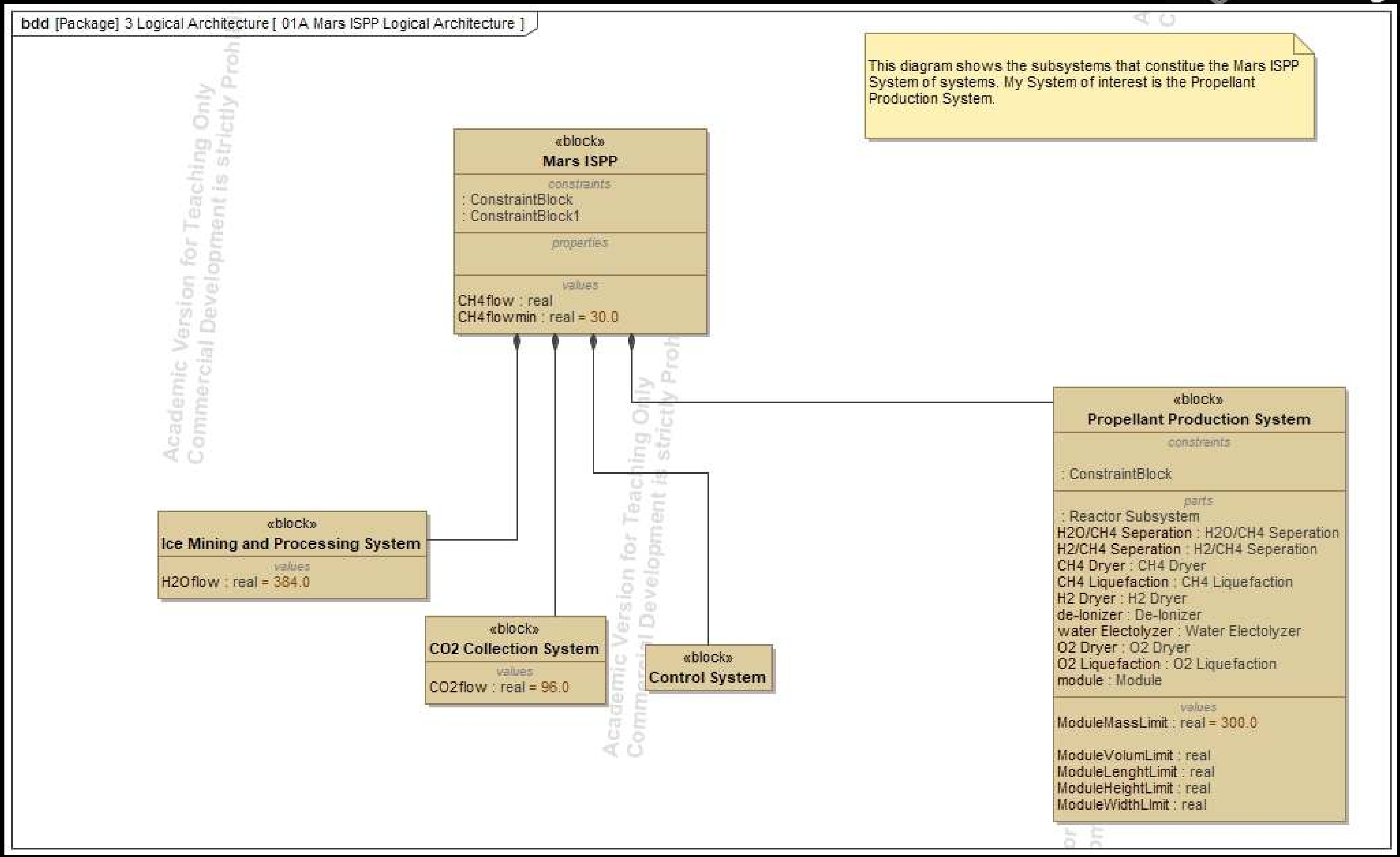
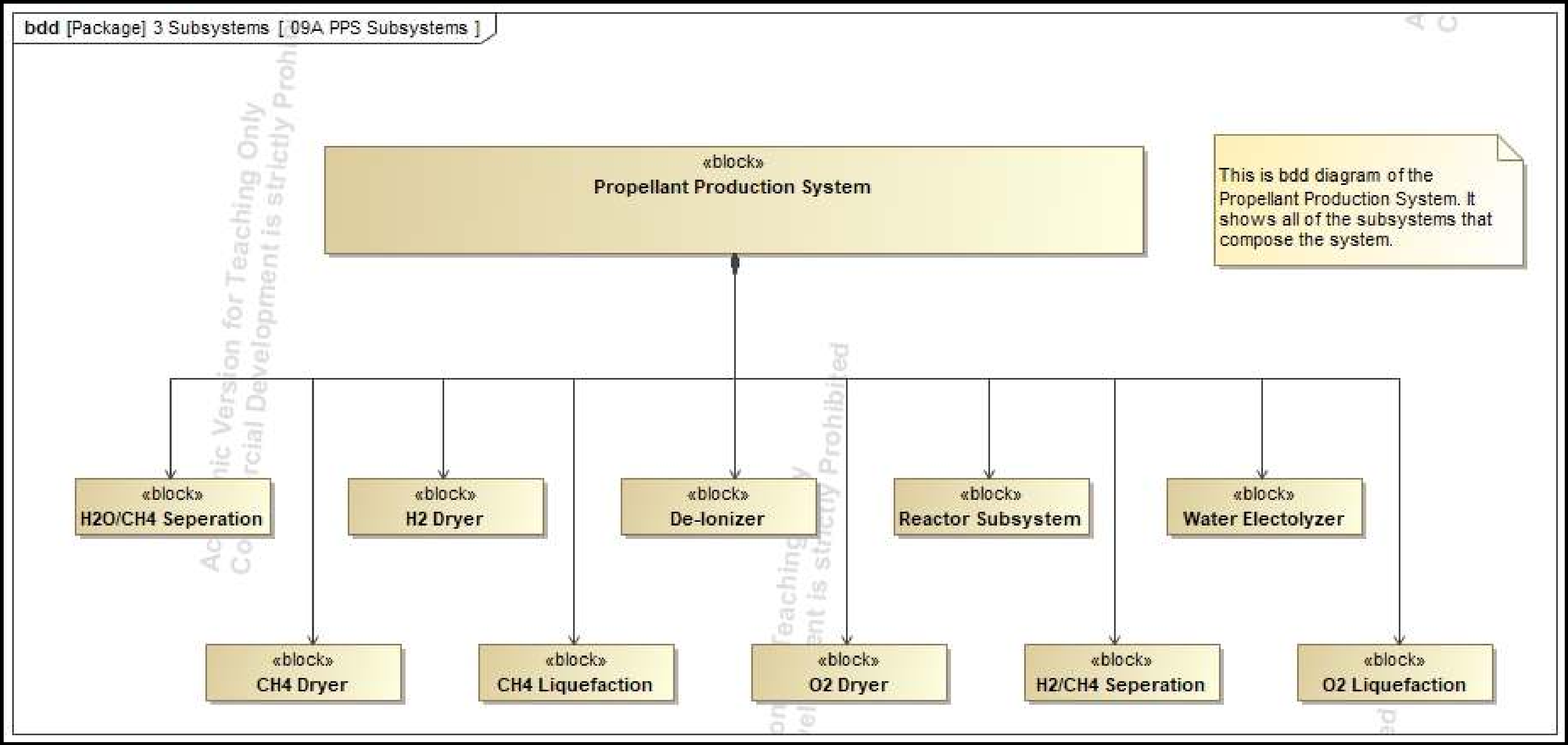


Solution Architecture - System View 2

Loyola Marymount University Systems Engineering



Solution Architecture – Data View

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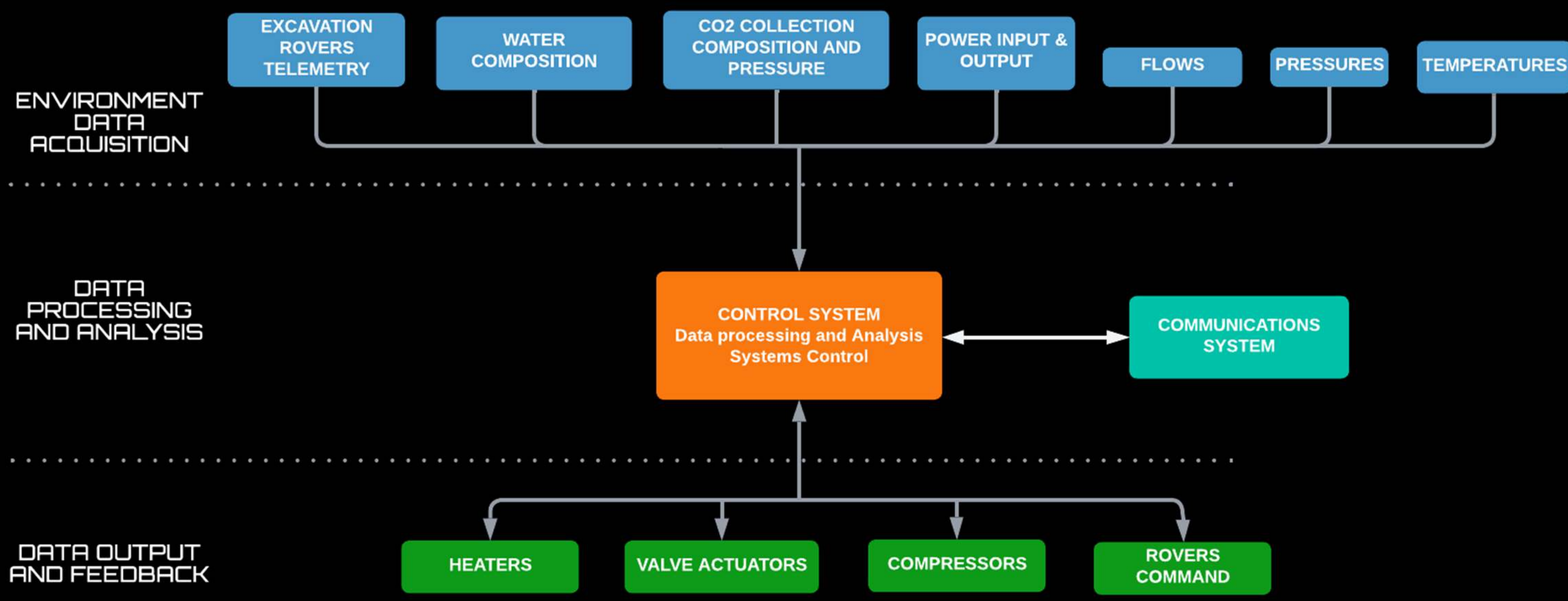

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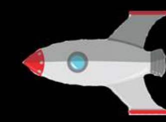

MoEs: Measures of Effectiveness

Detailed Requirements – ISPP System

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	Requirement	Verification Method
SR1	➢ The ISPP system shall be capable of producing a minimum of 30 Kg of methane per hour	➢ Process simulation using Mars atmospheric conditions and gravity ➢ System prototype testing using Mars atmospheric conditions
SR2	➢ The ISPP system shall be capable of producing a minimum of 110 Kg of oxygen per hour	➢ Process simulation using Mars atmospheric conditions and gravity ➢ System prototype testing using Mars atmospheric conditions
SR3	➢ The Ice mining and processing system shall be capable of extracting a minimum of 67.5 Kg of Ice per hour from Mars surface	➢ Process simulation using ice surface and sub-surface ice content data from Mars Rovers ➢ System prototype testing in Mars analog
SR4	➢ The Carbon dioxide collection system shall be capable of extracting a minimum of 8.25 Kg of CO2 per hour from Mars's atmosphere.	➢ System prototype testing using Mars atmospheric conditions ➢ Process simulation using Mars atmospheric conditions ang gravity
SR5	➢ The system shall be able to perform all its functions without failure in Mars environment for a period of 5 years	➢ Analysis of the system using reliability calculations, and models based on the design of the system ➢ System prototype testing in Mars analog
SR6	➢ All systems and subsystems shall be designed in compliance with starship cargo volume and load capacity	➢ Design review

[28-45]

ISPP: In Situ Propellant Production

Detailed Requirements – ISPP System

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	Requirement	Verification Method
SR7	➢ The ISPP system shall be fully operable by an autonomous control system.	➢ System prototype testing
SR8	➢ The Mars transfer vehicle shall have a minimum Delta-V capability of 6 Km/s for cruising and 8.5 Km/s for Mars entry.	➢ Demonstration

ISPP: In Situ Propellant Production

[28-45]

Requirements – ISSP System & Subsystems

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Requirements Derivation Map

ISPP: In Situ Propellant Production

Requirements – ISSP System & Subsystems

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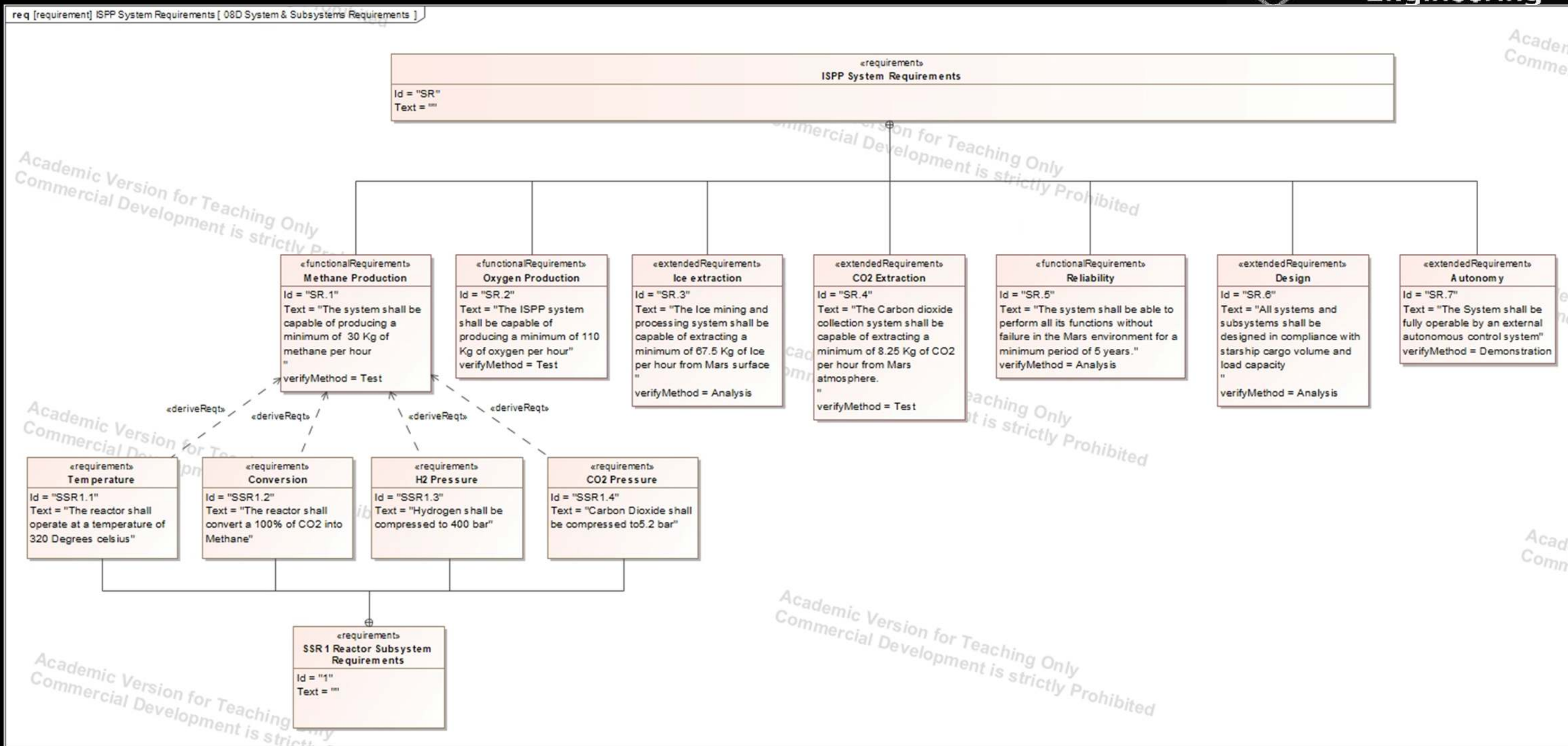

[29]

ISPP: In Situ Propellant Production

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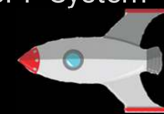

MoEs: Measures of Effectiveness

Implementation Plan

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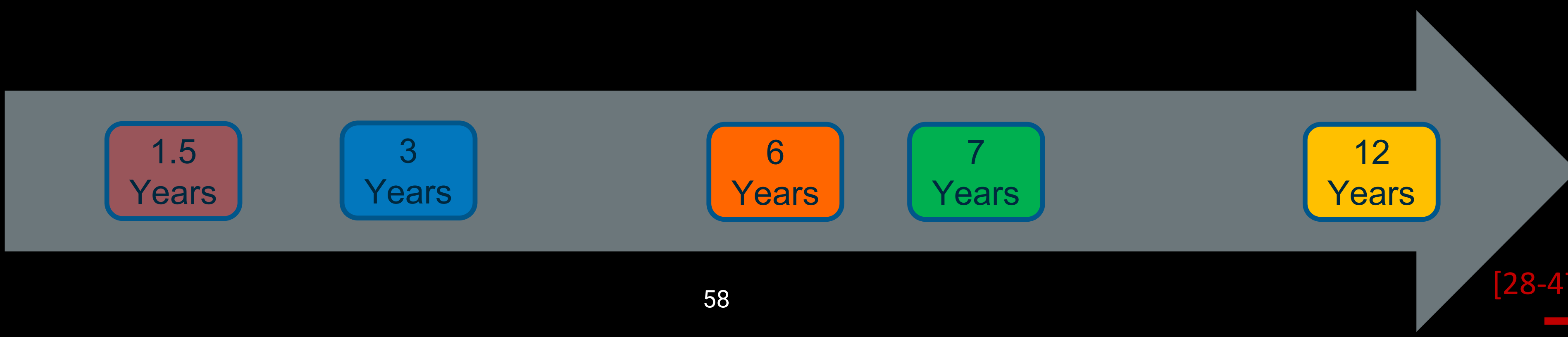
- Modeling (Digital Twin)
- Simulation
- Analysis
- Detailed design
- Prototyping
- Manufacturing
- Assembly & Integration
- Testing
- Launch
- Operations
- Mission Monitoring and Control
- Data gathering



[28-47]

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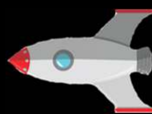

MoEs: Measures of Effectiveness

Verification Plan

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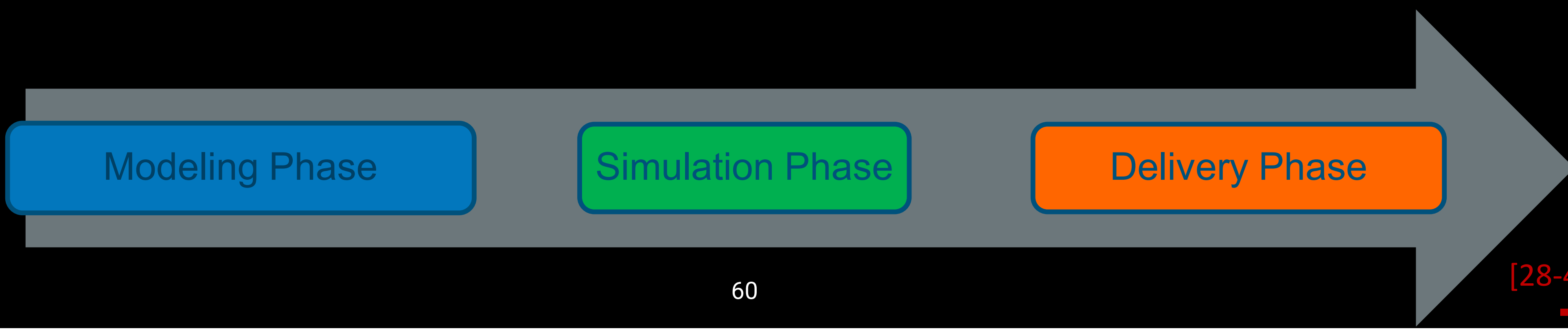
- Use of a Digital Twin for early integration & verification
- Chemical process simulation
- CFD fluids simulation
- Low gravity simulation
- Smaller scale prototype testing
- First article testing and inspection
- Test Prototypes in Mars Analogs
- Functional testing
- Operational testing
- Mechanical and structural testing
- Environmental testing



[28-45]

High-Level Requirements – Verification Status

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	Requirement	Verification Method	Verification Status
HR1	➢ The systems forming the Mars mission architecture shall be fully reusable.	➢ Design analysis ➢ Early integration and verification via digital twin model demonstration ➢ Functional testing ➢ Stress testing simulation	Pending
HR2	➢ The limiting technology for the mission shall be readily available before year 1 of the project.	➢ Demonstration of the capabilities and functionalities of the technologies	Pending
HR3	➢ The cost of the system shall be less than $10B.	➢ Financial analysis	Pending
HR4	➢ The Mars transfer vehicle shall be capable of reaching Mars in 180 days.	➢ Analysis of propulsive capabilities and orbital mechanics ➢ Demonstration using digital twin	Pending
HR5	➢ The system shall be designed to be expandable.	➢ Design analysis	Pending
SR6	➢ The system shall be capable of making trips from Mars to Earth every 26 months.	➢ Demonstration via digital twin ➢ Analysis of simulation data	Pending

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ISPP: In Situ Propellant Production

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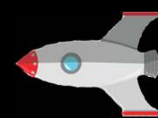

MoEs: Measures of Effectiveness

Validation Plan

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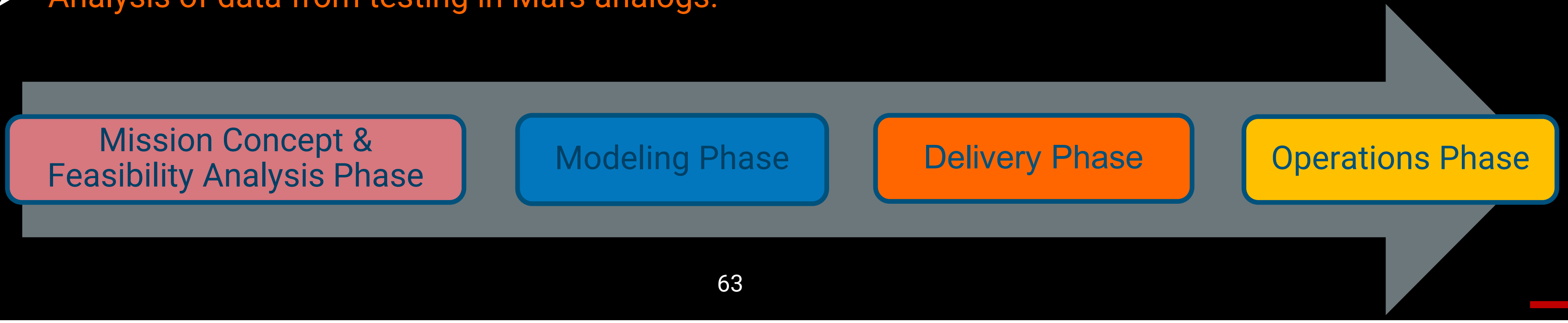
- Concept Of Operations Analysis
- Stakeholder requirements validation criteria definition.
- Re-evaluate alternatives semi-annually (TRL might increase) and determine whether the implemented solution is still the one that better satisfies the MOEs.
- Use of a Digital Twin for early validation
- Analysis of data from testing in Mars analogs.
- Analysis of mission data from the first two uncrewed spaceships
- Gather and analyze performance metrics monthly
- Gather and analyze propellant composition data monthly
- Determine whether the amount and quality of propellant produced satisfy the mission needs before sending any crewed spaceships to Mars.



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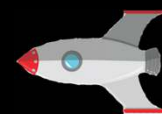

MoEs: Measures of Effectiveness

Risk Analysis

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- **Risk 1 – Chemical process failure**
  Description: Chemical process involved in producing Methane and Oxygen fails due to equipment malfunction.
  Mitigation: Design the chemical reactor subsystem with full redundancy.

- **Risk 2 – Loss of power**
  Description: Power supply temporarily or permanently interrupted.
  Mitigation: Design the power system with full redundancy and have an alternate power source to increase reliability further.

- **Risk 3 – Missing launch window (20 DAYS)**
  Description: Delays in production or testing could cause a schedule slip that can compromise the 20-day launch window.
  Mitigation: Plan to have enough time buffer to absorb delays in production or testing and still have the hardware ready to launch on time.

[50]

Risk Analysis

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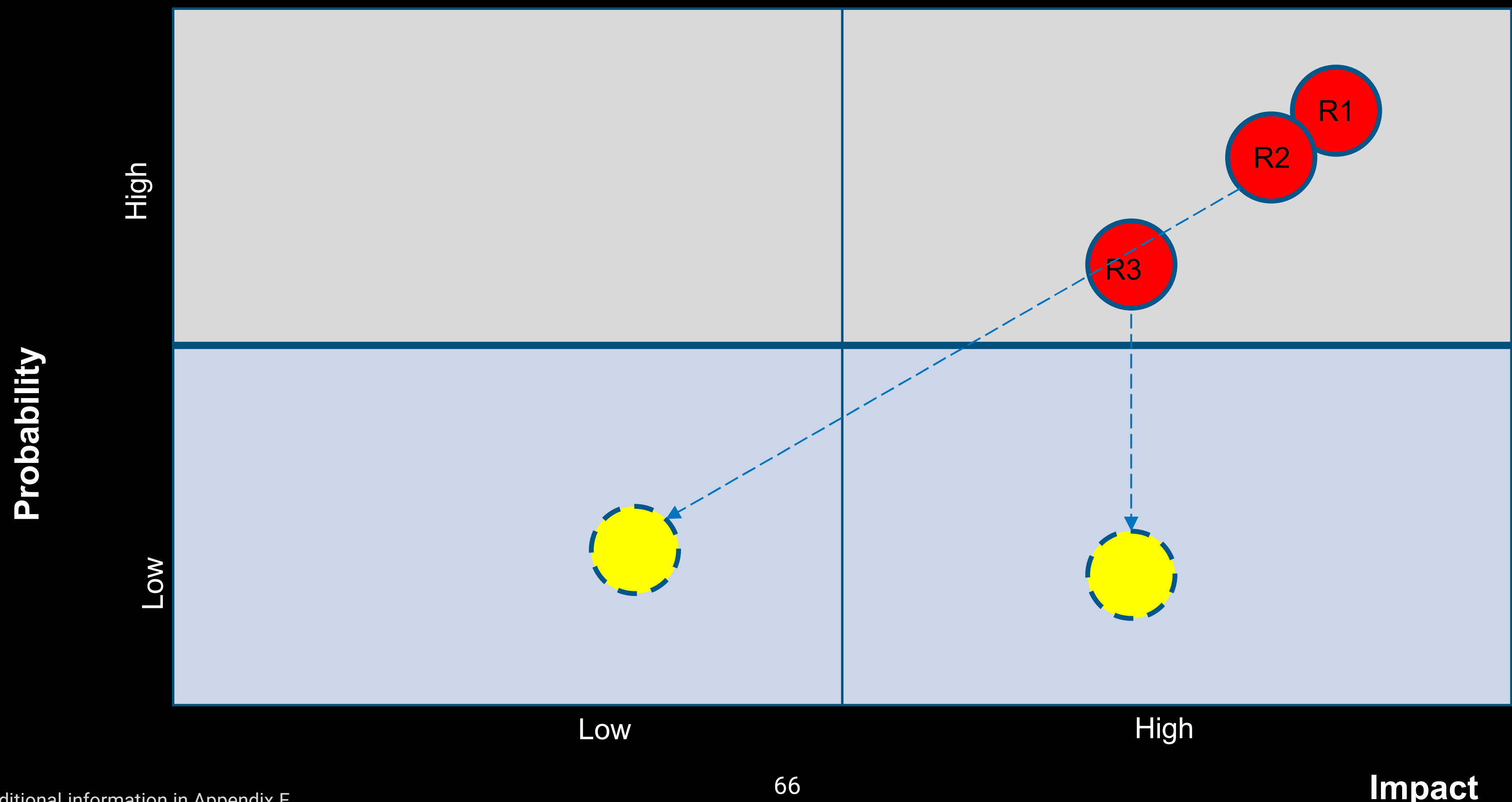
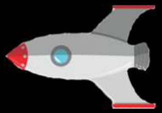


Additional information in Appendix E

Agenda



MoEs: Measures of Effectiveness

Cost Analysis

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Production Costs

- Mars ISPP System = **$2 - $6B**
- Starship's Raptor engine= $2M
  Starship Qty 9, Super Heavy Qty 33
  Total Engines = 42 ⇨ $84M
- Booster = $230M
- Starship = $200
- Tanker (In-orbit refilling) = $130M

Launch Costs

- Methane cost = $400/Ton
- Oxygen cost = $160/Ton
- Super heavy + Starship use 3.510 Ton LOX and 989 Ton LCH4
- Total Propellant cost per launch = $960,000 (to orbit) + (In-Orbit Refill)
- Launch Site Costs = $200,000 per launch

Total Launch Cost per trip to mars = $62 M (For one starship)

Total Mission Costs

~$10B

LOX: Liquid Oxygen
LCH4: Liquid Methane

Additional information in Appendix F

[4-7,50-52]

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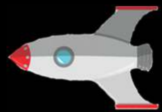

MoEs: Measures of Effectiveness

Ethical Considerations

- Astronauts' health and life
- Pollution of Earth
- Potential damage to Martian life if there is any
- Bringing Martian life (microbes) back to earth could wipe out life on earth

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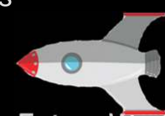

MoEs: Measures of Effectiveness

Conclusion

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In situ propellant production has a high potential to increase the short-term feasibility of the Mars exploration missions.

Based on my research, it's the best alternative for a mission to be launched before 2030.

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MoEs: Measures of Effectiveness

Recommendations for Future Work

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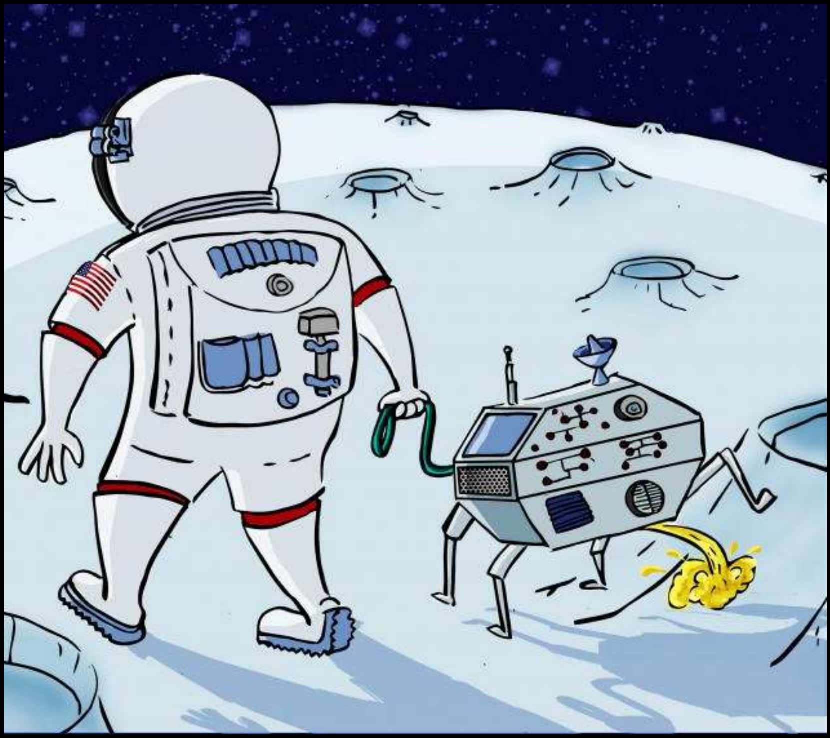
- Expansion of the model to include peripheral systems and subsystems
- Perform propellant production process simulations
- Perform research on Artificial Intelligence and Robotics
- Perform detailed design of systems and subsystems



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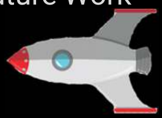

MoEs: Measures of Effectiveness

Learning Outcomes

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Systems Engineering

Working on this project has led to an increase in my knowledge and skills in:

- Space Exploration Missions
- Mars
- Orbit transfers
- Space Systems
- Rocket Engines
- Rocket Fuel
- System Modeling
- Research

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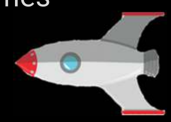

MoEs: Measures of Effectiveness

Acronyms

Loyola Marymount University Systems Engineering

AoA: Analysis of Alternatives

ISRU: In situ resource utilization

ISSP: In Situ Propellant Production

ISP: Specific Impulse

LOX: Liquid Oxygen

LCH4: Liquid Methane

MoE: Measure of Effectiveness

RP-1: Rocket Propellant One

SLS: Space Launch System

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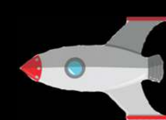

MoEs: Measures of Effectiveness

Appendix A
Additional Model Diagrams

MBSE Software

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Activity Diagram

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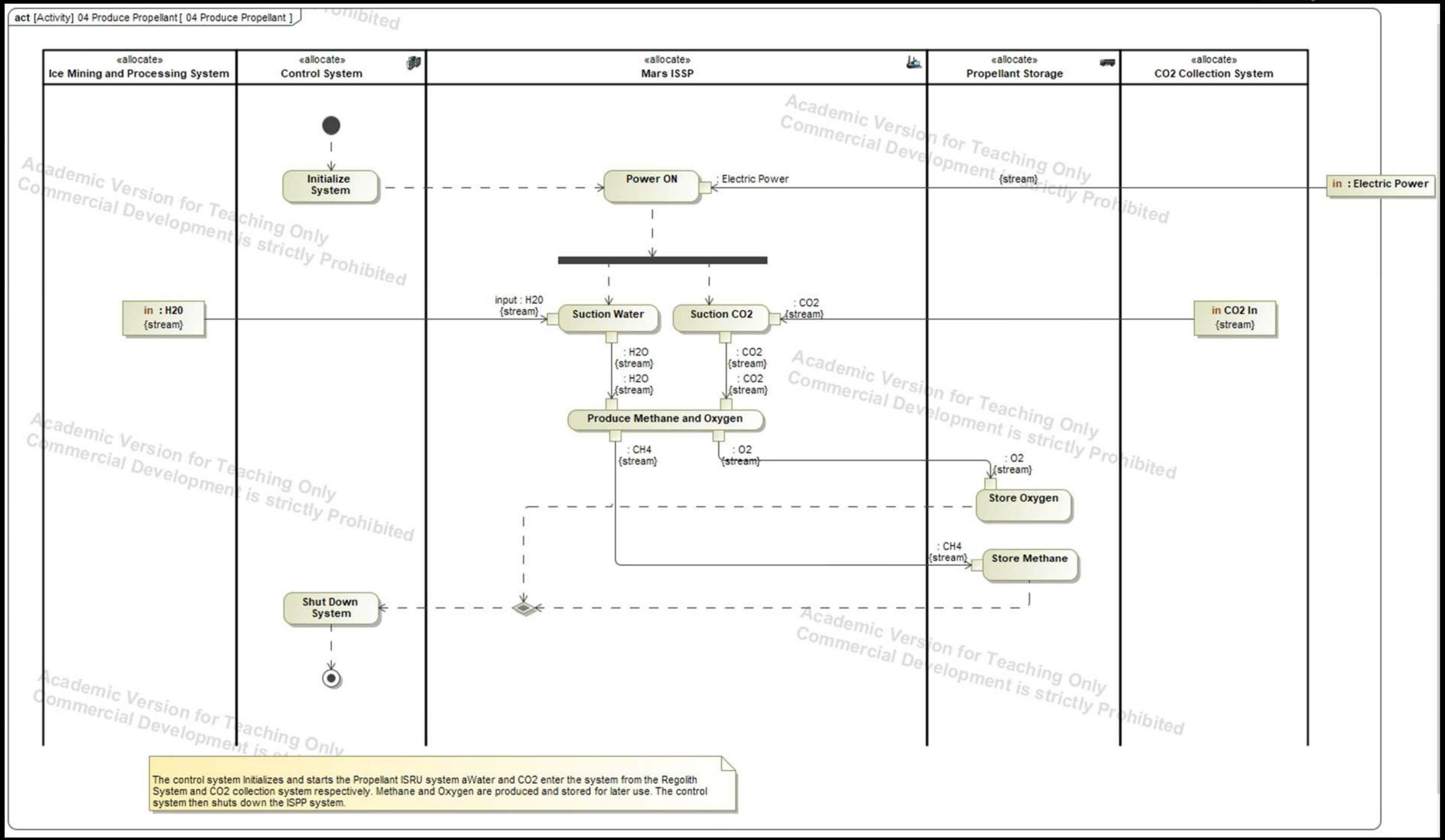

Activity Diagram

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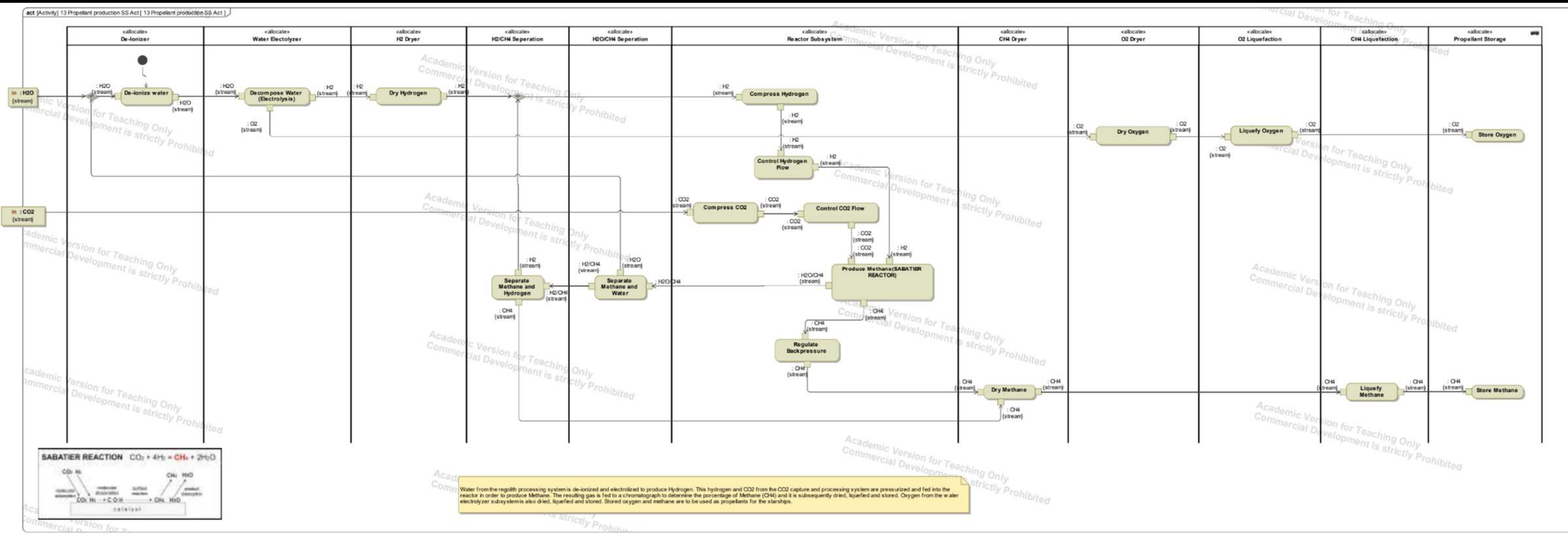

Parametric Diagram

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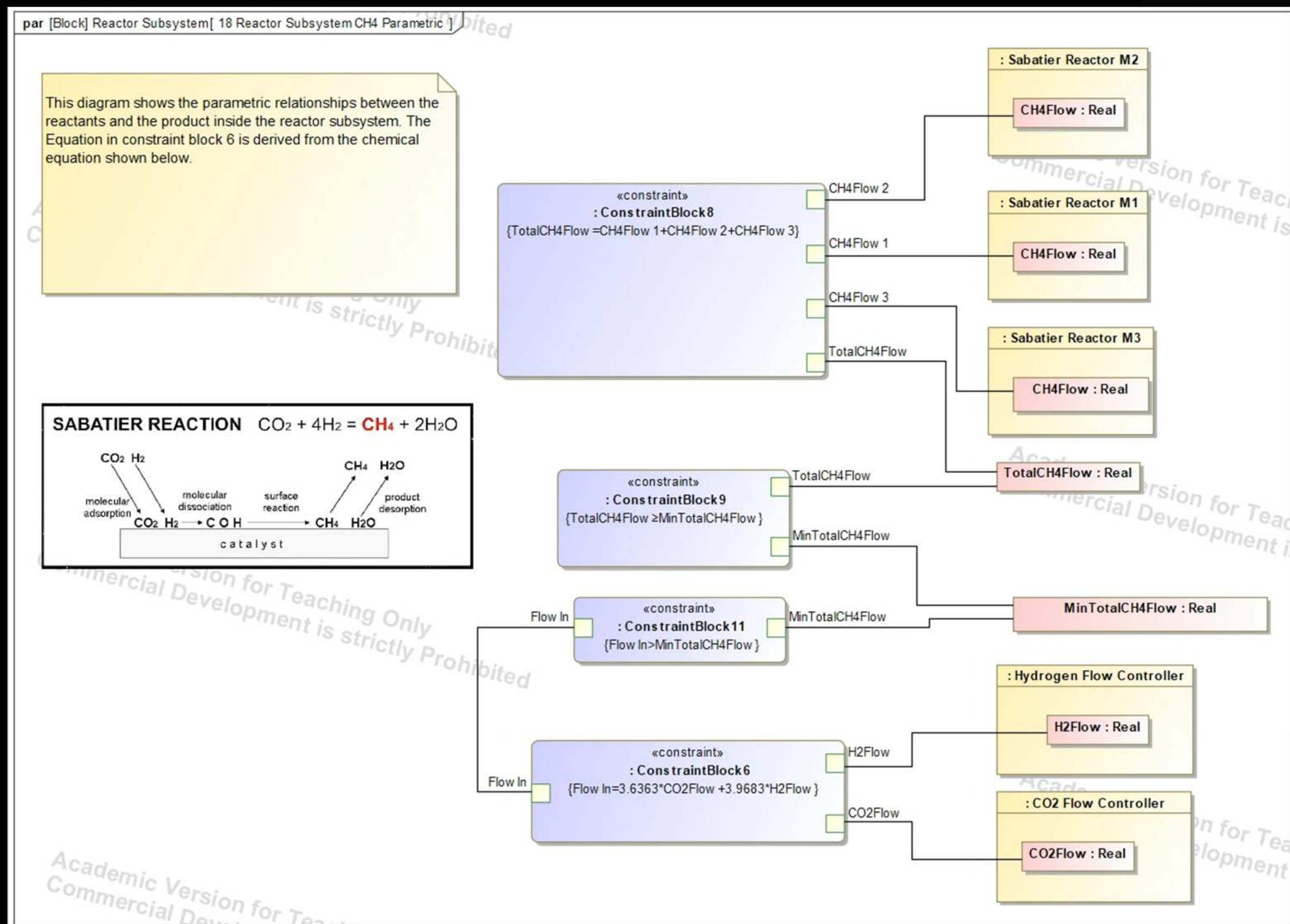
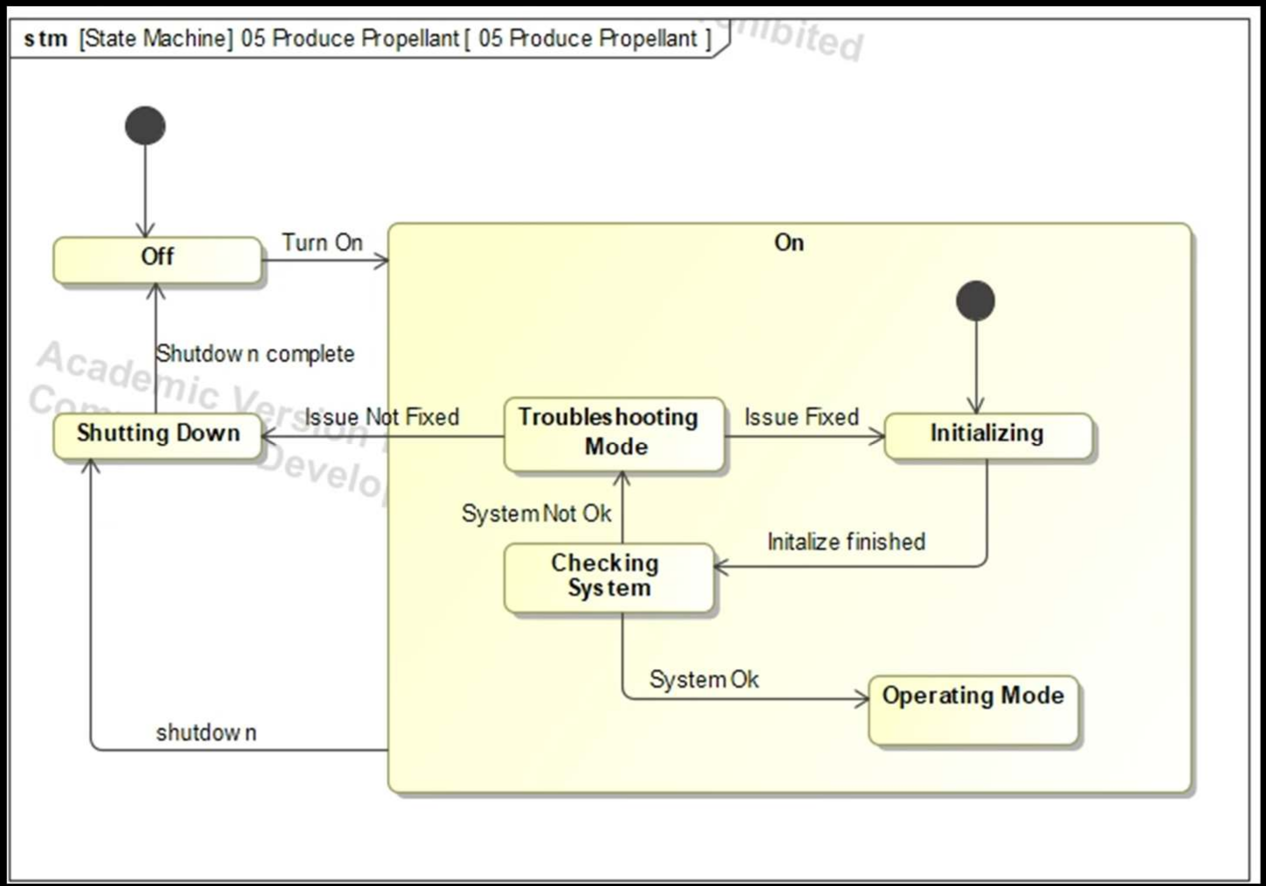


State Machine Diagram



Stakeholders Needs

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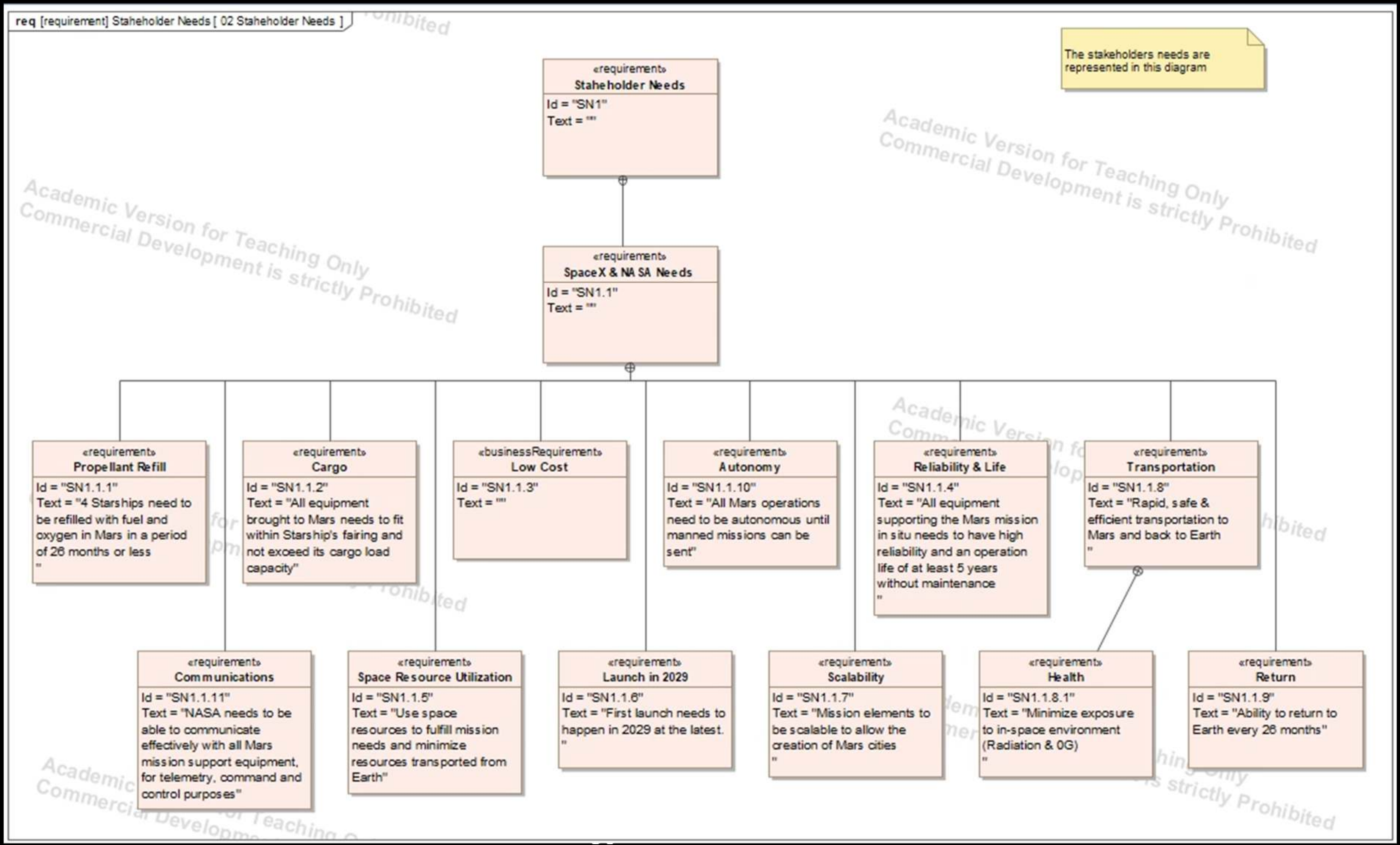
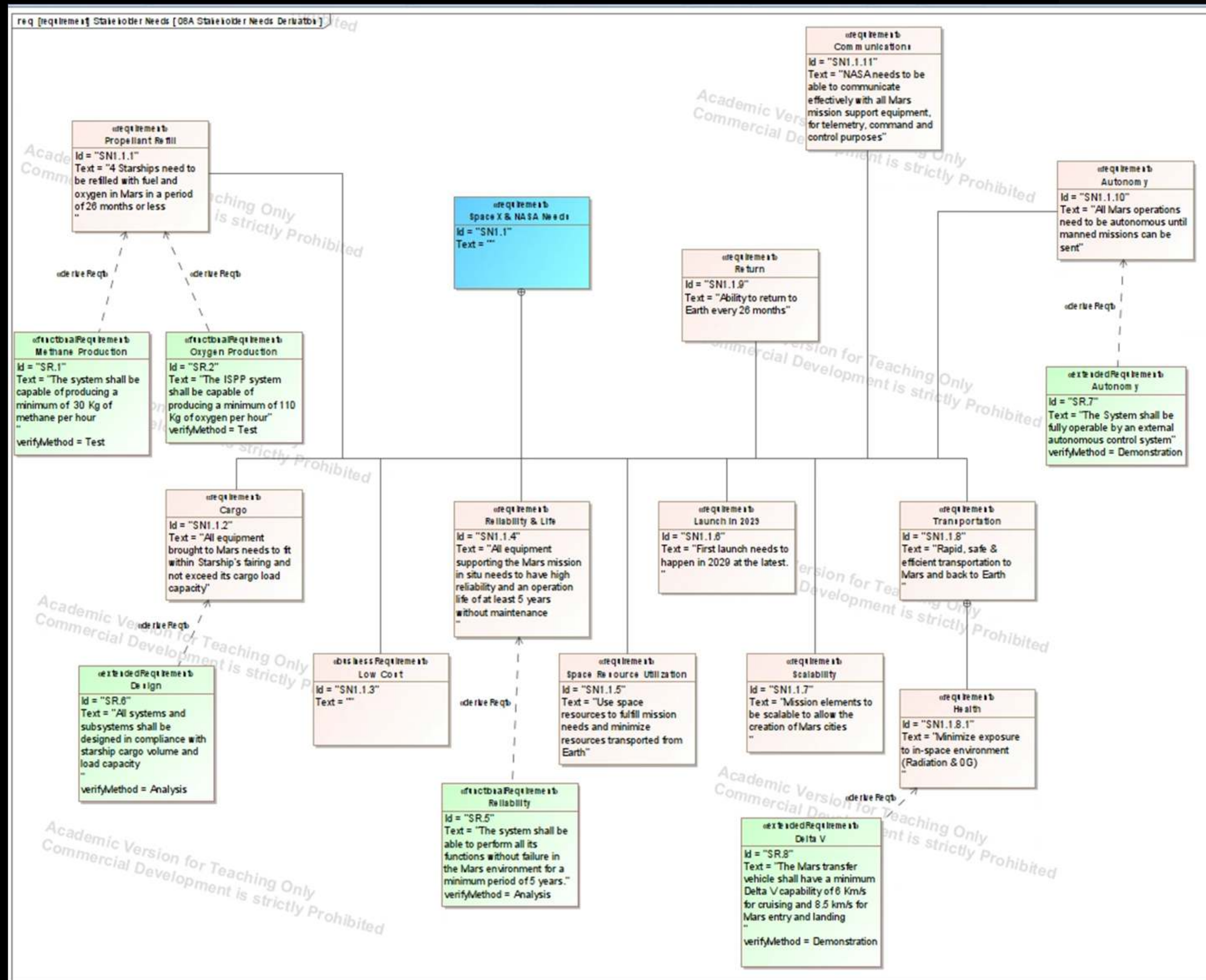


Requirements – ISSP System



Derived Requirements Matrix

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Legend
↗ DeriveReqt

		1 Stakeholder Needs / SN1 Staheholder Needs / SN1.1 SpaceX & NASA Needs: SN1.1.1 Propellant Refill	SN1.1.2 Cargo	SN1.1.3 Low Cost	SN1.1.4 Reliability & Life	SN1.1.5 Space Resource Utilization	SN1.1.6 Launch in 2029	SN1.1.7 Scalability	SN1.1.8 Transportation	SN1.1.8.1 Health	SN1.1.9 Return	SN1.1.10 Autonomy	SN1.1.11 Communications
1 System Requirements		4	1		1					1		1	
SR ISPP System Requirements													
SR.1 Methane Production	1	↗											
SR.2 Oxygen Production	1	↗											
SR.3 Ice extraction	1	↗											
SR.4 CO2 Extraction	1	↗											
SR.5 Reliability	1				↗								
SR.6 Design	1		↗										
SR.7 Autonomy	1											↗	
SR.8 Delta V	1									↗			

Requirement Relations

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Specification of Functional Requirement Methane Production

Functional Requirement relationships to other elements

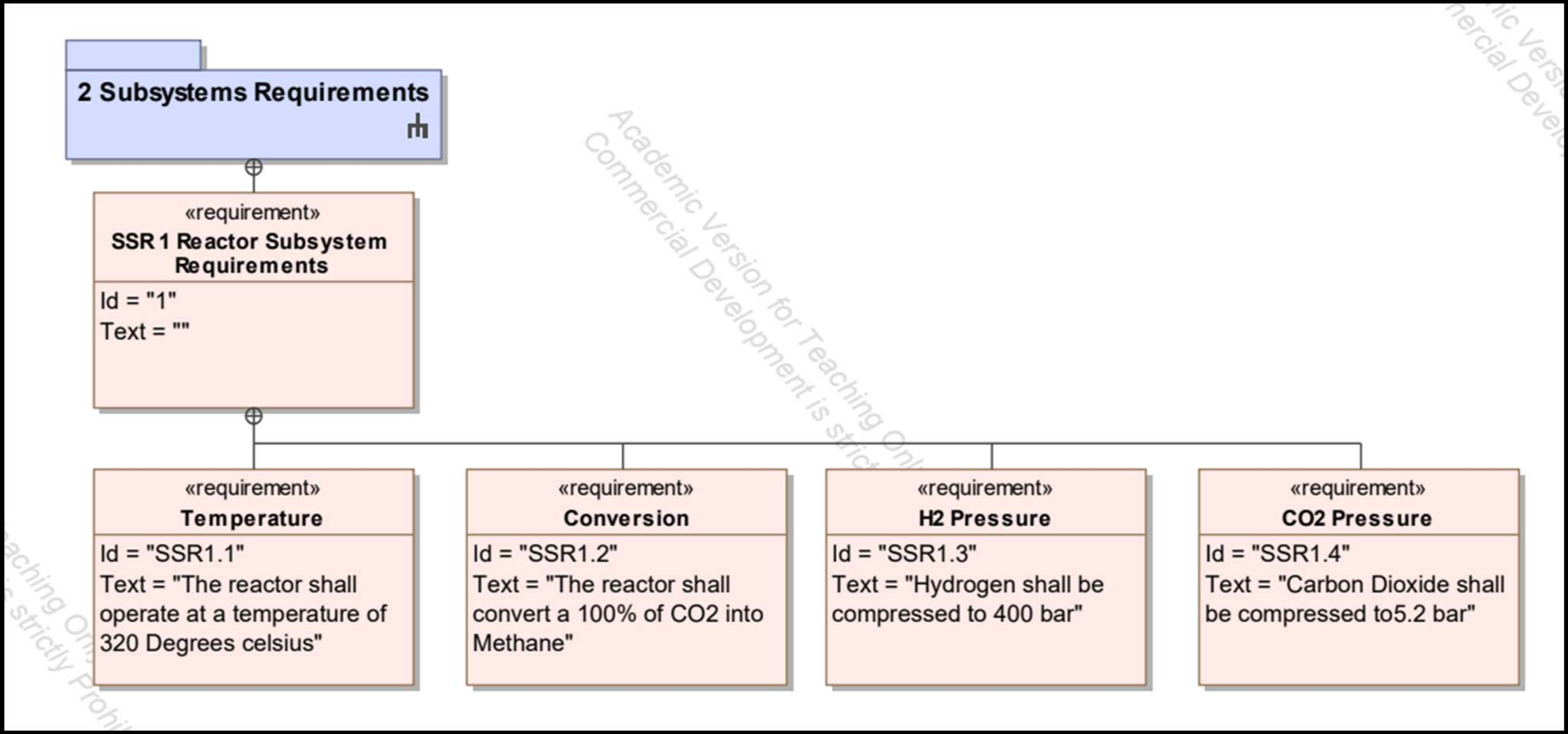
The Relations node contains a list of relationships which relate the selected Functional Requirement with other elements. Create outgoing or incoming relationships to this Functional Requirement. Use the relationship specification button to edit properties of a specific relationship.

- Methane Production
  - Usage in Diagrams
  - Documentation/Comments
  - Navigation/Hyperlinks
  - Constraints
  - Sub Requirements
  - Relations
  - Tags
  - Traceability
  - Language Properties

Relations

Name	Element	Direction	Element
Refine			
	SR.1 Methane Production [2 Solution ...	←- - - - -	Produce Methane(SABATIER REACTOR.
	SR.1 Methane Production [2 Solution ...	←- - - - -	Produce Methane(context Mars ISSP) ...
	SR.1 Methane Production [2 Solution ...	←- - - - -	CH4 Production [1 Problem Domain::1 .
	SR.1 Methane Production [2 Solution ...	←- - - - -	MinTotalCH4Flow : Real = 30.0 [2 Solu...
DeriveReqt			
	SR.1 Methane Production [2 Solution ...	← –	SSR1.4 CO2 Pressure [2 Solution Doma...
	SR.1 Methane Production [2 Solution ...	← –	SSR1.3 H2 Pressure [2 Solution Domai...
	SR.1 Methane Production [2 Solution ...	– →	SN1.1.1 Propellant Refill [1 Problem D...
	SR.1 Methane Production [2 Solution ...	← –	SSR1.2 Conversion [2 Solution Domain...
	SR.1 Methane Production [2 Solution ...	← –	SSR1.1 Temperature [2 Solution Doma...

Requirements – Reactor Subsystem



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Appendix B
Measures of Effectiveness

Measures of Effectiveness

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- **Technology Readiness Level (TRL): D**egree of maturity of the critical technology elements necessary to implement a solution. High TRL reduces cost and implementation time.
- **Earth Mars Transfer Time:** Amount of time it takes to travel from Earth to Mars or from Mars to Earth. It varies with different propulsion systems. A shorter transfer time also reduces the exposure to the in-space environment (Radiation and 0G).
- **Reusability:** The system's ability to be used multiple times during the mission or for multiple missions and still be capable of fulfilling its objective. It reduces cost and risk and improves mission continuity.
- **Cost:** Amount of money necessary to develop and operate the system.
- **Scalability:** The system's ability to be augmented in size and capabilities. A scalable architecture increases the feasibility of expanding the initial Mars outposts into cities in the future.

TRL: Technology Readiness Level

TRL

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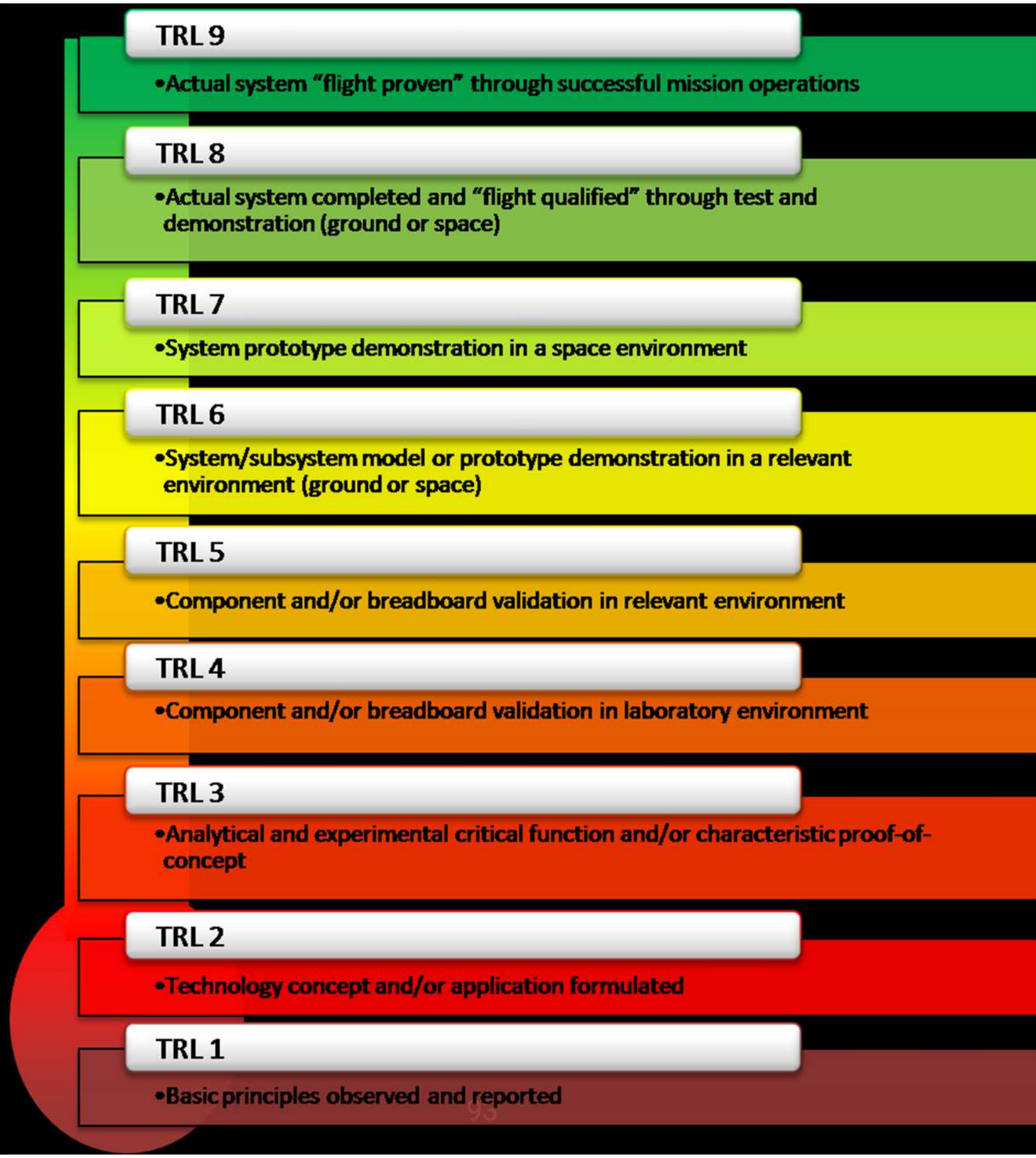

TRL: Technology Readiness Level

Technology Readiness Level (TRL)

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Level	Definition	TRL Description
1	Basic principles observed and reported	Scientific research begins to be translated into applied research and development.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies.
4	Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together.
5	Component and/or breadboard validation in a relevant environment.	The basic technological components are integrated with reasonably realistic supporting elements.
6	System/subsystem model or prototype demonstration in a relevant environment.	A representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment.
7	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system.
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions.
9	Actual system has proven through successful mission operations.	The actual application of the technology in its final form and under mission conditions.

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Appendix C
Alternatives

Alternatives

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In Situ Production of Fuel and oxygen

Strengths

- Long term cost and operational advantages
- Reduce the number of launches
- Enables Space Commercialization
- Abundance of CO2 in the atmosphere
- Estimated abundance of water ice

Weaknesses

- Challenging implementation
- Extreme operational conditions
- No personnel available to perform maintenance and repairs
- Water mining could present complex challenges

Alternatives

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Importing propellant to Mars from other solar bodies

Strengths

- High quantities of gases from different sources
- No need to produce; just collect

Weaknesses

- Challenging implementation
- Long travel time
- Not feasible in the short term
- High cost

Alternatives

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Alternative propulsion systems (Non-chemical, Advanced Propulsion)

Strengths

- Non-Chemical propulsion sub-system could be capable of bringing the starships back to Earth when it has little or no propellant left.
- Generally more efficient than chemical propulsion (higher ISP).

Weaknesses

- Not enough thrust to launch from earth (overcome Earth's gravity)
- The return trip can take a longer time.

Alternatives

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Hybrid propulsion systems (Chemical + non-chemical)

Strengths

- Non-Chemical propulsion sub-system could be capable of bringing the starships back to Earth when it has little or no propellant left.
- Higher ISP

Weaknesses

- Current non-chemical propulsion technology has lower thrust, so the return trip to Earth time can take a longer time

Alternatives

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Propellant Depots in Mars orbit

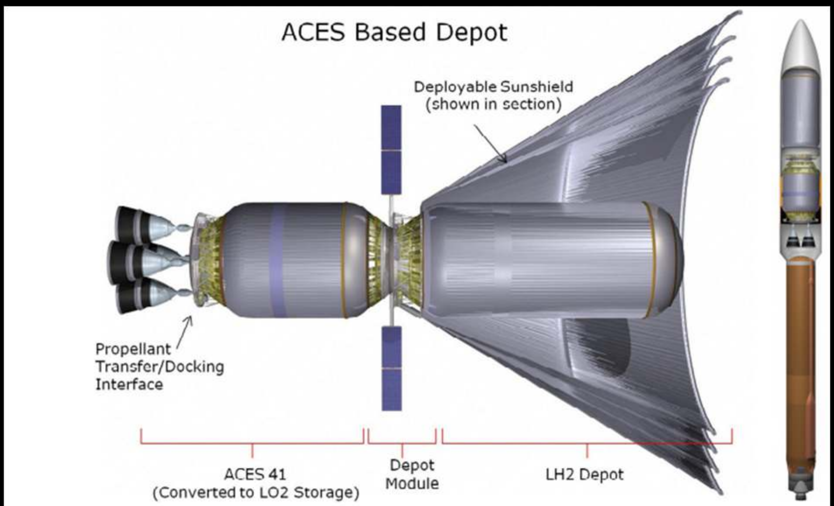
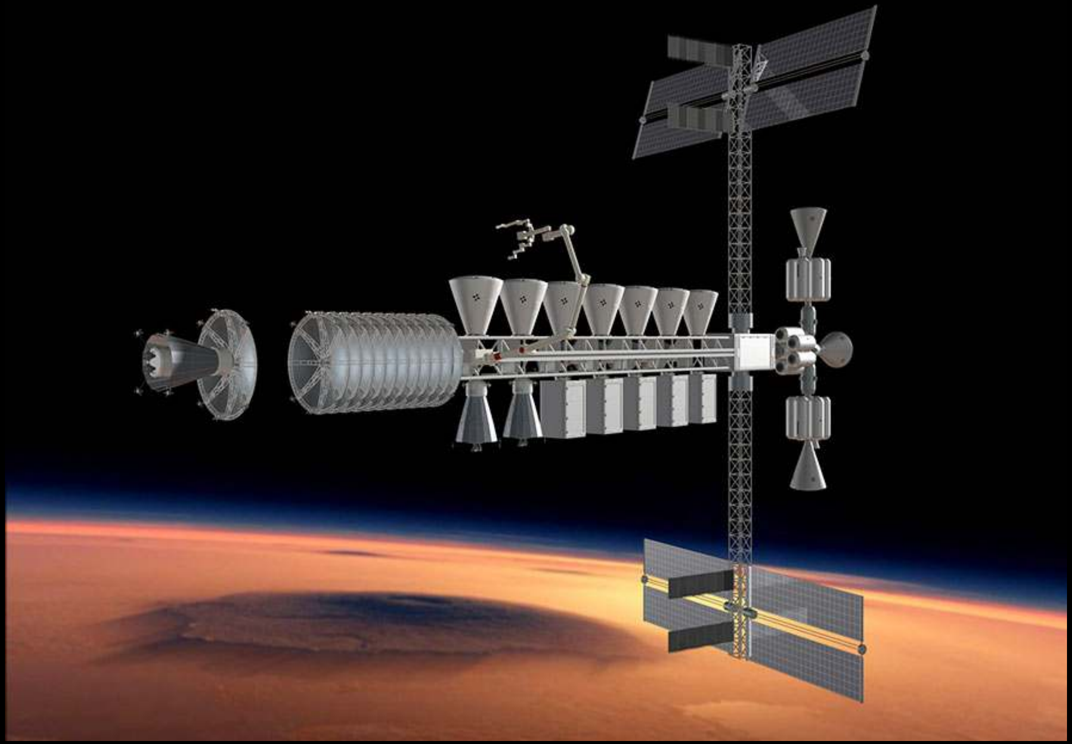


Figure 10. A Single Launch, Dual-Fluid Propellant Depot. Credit ULA



Alternatives

Propellant Depots in Mars orbit

Strengths

- Would enable Mars to be a strategic stop for trips between Earth and other planets
- Would provide economic and logistics benefits to a Mars colony
- Would facilitate the transfer to other solar bodies

Weaknesses

- Needs propellant to come from somewhere (not a source)
- Not Long development time, so not a short-term solution.

Alternatives

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Mega Spaceships

Strengths

- High cargo and passenger capacity
- Could serve as a temporary Mars habitat
- Could be used for long-distance missions

Weaknesses

- Long time to be designed and developed
- Very high cost
- Not likely to be able to launch from Earth with the current technology
- Higher loads and vibrations due to size

Appendix D
Additional Methodology Slides

Methodology

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- Define Problem Statement
- Define Scope
- Define stakeholders and their needs
- Research current literature
- Define and assess Measures of Effectiveness
- Talk to subject matter experts
- Identify and Asses Alternatives
- Develop Concept of Operations
- Develop System Architecture
- Develop Requirements
- Define Subsystems
- Develop a System model
- Develop Verification and Validation Plans
- Perform Risk and Opportunities Analysis
- Develop Cost Estimates
- Develop Implementation Plan

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Appendix E
Risk Analysis

Risk Analysis

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Type: internal –Technical

ID: R1

Title: Chemical Process Failure

Description: Chemical process involved in producing Methane and Oxygen fails due to equipment malfunction.

Original Assessment
Probability = Possible
Impact = Catastrophic

Mitigation: Design the chemical reactor subsystem with full redundancy.

Assessment after mitigation
Probability = Highly Unlikely
Impact = Moderate

Risk Analysis

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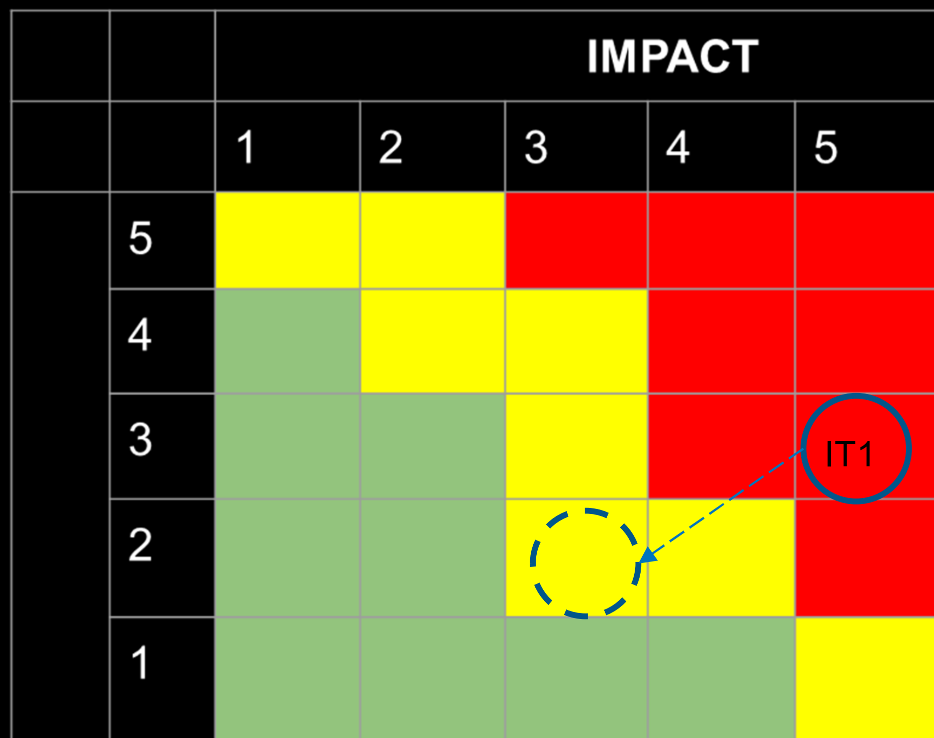
R1 - Chemical Process Failure



Risk Analysis

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Type: internal –Technical

ID: R2

Title: Loss of Power

Description: Power supply temporarily or permanently interrupted.

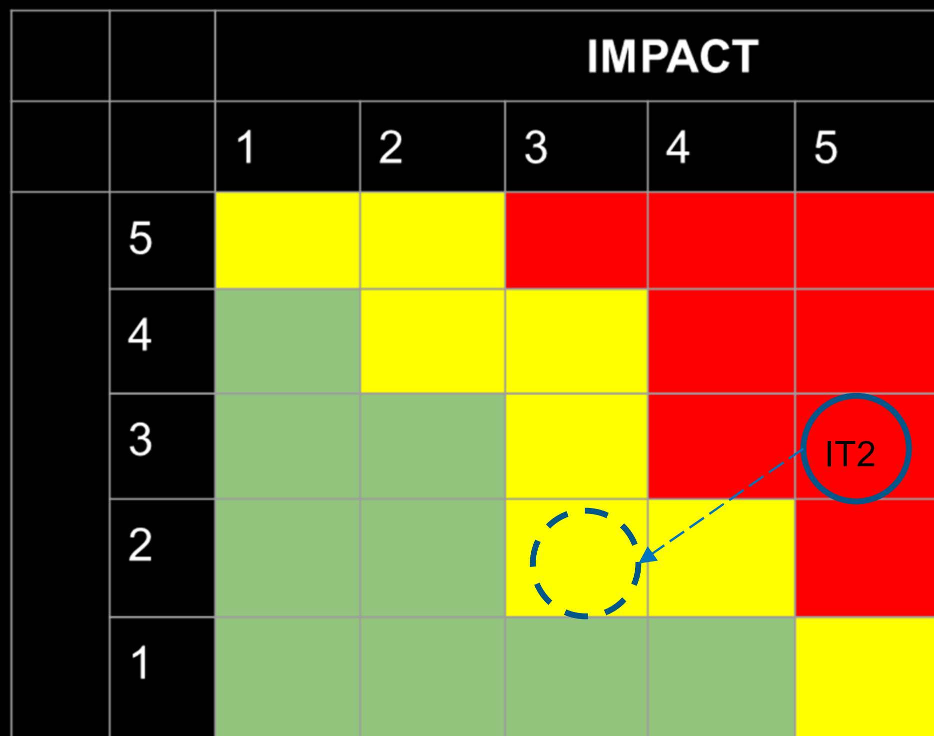
Original Assessment
Probability = Possible
Impact = Catastrophic

Mitigation: Design the power system with full redundancy and have an alternate power source to increase reliability further.

Assessment after mitigation
Probability = Unlikely
Impact = Moderate

Risk Analysis

R2 - Loss of Power



Risk Analysis

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Type: internal –Non-Technical

ID: R3

Title: Missing launch window (20 DAYS)

Description: Delays in production or testing could cause a schedule slip that can compromise the 20-day launch window.

Original Assessment
Probability = Likely
Impact = Major

Mitigation: Plan to have enough time buffer to absorb delays in production or testing and still have the hardware ready to launch on time.

- Have contingency testing facilities
- Have multiple suppliers

Assessment after mitigation
Probability = Unlikely
Impact = Major

Risk Analysis

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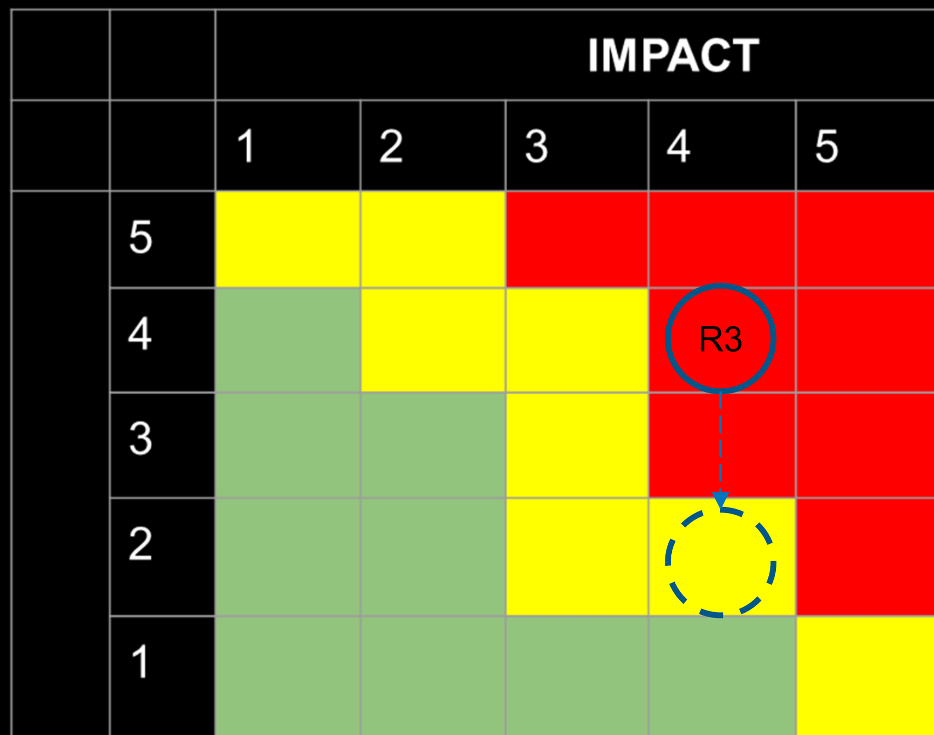
R3 - Missing launch window

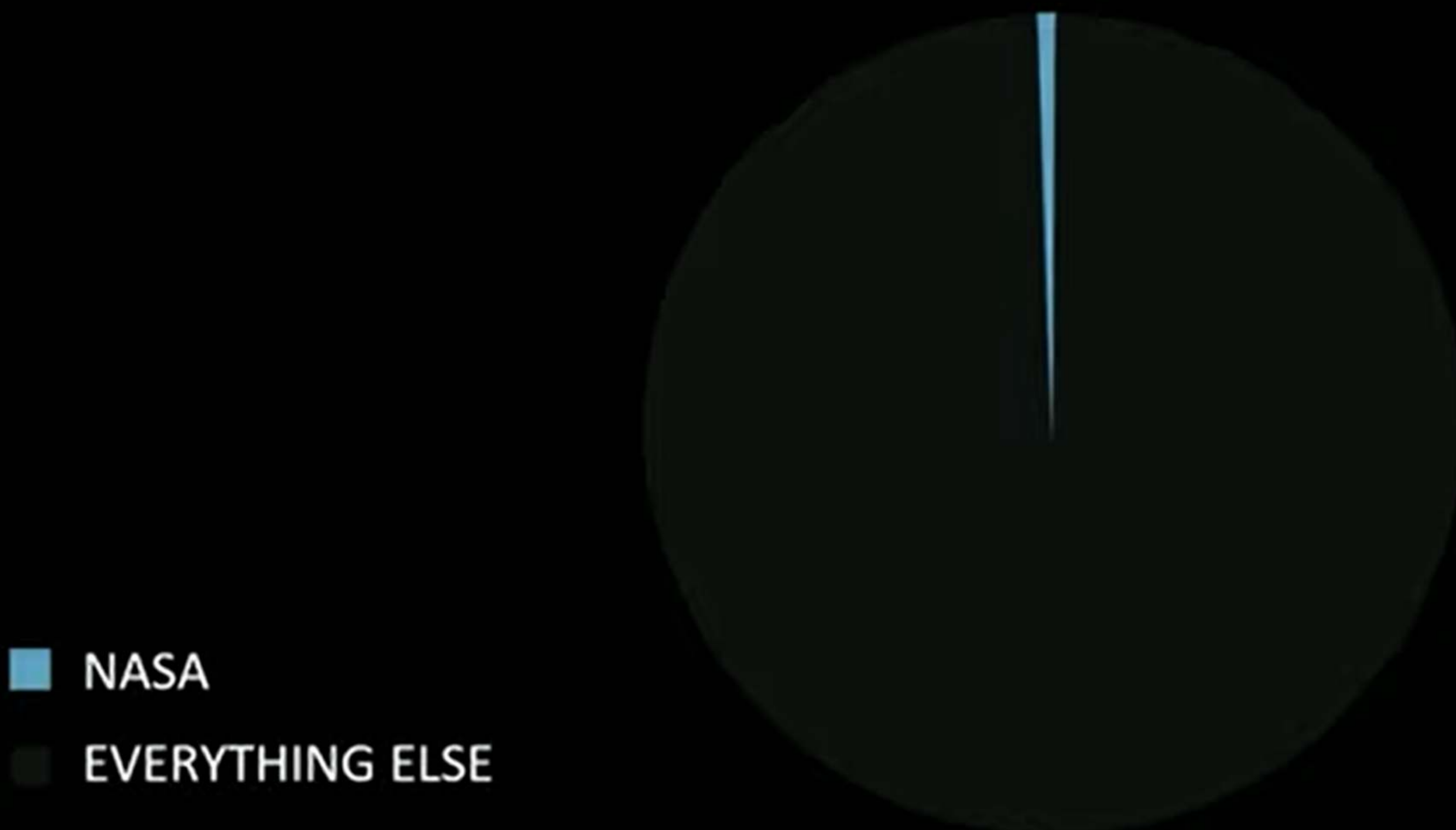


Appendix F
Additional Cost Analysis Slides

EVERYDAY ASTRONAUT

	Merlin	RD-180	F-1	Raptor	BE-4	RS-25
Price *(2019 dollars)*	**< $1M**	$25M	$30M	~ $2M	~ $8M	>$50M
Reusability	10 flights	No	No	**50 flights**	25 flights	19 flights
$ / kN Ratio	$1,170 : 1kN	$6,527 : 1kN	$4,431 : 1kN	**~$1,000 : 1kN**	~$3,333 : 1kN	$26,881 : 1kN
Potential cost *(per flight)*	$117 : 1kN	$6,527 : 1kN	$4,431 : 1kN	**~$20 : 1kN**	~$133 : 1kN	$1,414 : 1kN
Flight Record	71	79	17	Yet to fly	Yet to fly	**135**
Reliability	99.9%	100%	**100%**	N/A	N/A	>99.5%

FY2020: 0.36% OF U.S. BUDGET COMMITTED TO SPACE



IAC 2016 - Late Breaking News: Making Humans a Multiplanetary Species

COSTS

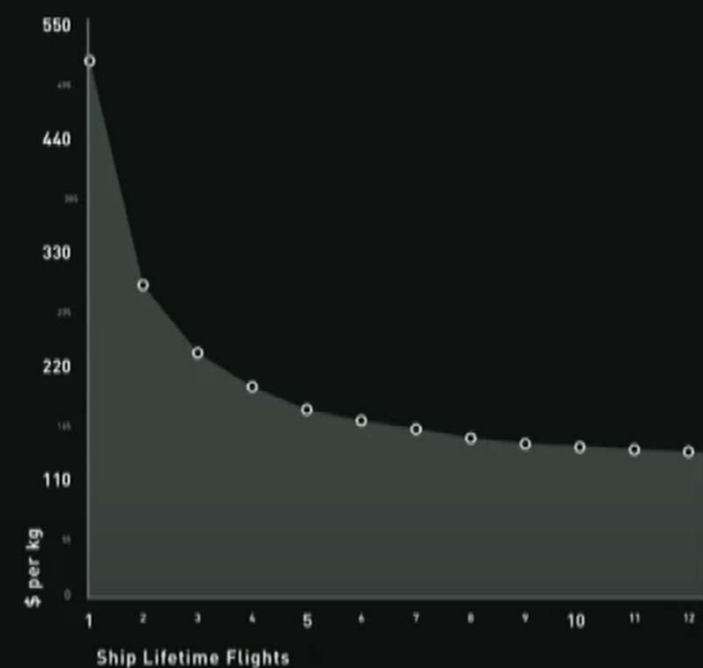
With full reuse, our overall architecture enables significant reduction in cost to Mars

	BOOSTER	TANKER	SHIP
FABRICATION COST	$230M	$130M	$200M
LIFETIME LAUNCHES	1,000	100	12
LAUNCHES PER MARS TRIP	6	5	1
AVERAGE MAINTENANCE COST PER USE	$0.2M	$0.5M	$10M
TOTAL COST PER ONE MARS TRIP (Amortization, Propellant, Maintenance)	$11M	$8M	$43

Cost Of Propellant: $168/t
Launch Site Costs: $200,000/launch
Discount Rate: 5%

Sum Of Costs: $62 M
Cargo Delivered: 450 T

Cost/ton to Mars: <$140,000



Appendix G
Additional Background Slides

Why Starship?

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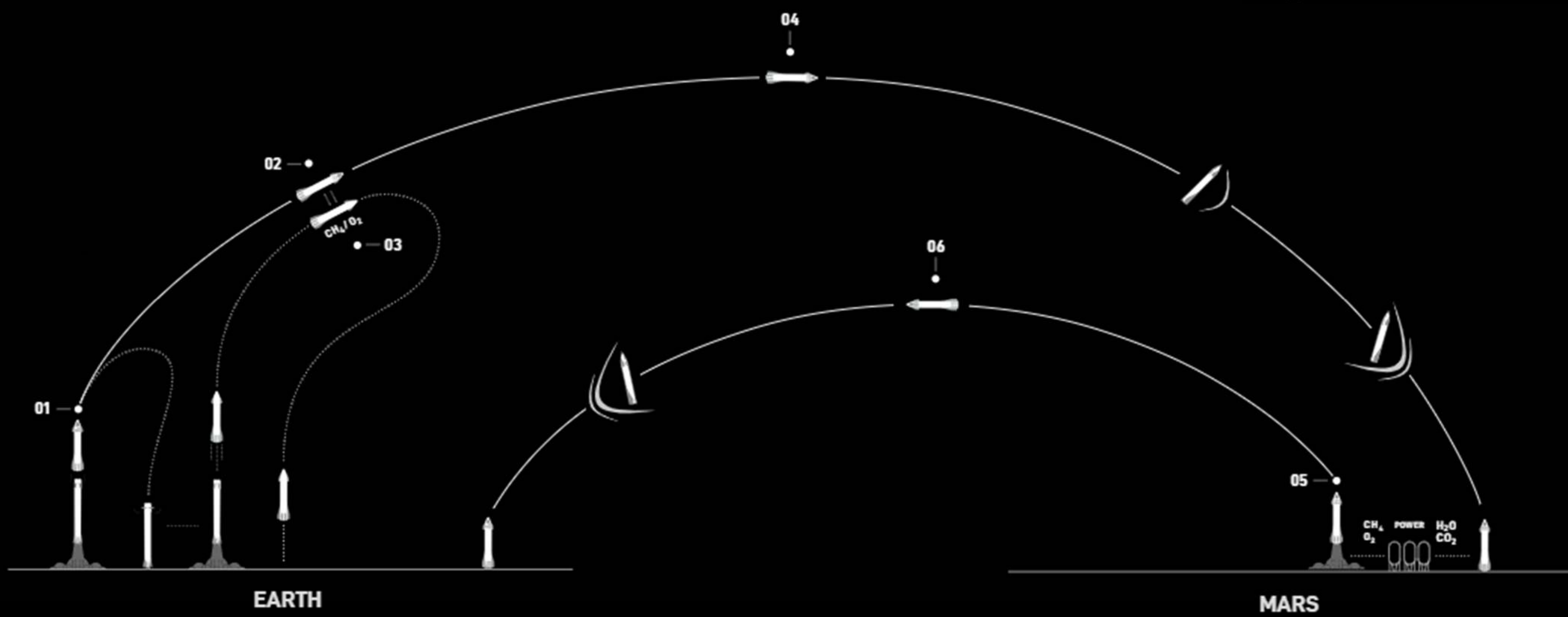


01. LAUNCH & BOOSTER RETURN

02. SHIP ARRIVES IN EARTH ORBIT

03. TANKERS REFILL SHIP AND RETURN TO EARTH

04. REFILLED SHIP TRAVELS TO MARS

05. SHIP REFILLED ON MARS USING LOCAL RESOURCES

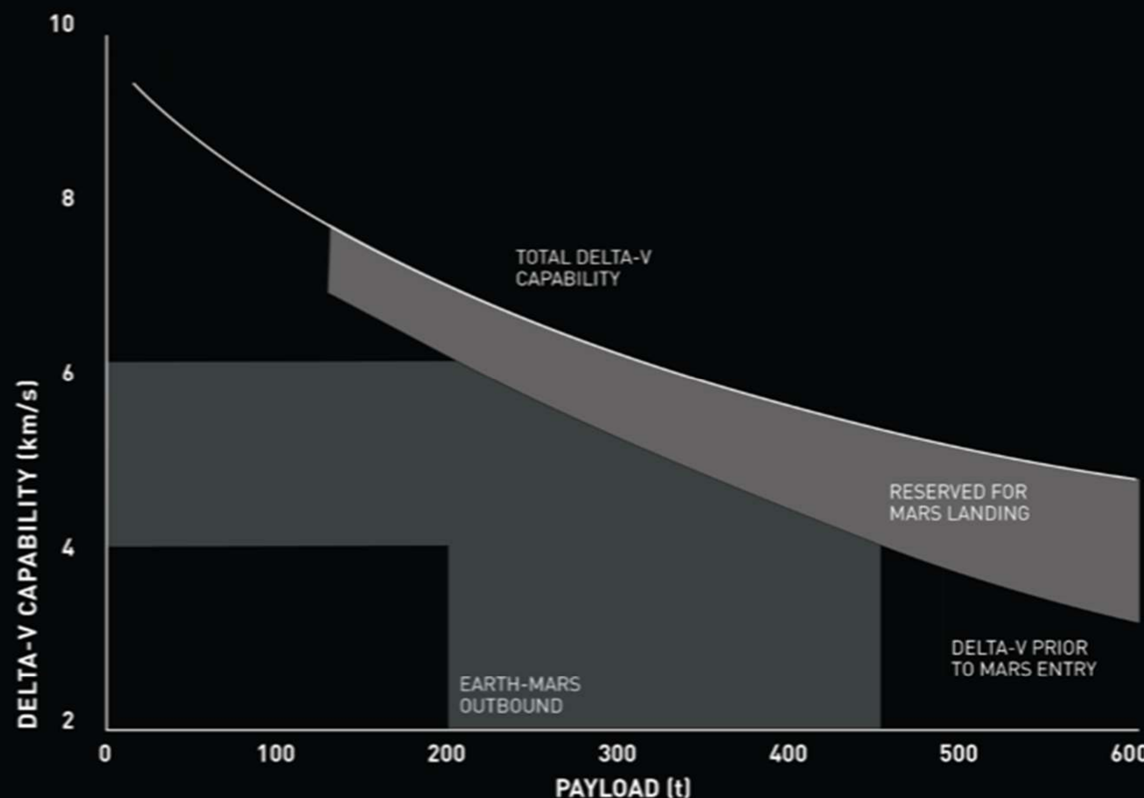
06. SHIP PERFORMS MARS ASCEND & DIRECT RETURN TO EARTH

SHIP CAPACITY WITH FULL TANKS

EARTH-MARS TRANSIT TIME (DAYS)
BY MISSION OPPORTUNITY

YEAR	TRIP TIME (d)
2020	90
2022	120
2024	140
2027	150
2029	140
2031	110
2033	90
2035	80
2037	100
AVERAGE	**115**

TMI DELTA V: 6 km/s
Mars Entry Velocity: 8.5 km/s



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Q&A

Backup Slides

Caveats & Limitations

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- Limited time and resources
- Limited knowledge of the technology
- Limited feedback from stakeholders

ISRU Capabilities for Human Exploration of the Moon and Mars

Resource Prospecting – Looking for Water

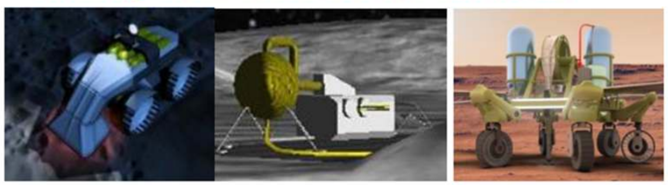
Hydrated minerals & subsurface ice on Mars

Resource Information

Resource Information

Mining Polar Water & Volatiles

Mining near surface ice on Mars



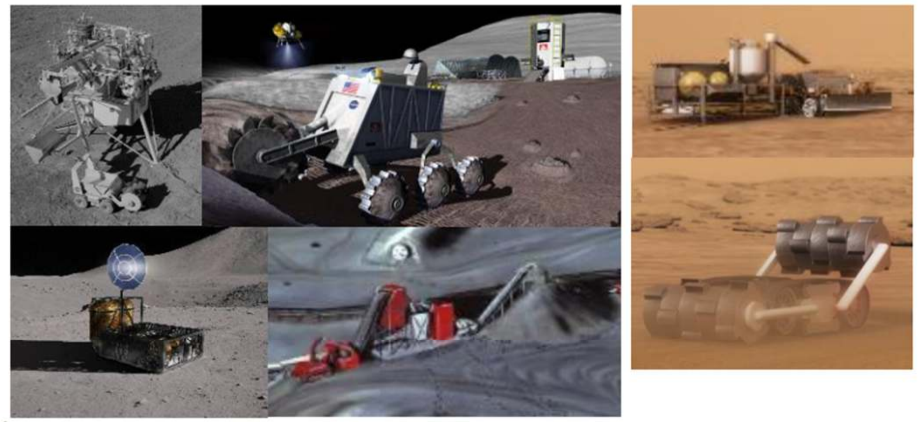
Water, Volatiles to Make Plastics

Civil Engineering & Surface Construction

Civil Engineering and Surface Construction

Excavation & Regolith Processing for O_2 Production

Excavation & Processing for H_2O Extraction

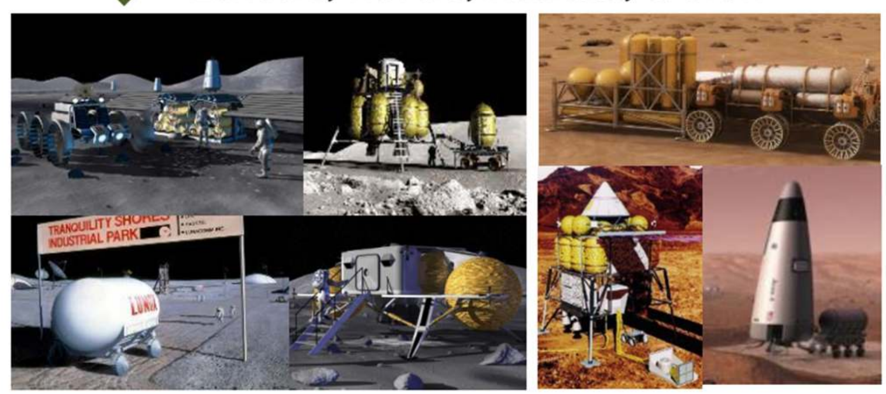


Water, O_2, H_2

O_2

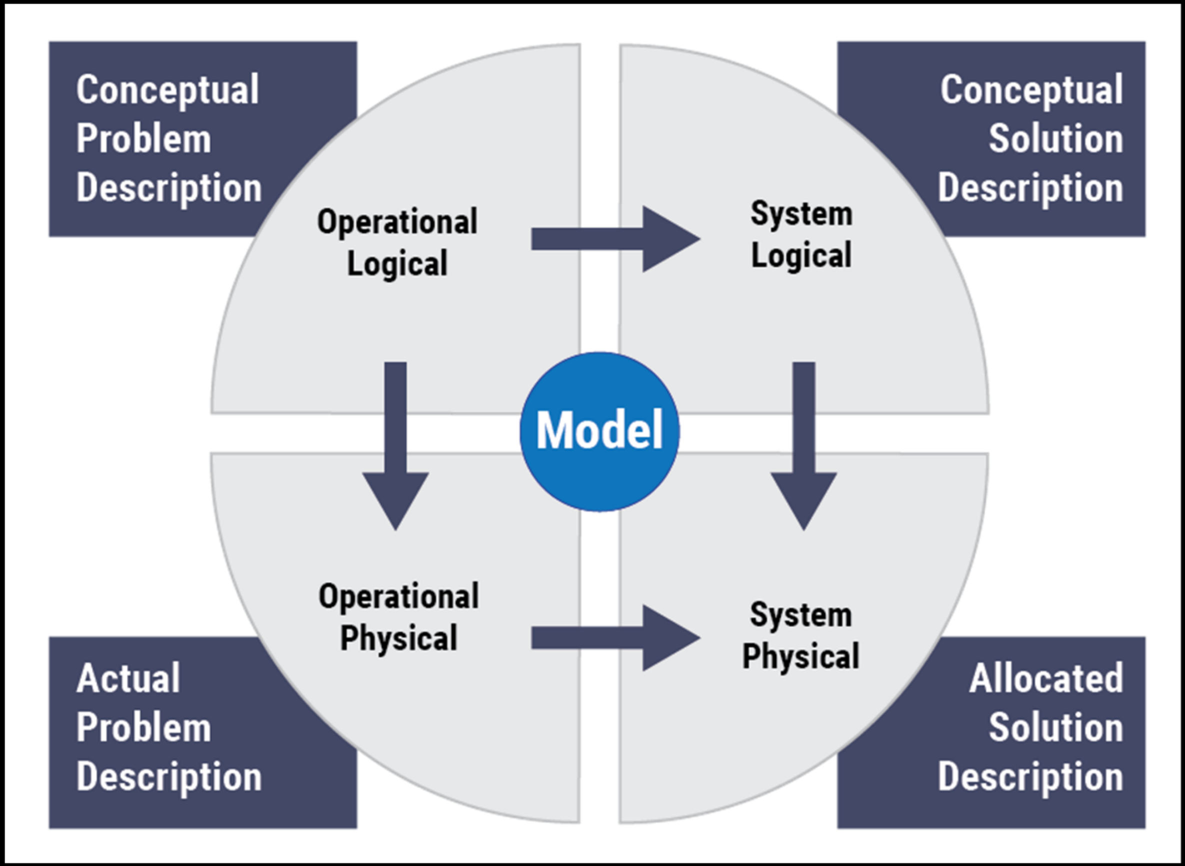
Regolith, O_2, Metals, Plastics, Binders

ISRU Consumable Users: Landers, Rovers, Habitats, & Crew



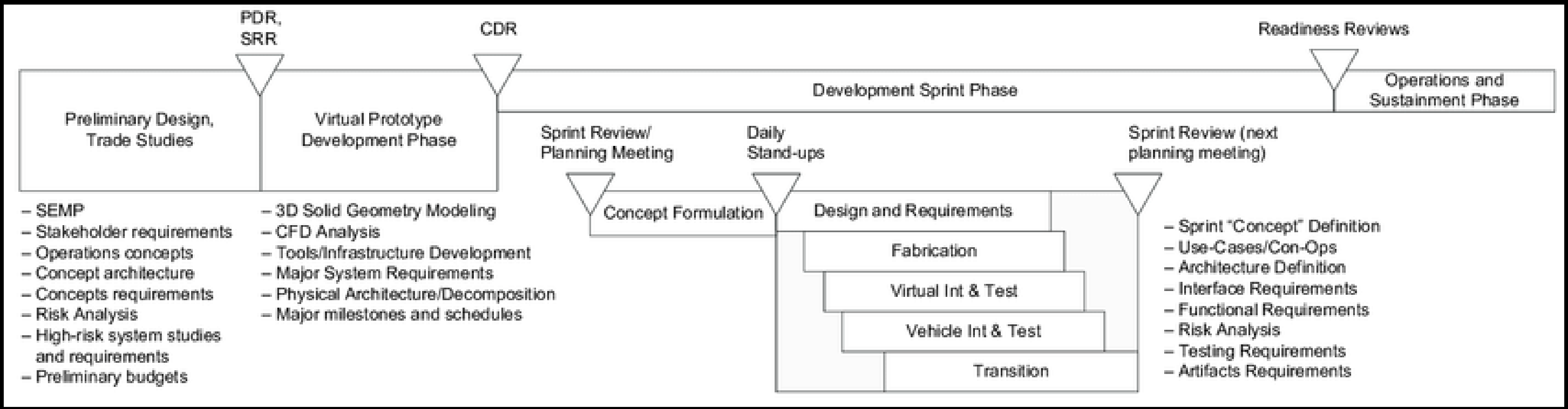
Methodology

Loyola Marymount University
Systems Engineering



Methodology

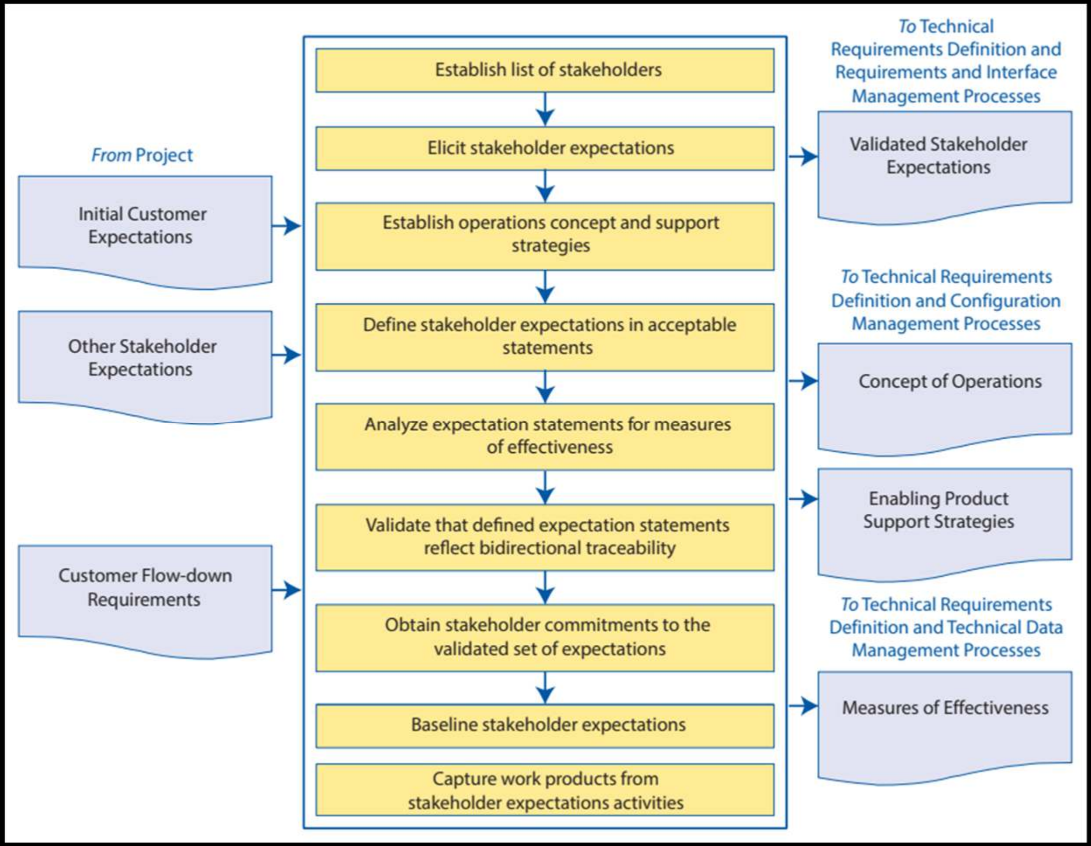
Loyola Marymount University Systems Engineering



NASA systems engineering lifecycle phases

Methodology

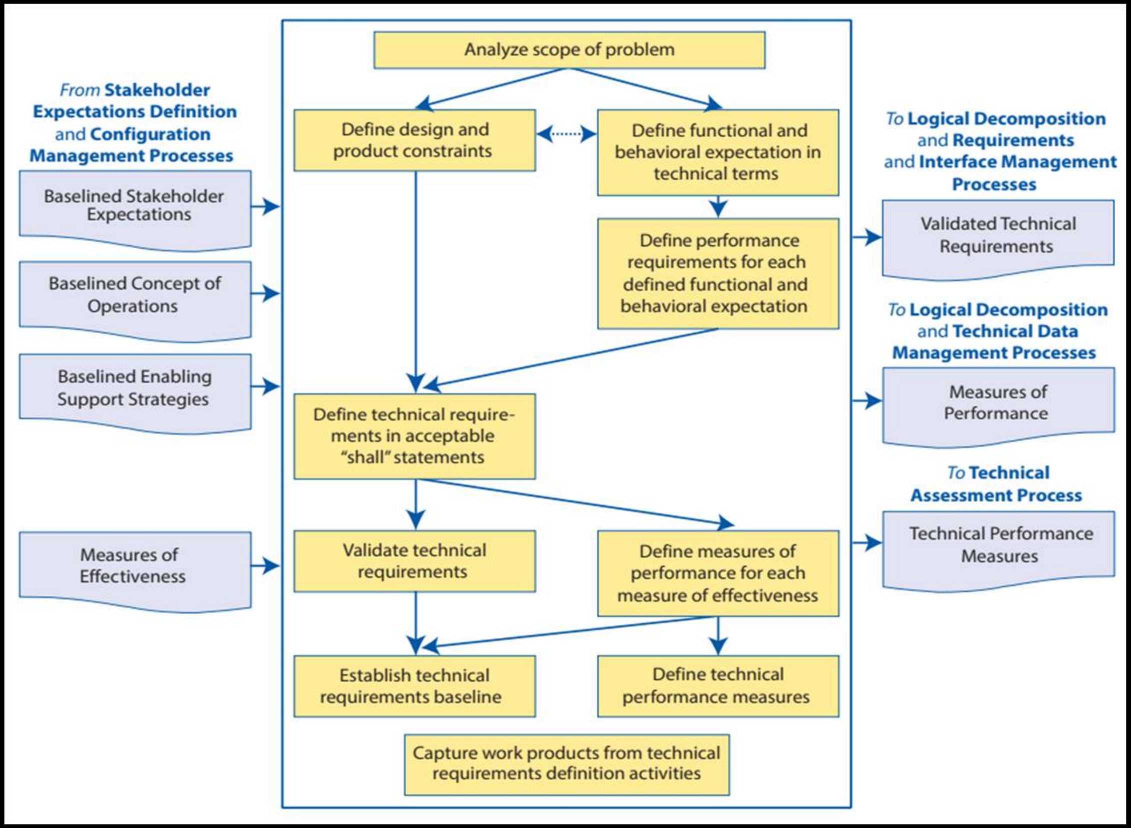
Loyola Marymount University
Systems Engineering



Stakeholders expectations definition process

Methodology

Loyola Marymount University Systems Engineering



Technical requirements definition process