Innovation Challenges in NASA's Planetary Program and a Policy Framework for Sustainable and Equitable Space Resource Utilization

by

Maya Nasr

B.S., Massachusetts Institute of Technology, 2018
M.S., Massachusetts Institute of Technology, 2021

Submitted to the Department of Aeronautics and Astronautics
in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY IN AERONAUTICS AND ASTRONAUTICS

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2023

Authored by: Maya Nasr
Department of Aeronautics and Astronautics
April 14, 2023

Certified by: Jeffrey A. Hoffman
Professor of the Practice, Aeronautics and Astronautics
Thesis Supervisor

Certified by: Donald Rapp
NASA JPL-Caltech (Retired)
Thesis Supervisor

Certified by: Tanja Masson-Zwaan
Assistant Professor, Leiden University
Thesis Supervisor

Certified by: Dava Newman
Apollo Program Professor, Aeronautics and Astronautics
Thesis Supervisor

Accepted by: Jonathan P. How
R. C. Maclaurin Professor of Aeronautics and Astronautics
Chair, Graduate Program Committee

Innovation Challenges in NASA's Planetary Program and a Policy Framework for Sustainable and Equitable Space Resource Utilization

by

Maya Nasr

Submitted to the Department of Aeronautics and Astronautics
on April 14, 2023 in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy in
Aeronautics and Astronautics

Abstract

The overall goal of this research is to systematically study planetary technology innovation, its challenges, and paths forward in the space sector, from institutional, strategic, policy and legal vantage points. Part I of this thesis delves into the challenges and opportunities for innovation in planetary technology at NASA. Six technology case studies were analyzed to understand NASA's enterprise architecture and its technology investment, development, and maturation frameworks, uncovering management and program challenges for efficient development and integration of innovative planetary technologies. The research identified policy and structural challenges and cultural challenges, highlighting the need for a fundamental shift in philosophy to incorporate new technology and risk into call for proposals. The research also assessed the difficulties faced by NASA's Jet Propulsion Laboratory (JPL) and suggested changes to its enterprise architecture. The Chaotic 2.0 architecture was found to be the most flexible and a pain point analysis conducted. An implementation strategy was proposed, and future-proofing analysis conducted to outline future phases of JPL's enterprise architecture. Overall, the research provided valuable insights and recommendations for enhancing technology innovation and management within NASA and the broader space sector.

Part II of this thesis proposes a sustainable and equitable policy framework for space exploration and natural resource utilization. The research reviewed existing policies, laws, and guidelines, identifying gaps and inadequacies for space resource governance. Drawing from lessons learned from resource governance on Earth and historical policies, the research recommended best approaches for policy and governance for space resources. These approaches were adapted to the unique circumstances of space, resulting in an improved plan for international management of space resources as multinational exploration and ISRU increase.

Thesis Supervisor: Jeffrey A. Hoffman
Title: Professor of the Practice, Aeronautics and Astronautics
Thesis Committee Chair

Thesis Supervisor: Donald Rapp
Title: NASA JPL-Caltech (Retired)

Thesis Supervisor: Tanja Masson-Zwaan
Title: Assistant Professor, Leiden University

Thesis Supervisor: Dava Newman
Title: Apollo Program Professor, Aeronautics and Astronautics

Acknowledgments

This research would have not been possible without the combined efforts and support from many people. First and foremost, thank you to my advisor, Prof. Jeffrey Hoffman. You have been a constant source of support and inspiration since my very first aerospace engineering class at MIT nearly a decade ago. Your kindness, guidance, and unwavering belief in your students have been invaluable, particularly during the difficult moments of my PhD. I am forever grateful for your mentorship.

To my committee members, Donald Rapp, Tanja Masson-Zwaan, Dava Newman, and my thesis evaluators Oli de Weck, and Martin Elvis, I am deeply indebted to you for your time, expertise, and feedback throughout my work. Your unwavering dedication and patient guidance have been instrumental in helping me navigate the complexities of my research.

I would also like to extend my heartfelt thanks to all the interviewees across NASA who generously gave their time and resources, in addition to my colleagues in the MIT 16.855 "Systems Architecting Applied to Enterprises" class, for making this research possible.

Thank you to the MOXIE Principal Investigator, Mike Hecht, and to the MOXIE team at MIT, MIT Haystack Observatory, NASA Jet Propulsion Laboratory (JPL) and outside. This once-in-a-lifetime opportunity to work on the MOXIE team over the last 7 years has been a career highlight that I will carry with me after MIT.

To my undergraduate academic advisor, Prof. Raul Rodovitzky, thank you for your endless support during my undergraduate years. Your kindness and mentorship were invaluable in navigating the challenges of that period, and I am forever grateful for that.

I would also like to express my appreciation to the Space Generation Advisory Council (SGAC) for providing me with an incredible community of friends and colleagues in the field of space law and policy. Your support has helped me gain confidence in my work in this field.

MIT, you have been the most life-changing thing that has ever happened to me, since I was a 16-year-old kid. Thank you for shaping me into the person I am today through the toughest and happiest moments. To my friends both inside and outside of MIT, thank you for the wonderful memories and for being there for me during every difficult and happy moment.

Lastly, my biggest thank you goes to my family—my wonderful mom and dad, Akhlas and Radwan, and my amazing brother, Samir. You are the reason I was able to leave Lebanon and pursue my dreams at MIT. Thank you for your unwavering love, support, and encouragement despite the horrific circumstances in Lebanon. I hope to continue to make you proud.

I would also like to thank my funding sources. Portions of this research were carried out at MIT under a contract with the National Aeronautics and Space Administration (NNH17CH01C). Other funding sources were from the Massachusetts Institute of Technology (MIT) Department of Aeronautics and Astronautics and from the Zonta International Amelia Earhart Fellowship.

Table of Contents

List of Figures

List of Tables

List of Acronyms

ADAPT – Autonomous Descent and Ascent Powered-flight Testbed
AFM – Atomic Force Microscope
ALHAT – Autonomous Landing Hazard Avoidance Technology
AO – Announcement of Opportunity
APEX – Athena precursor experiment
ARIES – ARchitecting Innovative Enterprise Strategy
ASM – Acquisition Strategy Meeting
ASPI – Australian Strategic Policy Institute
ASTRA – Advanced Space Technology Roadmapping Architecture
ATP – Authority to Proceed into Formulation
ATS – Antarctic Treaty System

BGR – Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe)

CA – Continuation Assessment
CAC – Carbon dioxide Acquisition and Compression
Caltech – California Institute of Technology
CDR – Critical Design Review
CEH – Cost Estimating Handbook
CERR – Critical Events Readiness Review
CFC – Cobalt-rich Ferromanganese Crusts
CIF – Center Innovation Fund
CIO – Chief Information Officer
CLPS – Commercial Lunar Payload Services
COBALT – CoOperative Blending of Autonomous Landing Technologies
CogE – GNC Cognizant Engineer
COMRA – China Ocean Mineral Resources Research and Development Association
COPUOS – Committee on the Peaceful Uses of Outer Space
COTS – Commercial Off-The-Shelf
CRM – Continuous Risk Management
CSLA – Commercial Space Launch Act
CTs – Characterization Tests

DARPA – Defense Advanced Research Projects Agency
DART – Double Asteroid Redirection Test
DEM – Digital Elevation Map
DIMES – Descent Image Motion Estimation System
DNP – Develop New Products
DoD – Department of Defense
DORD – Deep Ocean Resources Development Co. Ltd.
DOT – Deep space Optical Terminals
DR – Decommissioning Review
DRM – Design Reference Mission
DRR – Disposal Readiness Review

DS1 – Deep Space 1
DSAC – Deep Space Atomic Clock
DSC – Differential Scanning Calorimeter
DSN – Deep Space Network
DSOC – Deep Space Optical Communications
DSP – Digital Signal Processing
DTs – Development Tests

ECF – Early Career Faculty
ECI – Early Career Initiative
EDL – Entry, Descent, and Landing
EDTs – Engineering Development Tests
EEZ – Exclusive Economic Zone
EGA – Evolved Gas Analyzer
EMC – Electromagnetic Compatibility
EMT – Engineering-Model Thrusters
EPFL – École Polytechnique Fédérale de Lausanne
EQM – Engineering Qualification Model
ESA – European Space Agency
EscaPADE – Escape and Plasma Acceleration and Dynamics Explorers
ESDMD – Exploration Systems Development Mission Directorate
ESI – Early-Stage Innovations

FA – Formulation Agreement
FAD – Formulation Authorization Document
FBC – Faster, Better, Cheaper
FFRDC – Federally-Funded Research and Development Center
FMECA – Federally Failure Mode, Effects & Criticality Analysis
FOALS – Fuel Optimal and Accurate Landing System
FPGA – Field-Programmable Gate Array
FRR – Flight Readiness Review
FT – Flight Terminal

GAO – General Accounting Office
GCD – Game Changing Development
GNC – Guidance, Navigation, and Control
GRC – NASA Glenn Research Center
GRNS – Gamma Ray and Neutron Spectrometer

HED – Hughes, Electron Dynamics
HEDS – Human Exploration and Development of Space
HEO – Human Exploration and Operations
HEOMD – Human Exploration and Operations Mission Directorate (HEOMD)

IA – Independent Assessment
IBRD – International Bank for Reconstruction and Development
IDA – International Development Association
IDIC – Indefinite Delivery, Indefinite Quantity

IFREMER – Institut français de recherche pour l'exploitation de la mer
IMF – International Monetary Fund
I-MIM – International-Mars Ice Mapper
IMLEO – Initial Mass to Low Earth Orbit
IOM – Interoceanmetal Joint Organization
IRB – Institutional/Independent Review Board
ISA – International Seabed Authority
ISPP – In-Situ Propellant Production
ISRU – In-Situ Resource Utilization
ISS – International Space Station
IT – Information Technology
ITA – Independent Technical Authority
ITLOS – International Tribunal for the Law of the Sea

JAXA – Japan Aerospace Exploration Agency
JPL – Jet Propulsion Laboratory

KDP – Key Decision Point

LaRC – NASA Langley Research Center
LCC – Life-Cycle Cost
LCR – Life-Cycle Reviews
LICIA – Light Italian CubeSat for Imaging of Asteroids
IPS – Ion Propulsion System
LRR – Launch Readiness Review
LTS – Long-Term Sustainability
LunaH-Map – Lunar Polar Hydrogen Mapper
LuSTR – Lunar Surface Technology Research Opportunities
LV – Launch Vehicle

MarCO – Mars Cube One
MARDI – Mars Descent Imager
MARIE – Mars Radiation Environment Experiment
MARV – Martian Autonomous Rotary-Wing Vehicle
Mastcam-Z – Mast-Mounted Camera System
MatISSE – Maturation of Instruments for Solar System Exploration
MAR – Mission Assurance Requirements
MAVs – Mars Ascent Vehicles
MBED – Model-Based Engineering Design
MBSE – Model-Based Systems Engineering
MCR – Mission Concept Review
MCS – Monitor and Control System
MDR – Mission Definition Review
MEDLI2 – Mars Entry, Descent, and Landing Instrumentation 2
MET – Meteorological Station
MECA – Mars Environmental Compatibility Assessment
MECA – Microscopy, Electrochemistry, and Conductivity Analyzer
MEDA – Mars Environmental Dynamics Analyzer

MEPAG – Mars Exploration Program Analysis Group
MER – Mars Exploration Rovers
MICAS – Miniature Integrated Camera/Spectrometer
Mini-TES – Mini Thermal Emission Spectrometer
MIP – Mars ISPP Precursor
MIT – Massachusetts Institute of Technology
MOXIE – Mars Oxygen In-Situ Resource Utilization Experiment
MPIAT – Mars Program Independent Assessment Team
MPPG – Mars Program Planning Group
MRO – Mars Reconnaissance Orbiter
MRR – Mission Readiness Review
MSL – Mars Science Laboratory

NASA – National Aeronautics and Space Administration
NASA-STD – NASA Technical Standard
NC's – Non-Claimants
NDIR – Non-Dispersive Infrared Radiation
NEAs – Near-Earth Asteroids
NEXT – NASA Evolutionary Xenon Thruster
NGO – Non-Governmental Organization
NIAC – NASA Innovation Advanced Concepts
NID – NASA Interim Directive
NIR – Near-Infrared
NMP – New Millennium Program
NoDD – No-Due-Dates
NORI – Nauru Ocean Resources Inc
NPD – NASA Policy Directive
NPR – NASA Policy Requirements
NPT – NSTAR Project Tests
NSTAR – NASA SEP Technology Application Readiness
NSTGRO – NASA Space Technology Graduate Research Opportunities

ODR – Only Design Review
OIG – Office of Inspector General
OJT – On-the-Job Training
OM – Optical Microscope
OMB – Office of Management and Budget
ORR – Operational Readiness Review
OST – Outer Space Treaty

PanCam – Panoramic Camera
PAPAC – Provide Aerospace Products and Capabilities
PDR – Preliminary Design Review
PEA – Program Element Appendix
PEMC – Project and Engineering Management Council
PEPE – Plasma Experiment for Planetary Exploration
PFAR – Post-Flight Assessment Review
PFR – Problem/Failure Reporting Procedures

PICASSO – Planetary Instrument Concepts for the Advancement of Solar System Observations
PIR – Program Implementation Review
PIXL – Planetary Instrument for X-ray Lithochemistry
PLAR – Post-Launch Assessment Review
PMN – Polymetallic Nodules
PMS – Polymetallic Sulphides
PP&C – Project Planning and Control
PPR – Periodic Project Review
PRA – Periodic Probabilistic Risk Assessment
PRR – Production Readiness Review
PSD – Planetary Science Division
PTC's – Pre-Treaty Claimants

Q-PACE – CubeSat Particle Aggregation and Collision Experiment

R&D – Research and Development
R&T – Research and Technology
R&TD – Research and Technology Development
RC's – Reserved Claimants
RF – Radio Frequency
RIDM – Risk-Informed Decision Making
RIMFAX – Radar Imager for Mars' Subsurface Experiment
RM – Risk Management
ROI – Return on Investment
ROK – Republic of Korea
REE – Rare Earth Elements
RWGS – Reverse Water Gas Shift

SALMON – Stand Alone Missions of Opportunity Notice
SAR – System Acceptance Review
SBIR – Small Business Innovation Research
ScaN – Space Communications and Navigation
SDG's – Sustainable Development Goals
SDLC – Software Development Life Cycle
SDR – System Definition Review
SE – Systems Engineering
SEA – Systems Engineering Advancement
SEP – Solar Electric Propulsion
SHERLOC – Scanning Habitable Environments with Raman & Luminescence for Organics and Chemicals
SIMPLEx – Small, Innovative Missions for PLanetary Exploration
SIR – System Integration Review
SMD – Science Mission Directorate
SMSR – Safety and Mission Success Review
SOMA – NASA Science Office for Mission Assessments
SOMD – Space Operations Mission Directorate
SOXE/SOE – Solid Oxide Electrolysis
SPLICE – Safe & Precise Landing – Integrated Capabilities Evolution

SPT – Stationary Plasma Thruster
SRB – Standing Review Board
SRR – System Requirements Review
SSI – Surface Stereo Imager
SSR – Space Sustainability Rating
SSTP – Small Spacecraft Technology Program
STMD – Space Technology Mission Directorate
STTR – Small Business Technology Transfer
STRG – Space Tech Research Grants
STRI – Space Technology Research Institutes
SWOT – Strengths, Weaknesses, Opportunities, Threats

TA – Thermal Analyzer
TD – Technology Development
TDM – Technology Demonstration Missions
TECP – Thermal and Electrical Conductivity Probe
TMC – Technical, Management, and Cost
TOML – Tonga Offshore Minerals Ltd
TQM – Total Quality Management
TRA – Technology Readiness Assessment
TRL – Technology Readiness Level
TRN – Terrain Relative Navigation
TWAIL – Third World Approaches to International Law

UAE – United Arab Emirates
UCLA – University of California, Los Angeles
UN – United Nations
UNCLOS – United Nations Convention on the Law of the Sea
USA/US – United Stated of America

V&V – Verification and Validation
VIPER – Volatiles Investigating Polar Exploration Rover

WCL – Wet Chemistry Laboratory

PART I: Innovation Challenges in NASA's Planetary Program

Chapter 1: Introduction and Background

This chapter introduces the National Aeronautics and Space Administration (NASA), its organizational structure, its strategy over the years, and its ongoing programs and initiatives, with a focused section on NASA's Jet Propulsion Laboratory (JPL). The chapter then draws on various sources to portray the proposed problem statement, before outlining the defined research objective, questions, and motivation.

1.1 Problem Statement and Objectives

1.1.1 Problem Statement

"An engineer can do for a dollar what any fool can do for two." — Arthur Mellen Wellington

This abridged quote from Wellington, the famous writer of "The Economic Theory of the Location of Railways", is the essence of the introduction of his magnum opus that says (Wellington, 1887),

> "It would be well if engineering were less generally thought of, and even defined, as the art of constructing. In a certain important sense, it is rather the art of not constructing; or, to define it rudely but not inaptly, it is the art of doing that well with one dollar, which any bungler can do with two after a fashion."

When looking at the National Aeronautics and Space Administration (NASA), one can see some of the brightest of engineers, trained to think critically, to tackle complex problems, and to create innovative solutions for the latest cutting-edge technologies in space. However, have this engineering process and the structures around it been efficient, effective, and cost-effective, per Wellington's quote, or have they been an inefficient hinderer for innovation?

NASA is the governmental agency responsible for the United States' civilian space program and for aeronautics and space research. Since its establishment in 1958, in response to the Soviet Union's achievements at the time (NASA History Office Program, 2018), the agency has been a vital player in the global space community. Throughout its various missions, programs, and initiatives, NASA has pushed the boundaries of knowledge of the universe and instilled the excitement for exploration and discovery in countless generations that it inspired.

At the same time, however, the agency has constantly faced various challenges while managing and executing these programs. The challenges include balancing long-term goals with the need for short-term results, coordinating with contractors, international partners, other government agencies, and the commercial sector, and grappling with broader issues such as budget constraints and the changing political priorities between administrations. These challenges contribute to NASA's cost and schedule overruns, restraining and stifling innovation at the agency and its ability to push the technological envelope in space. This thesis focuses on these challenges at NASA, within its complex systems and interconnected environments, incorporating enterprise architecture and system architecting tools to understand the evolution and potential of the agency in an ever-changing domain and the key transformations needed to enable it, and its Jet Propulsion Laboratory (JPL) in particular, to reinstill innovation in technology investment, development, and maturation.

Before delving into the details of such challenges, it is important to understand NASA's organizational structure, its strategy over the years, and its ongoing programs and initiatives.

1.1.1.1 NASA Organization Structure

NASA is a complex organization, with a highly specialized and hierarchical organizational structure to cover its wide range of missions, programs, partnerships, and activities. As a governmental agency, NASA is led by its Administrator, appointed by the President of the United States who is responsible for carrying out the administration's vision for the agency (Loff, 2022). *Figure 1* presents NASA's organization chart, published by the agency, (NASA, 2023). Aside from the Administrator, the Office of the Administrator houses a number of critical positions including the Deputy Administrator, Associate Administrator, Chief of Staff, Deputy Associate Administrator for Business Operations, Deputy Chief of Staff, Associate Administrator, Office of Technology, Policy and Strategy, Chief Technologist, Associate Administrator for Space Security Interests, Chief Resilience Officer, Chief Program Management Officer, and Director of Space Architectures (NASA, 2023).

Since September 2021, NASA has been divided into five mission directorates, each one of which is led by its respective Associate Administrator. The mission directorates are Aeronautics Research, Exploration Systems Development, Science, Space Operations, and Space Technology (NASA, 2023). This organization is based on an update, announced by NASA Administrator Bill Nelson in 2021, that divided up the previous Human Exploration and Operations Mission Directorate (HEOMD) into two separate mission directorates: the Exploration Systems Development Mission Directorate (ESDMD) and the Space Operations Mission Directorate (SOMD) (NASA, 2022). This research focuses on the Science Mission Directorate (SMD) and the Space Technology Mission Directorate (STMD), and their representative entities in NASA Headquarters (HQ).

The Science Mission Directorate (SMD) focuses on NASA's space research program in Earth and space science and heavily engages the science community within its activities and plans. SMD has five scientific pursuits Earth Science, Planetary Science, Biological and Physical Sciences, Heliophysics, and Astrophysics (NASA Science, 2023). Each of these divisions is guided by its own decadal survey—a comprehensive, science-community-driven review of NASA's science programs that is conducted by the National Academy of Sciences approximately every 10 years to provide guidance and recommendations for the priorities and goals for the agency and other stakeholders (NASA Science, 2023). Throughout these divisions, SMD also supports the development of new technologies targeted to enable SMD science (Science-enabling Technology, 2023). This research focuses on the Planetary division of SMD that encompasses the Mars Exploration Program in addition to space flight missions and research on the solar system formation and evolution and understanding planetary environments.

The Space Technology Mission Directorate (STMD), on the other hand, is the organization within NASA that is dedicated to identifying and developing solutions for technological challenges. STMD's portfolio covers a wide range of disciplines for technology development, many of which are multi-purpose, multi-application, cross-cutting technologies. In its technology investment, STMD partners with other NASA directorates, universities, government agencies, commercial partners, and small businesses (Space Technology Mission Directorate, 2022).

NASA's work is also spread out across the United States between ten research centers, each specializing in and responsible for carrying out specific aspects of NASA's work. These centers are Armstrong Flight Research Center, Ames Research Center, Glenn Research Center, Goddard Space Flight Center, Jet Propulsion Laboratory, Johnson Space Center, Kennedy Space Center, Langley Research Center, Marshall Space Flight Center, and Stennis Space Center. This research largely focuses on NASA's Jet Propulsion Laboratory (JPL).

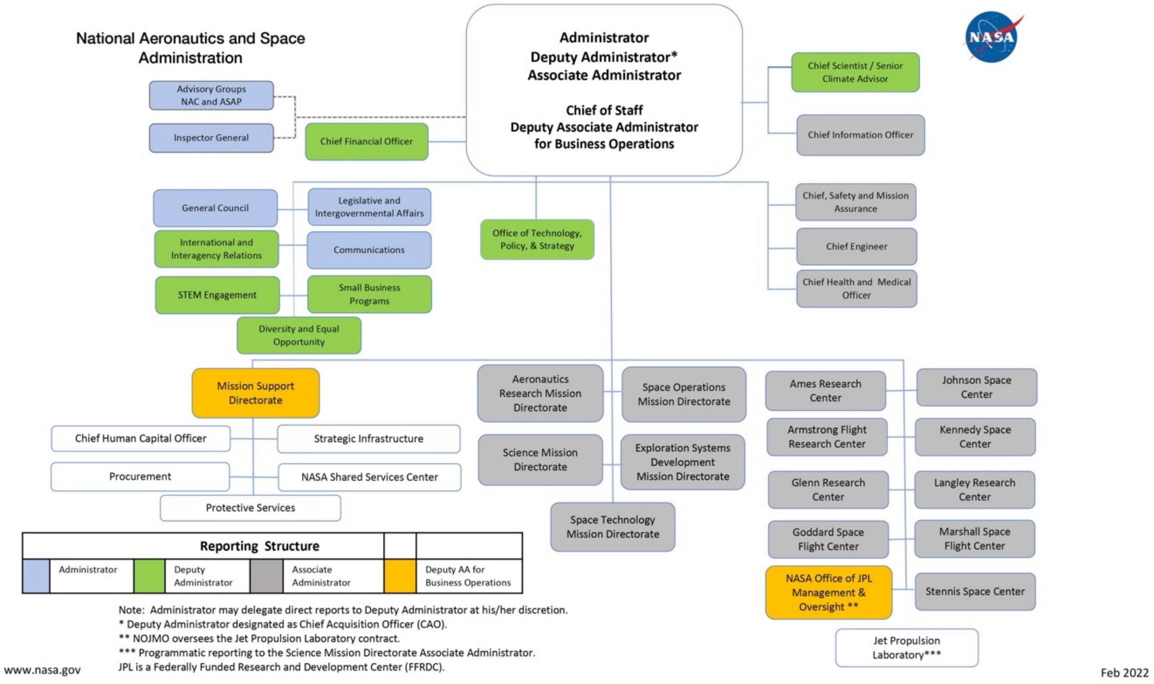


Figure 1. NASA Organization Chart. (NASA, 2023)

1.1.1.2 NASA Jet Propulsion Laboratory (JPL)

NASA's Jet Propulsion Laboratory (JPL) is a federally funded research and development center (FFRDC) managed by Caltech under contract from NASA. It has about 6,300 employees and operated with a budget of $2.4B in FY2021 (About JPL). As NASA's only FFRDC, JPL specializes in deep space robotic exploration and operates NASA's Deep Space Network, a worldwide network of U.S. spacecraft communication facilities that supports NASA's interplanetary spacecraft missions along with radar and radio astronomy observations to explore the universe. Nearly a third of the organization's budget is spent on Earth Science. Additionally, JPL is responsible for aligning its research and development (R&D) efforts with NASA's strategic plan. Contracts are passed down from NASA leadership to JPL and addressed by the mission directorates. Because of this structure, JPL operations and activities are dictated by NASA and the lab can only expand efforts within the realms that it specializes in.

In the NASA 2022 Strategic Plan, JPL was assigned the following strategic goal contributions: (1) "Expand Human Knowledge Through New Scientific Discovery", (2) "Extend Human Presence to the Moon and onto Mars for Sustainable Long-term Exploration, Development, and Utilization", (3) "Catalyze Economic Growth and Drive Innovation to Address National Challenges", and (4) "Enhance Capabilities and Operations to Catalyze Current and Future Mission Success" (NASA, 2022).

Attracted by its successful track record, inspiring vision in planetary exploration and structural complexity as an enterprise, this research chose JPL as the enterprise for a deeper-dive case study. JPL has constantly faced various challenges and complexities from liaisons with NASA Headquarters and other NASA centers that promote collective efficiency instead of competition over resources, to uncertainty in funding and budgets both on an enterprise level and on a mission level, to initiating innovation and creativity within JPL's highly capable and R&D-focused workforce with minimal interference with their work while preserving the legacy system, and to relationships with rising commercial space enterprises to better serve the industry. Such challenges present potential transformational areas for JPL that this research focuses on.

1.1.1.3 NASA Mission Classification

NASA has several categories in which missions are classified based on their size, complexity, and cost on one hand and based on their risk class on the other. Missions at NASA can be directed from the administration or can go through a competition process based on submitted proposals. Based on mission size, complexity, and cost, NASA's classification includes three categories: Discovery, New Frontiers, or Solar System Exploration missions—where the former two are competed missions (NASA, 2019).

Established in 1992, Discovery missions are smaller principal investigator (PI) led planetary missions, selected through an open, peer-reviewed, competed process. These more focused scientific investigation missions are relatively low-cost—under $450M excluding launch costs, operations, or data analysis—and with a 36-month launch cadence. Some examples are the Mars Pathfinder that carried and demonstrated that first Mars rover, MESSENGER to Mercury, Dawn to the asteroids Vesta and Ceres, InSight on Mars, Lucy to the Trojan Asteroids, and Psyche to the metal-rich asteroid Psyche (NASA, 2019; Maue, 2021).

One NASA program that ended in 2010 and got incorporated within the Discovery program was the Mars Scout Program. The Mars Scout missions, analogous to Discovery missions, were PI-led, price-fixed missions that specifically targeted the Mars program's science goals that were "not otherwise covered in the baseline Mars plan" (Matousek, 2001). Mars Scout missions were also intended to "allow more risky technologies and approaches to be applied in the investigation of Mars" (Shotwell, 2005). The first of these missions was the Phoenix lander that landed in 2008 on the surface of Mars (Phoenix, 2022).

The other category for competed missions is New Frontiers which was established in 2003 targeting mid-size planetary missions. These PI-led missions are responsible for targeting high-priority goals to the science community. With a 60-month launch cadence, these missions are capped at $850M excluding launch costs, operations, or data analysis. Some examples are the New Horizons mission to Pluto, the Juno mission to Jupiter, and Dragonfly to Titan (NASA, 2019; Maue, 2021).

The largest, most complex, and most of expensive of NASA's missions are the large Strategic Science Missions, also known as Flagships. These missions fall under the Solar System Exploration Program and are assigned directly to a NASA center or an implementing organization with the goal of addressing the most important and challenging scientific questions facing the agency. Due to their complexity and very low risk requirements, the missions tend to be over $1B in cost. Some examples are the Mars Science Laboratory, Cassini to Saturn, the Mars Curiosity and Perseverance rovers, the James Webb Space Telescope, and Europa Clipper (NASA, 2019; Maue, 2021).

Another classification for missions that the research later mentions are ones that fall under the research and technology development New Millennium Program (NMP). NMP was active between 1996 and 2009, aiming to "identify and space-flight validate breakthrough technologies that will significantly reduce risks and costs and ultimately benefit future NASA science missions" (New Millenium Program). An example of these missions is the Deep Space 1 Flyby mission.

The other classification of missions at NASA is based on their risk class profiles. Missions fall into class A-D per their individual risk profile, usually associated with "technical and quality issues that impact mission success" (Johnson-Roth, 2011). According to Section 3.1 "NASA Mission and Instrument Risk Classification" of NASA's Procedural Requirements NPR 8705.4A, the following are the definitions of each of the mission or instrument risk tolerance class (NPR 8705.4A, 2021):

- "3.1.3.1 Class A: The lowest risk tolerance that is driven more by technical objectives. This would normally represent a very high priority mission with very high complexity, as described in Appendix C.

- 3.1.3.2 Class B: Low risk tolerance that is driven more by technical objectives. This would normally represent a high priority mission with high complexity, as described in Appendix C.

- 3.1.3.3 Class C: Moderate risk tolerance that is driven more by technical objectives. This would normally represent a medium priority mission with medium complexity, as described in Appendix C.

- 3.1.3.4 Class D: High risk tolerance that is driven more by programmatic constraints. This would normally represent a lower priority mission with a medium to low complexity, as described in Appendix C".

Table 1 adapted from Appendix C of NPR 8705.4A presents the details of mission and instrument risk classification considerations at NASA. These considerations include the mission's (or instrument's) priority, primary lifetime, complexity, and life-cycle cost. These risk classifications, in addition to the previously discussed mission classification are critical to the NASA challenges that this research tackles in its upcoming chapters.

Table 1. Mission and Instrument Risk Classification Considerations (adapted from Appendix C of *(NPR 8705.4A, 2021)*)

Mission and Instrument Risk Classification Considerations		
Priority (Relevance to Agency Strategic Plan, National Significance, Significance to the Agency and Strategic Partners)	Very High:	Class A
	High:	Class B
	Medium:	Class C
	Low:	Class D
Primary Mission Lifetime	Long, > 5 Years:	Class A
	Medium, 5 Years > – > 3 Years:	Class B
	Short, 3 Years > – > 1Years:	Class C
	Brief, < 1 Year:	Class D
Complexity and Challenges (Interfaces, International Partnerships, Uniqueness of Instruments, Mission Profile, Technologies, Ability to Reservice, Sensitivity to Process Variations)	Very High:	Class A
	High:	Class B
	Medium:	Class C
	Medium to Low:	Class D
Life-Cycle Cost	Very High:	Class A
	High:	Class B
	Medium:	Class C
	Medium to Low:	Class D

Note that aside from mission classifications, there are two other categories for instrument classification that will be mentioned throughout this thesis:

- Enabling (a pull technology) vs. Enhancing (a push technology), verbatim as defined in NASA's Technology Roadmaps document (NASA, 2015):
    - "Enabling technology candidates satisfy a capability need for a space mission or aeronautics roadmap outcome by providing the desired performance within acceptable cost and risk".
    - "The enhancing technology candidates provide significant benefits over the current state of the art but are not required for a specific mission or aeronautics roadmap outcome. These push technology candidates include emerging or radically different

ideas or approaches and often take years to advance but can inspire new and different missions and mission architectures to accomplish long-term strategic goals".

- Focused vs. Base (Caffrey, Udomkesmalee, Hayati, & Henderson, 2004):
  - "Focused Technology addresses technologies that are specific and critical to near-term missions."
  - "Base Technology addresses those technologies that are applicable to multiple missions, and which can be characterized **as** longer term, higher risk, and high payoff technologies."

1.1.1.4 Different Eras

1.1.1.4.1 NASA

NASA has had a non-linear trajectory in its strategies for missions over time, adjusting to the various historical and political circumstances in different eras of space exploration and technological development. *Figure 2* shows NASA's fluctuating budget over between 1959 and 2022 (Roberts, 2022), with peaks and troughs corresponding to these different eras. NASA's budget peaked during the Apollo era of the 1960s and 1970s, but it drastically dropped after the end of that program causing the agency to face budget cuts and funding challenges in the 1980s and 1990s.

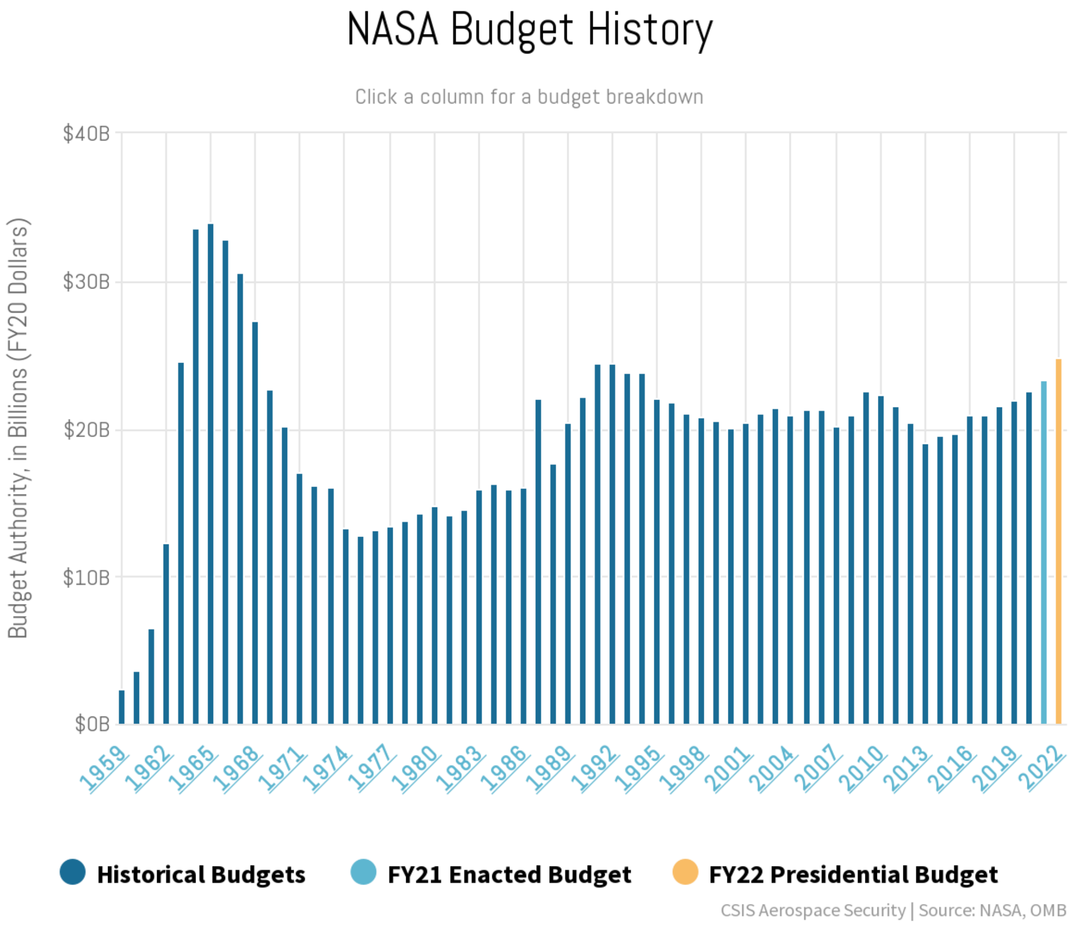


Figure 2. NASA Budget History 1959-2022 *(Roberts, 2022)*

To adapt to budget cuts, NASA's Administrator from 1992 to 2001 Dan Goldin championed the so-called "faster, better, cheaper" (FBC) era at NASA in the 1990s and early 2000s. Tied back in its origin to Kelly Johnson's philosophy in the Skunk Works (Johnson & Smith, 1989; Rich , 1996), the FBC mantra's goal in its concerted effort was to streamline NASA's operations and reduce costs by adopting a more agile and cost-effective approach to spacecraft development and mission execution. This approach meant a faster cadence, smaller and cheaper spacecraft, more risk, and less procedural managerial oversight to eliminate any non-value-added activities. Goldin describe the situation at NASA at the time saying (Frank, 2019),

> "There's a paradox at work here that creates a downward spiral. Launching fewer spacecraft means scientists want to pile every instrument they can onto whatever's going to fly. That increases the weight, which increases the cost of the spacecraft and the launcher. Fewer spacecraft also means we can't take any risk with the ones we launch, so we have to have redundancy, which increases weight and cost, and we can't risk flying new technology, so we don't end up producing cutting edge technology."

In a speech delivered to JPL at the time, Goldin held a large stack of books and said (JPL and the Space Age: The Pathfinders, 2022):

> "The Mars Surveyor was supposed to be faster, better, cheaper. (drops a stack of books) […] This is not the way to do things. There is no excuse for all this paper in that package. And what this package called out is the famous JPL Procurement Forms manual. Now, do you wanna spend your remaining days in the space program dealing with garbage like this? Who has the courage to say that this is unnecessary? This is not what we're about, we're about leaving Earth. We're not about paper."

Reinventing NASA's business strategy, Goldin adapted the agency's programs and activities for $40 billion less than the initial envisioned budget plan when he took office (NASA History, 2009). The FBC mantra had important practices for innovative and more cost-effective missions, one of which is the increased mission cadence— "a major enabler of innovation and the driver for the training and testing of the next generation of managers, engineers, and scientists" as described by (Paxton, 2007). Mission cadence is critical for retaining knowledge and competence, with a widely held set of "lessons learned" (Paxton, 2007).

FBC featured many successful examples such as Mariner 4, 6, 7, and 9, Viking 1 and 2, Mars Global Surveyor, Mars Pathfinder, 2001 Odyssey, Mars Express, Spirit and Opportunity twin Mars rovers, Mars Reconnaissance Orbiter, and the Phoenix Mars Lander. However, at ~37% success rate in its missions, this era was infamously remembered by its mission failures that put FBC to an end (Jolly, 2002). Two of its main failures were the loss of both the Mars Climate Orbiter and the Mars Polar Lander in 1999 (Young, et al., 2000). The former failure was a navigation error due to the navigation team providing the needed spacecraft operating data in the wrong English instead of metric units. The latter had several candidate failure modes, some of which are the premature shutdown of the descent engines due to spurious signal from the touchdown sensor (Young, et al., 2000). Investigations started taking place for the FBC failures, such as The Mars Program Independent Assessment Team (MPIAT) that was established then, chaired by Thomas Young, to investigate and study the successes and failures of the Mars and Deep Space Missions that took place. For the Mars Climate Orbiter, the Mishap Investigation Board concluded that (Mars Climate Orbiter Mishap Investigation Board, 2000),

> "The "Faster, Better, Cheaper" paradigm has successfully challenged project teams to infuse new technologies and processes that allow NASA to do more with less. The success of "Faster, Better, Cheaper" is tempered by the fact that some projects and programs have put too much emphasis on cost and schedule reduction (the "Faster" and "Cheaper" elements of the paradigm). At the same time, they have failed to instill sufficient rigor in risk management throughout the mission lifecycle. These actions have increased risk to an unacceptable level on these projects."

This high mission failure rate left a negative memory of FBC at NASA, with the famous running joke at the agency whenever the "faster, better, cheaper" phrase is mentioned, to respond "pick two!" (Frank, 2019). However, the public's selective memory can forget that FBC started off strongly, with a 90% success rate in its first ten missions. This success created a sense of overconfidence as described by (Launius & McCurdy, Eds., 2016),

> "In hindsight, it becomes apparent that [NASA's] success in the nineties had led the review and selection committees to accept very ambitious and complex proposals with a very high science return on budgets and schedules that were quite optimistic."

Additionally, when studied with different metrics, like cost-effectiveness or mission performance in terms of the science output per dollar of mission cost, the legacy of the FBC era shifts away from the failure stigma associated with it. According to (Dillon & Madsen, 2015), "FBC missions resulted in more scientific publications (and citation-weighted publications) per dollar of mission cost than did missions developed under other paradigms". This supportive view for the FBC narrative can be also further understood through the lens of (McCurdy, 2003)'s phrase, "The largest obstacle to low-cost innovation is the belief that it cannot be done."

Despite the lack of consensus on the FBC ideology and its benefits, the legacy of this era is critical due to its lasting policy impacts on the agency. In a study by (Eaton, et al., 2022), it was found that cost, schedule, and technical performance objectives were the main metrics associated with ensuring mission success, aligned with the perceived FBC causes of failures. (Eaton, et al., 2022) also concluded that "FBC appears to have influence in NASA policy and practice regarding risk acceptance, funding distributions, and civil servant workforce".

The FBC era led by Goldin was followed by former NASA Administrator Sean O'Keefe who started the initial work on the Moon-Mars program (Lambright, 2009). In April 2005, during President George W. Bush's administration, Michael Griffin succeeded O'Keefe to become NASA's 11th administrator (NASA, 2006). The Griffin era, up until 2009, featured challenges in NASA's budget and direction, but it was also marked by a focus on the completion of the International Space Station and NASA's "return to the Moon" with the Constellation Moon-Mars program (Lambright, 2009).

In February 2009, after President Barack Obama took office, NASA's budget increased (Iannotta, 2009) and priorities shifted with Administrator Charles F. Bolden up until 2017 (NASA, 2017). The new budget scrapped the Constellation program and focused efforts on increasing the commercial sector partnerships and ISS operations (Matson, 2010). Bolden's era also featured the establishment of the Space Technology Mission Directorate (STMD) for development of cross-cutting technologies, in addition to the development of the Space Launch System and the Orion Crew Capsule (NASA, 2017). Multiple successful planetary missions took place in Bolden's era, notably including the Mars Curiosity Rover landing and the Juno mission to Jupiter (NASA, 2017).

Following Bolden was the era of Administrators Jim Bridenstine then Bill Nelson from 2018-2021 and from 2021 onwards respectively. One of the main highlights of Bridenstine's era were the Artemis program to "land the first woman and the next man on the surface of the Moon by 2024", in addition to further corroborating the commercial partnerships throughout the Commercial Crew Program and the Commercial Lunar Payload Services (CLPS) Program to involved private partnerships for lunar surface activities (NASA, 2018).

With Bill Nelson's era at NASA ongoing at the time of this research, the main perceived highlights in the 2021-2022 period were the continuation of the Artemis program through the first successful launch of the Space Launch System (SLS) with the uncrewed Orion spacecraft, the successful launch and imagery from the James Webb Space Telescope, the Double Asteroid Redirection Test (DART) successful planetary defense demonstration, in addition to the advancement of the CLPS program and the continued support for U.S. small businesses for technology development efforts that help the agency (McGuinness & Warner, 2022).

1.1.1.4.2 JPL

Since the end of the Cold War, JPL has undergone several institutional, systematic, and managerial changes throughout its eras, adapting to the different political, scientific, and commercial demands. As JPL's focus shifted from rockets to deep-space missions after Sputnik, the laboratory continued to utilize its strong established systems management approach since the 1950's and 1960's for its high-cost ~$1B missions like Galileo and Voyager (Koppes, 1982; Johnson S. B., 2006). This systems-engineering-heavy approach was aimed for high reliability, but it also came at a high cost, accounting for all the needed formal procedures, systems interface documentation, and rigorous risk reviews and testing to prevent any potential failures (Johnson S. B., 2006).

During the 1990's, however, JPL and NASA faced steep budget cuts, adding a forcing function of having to prioritize cost control. According to JPL's archives, because of cost overruns and mission delays, JPL was perceived at the time as "out of control" and "fat, complacent, arrogant, with little regard for cost" (Westwick, 2007; Huntress, 1992; McCleese, Sander, & Barber, 1991; Casani, 1991). This period coincided with the previously discussed Faster, Better, Cheaper (FBC) era at NASA. To adapt to the new reality, JPL had to shift its management styles and focus on smaller, lower-cost missions.

In 1991, during Ed Stone's era as director of JPL, the laboratory adopted Total Quality Management (TQM) and then embraced reengineering management style few years later as a "way to ride out the budget cuts and extract more productivity from its remaining staff" (Westwick, 2007). These two management theories were growing in corporate America at the time, attempting a shift "from the classic hierarchy of the vertically integrated firm to a flexible, nonhierarchal structure" (Nohria, Dyer, & Dalzell, 2002; Westwick, 2007) while still preserving a "space for individual autonomy against top-down control and thus resonated with the technical community's emphasis on individual creativity" (Westwick, 2007). Despite their popularity in the corporate world and manufacturing industry, these two management approaches were more difficult to apply in research and development (R&D) institutions such as JPL, whose goal is not profit but rather driven by technical innovation and accountability (Westwick, 2007). Such challenges have been also pointed out for institutions such as the Massachusetts Institute of Technology (MIT) (Williams R. , 2002). However, both approaches align with the FBC notion and could help in cost and schedule reduction, especially since NASA itself adopted TQM only few months after JPL (Westwick, 2007).

TQM is a management approach whose goal is to improve the quality of an organization’s products, services, and processes by focusing on employee empowerment and customer satisfaction. Building on TQM, reengineering completely redesigns an organization's processes and structures to improve efficiency and effectiveness, by having generalized processes driving the organization instead of specific tasks (Westwick, 2007). These management approaches come after many other management theories such as Taylorism—the Scientific Management Theory— (Aitken, 1989; Nelson, ed, 1992; Jordan, 1994; Sheldrake, 1997; Kanigel, 2005) and systems engineering (Simon, 1977; Bugos, 1993; Hughes, 2000; Johnson S. B., 2006).

At JPL, TQM and reengineering helped the laboratory in reducing costs, streamlining its operations and development processes, improving communication and collaboration among different teams, in addition to improving the efficiency and effectiveness of JPL’s operations. These management approaches reduced the bureaucracy and increased JPL’s agility and responsiveness through the consolidation of different functions and the elimination of redundant processes, creating a new paradigm shift to a “workflow-based organization” (Westwick, 2007).

However, soon after, it became clear how TQM and reengineering undermined the systems engineering core of JPL’s management for years before, causing resistance from some of JPL’s older legendary project managers, and a comical increase in complexity of abstracting process to flowcharts. Additionally, the new approaches increased the number of delegators to leaders and as (Westwick, 2007) describes, “Reengineering also obeyed the law of unintended consequences. In seeking to delegate authority to “process owners” at the lowest possible level, it had produced a vast number of processes that complicated the bureaucracy instead of simplifying it”.

After the 1998 failures during NASA’s FBC era, JPL had to face yet another reality. Having had potentially diverted the time and efforts of employees from focusing on mission success, JPL’s management approaches were in need for reassessment, slowly bringing back some rigor from its previous systems engineering practices of peer review and risk assessment. In 2001, a new director, Charles Elachi, took lead of JPL “reinforcing the renewed appreciation for traditional management modes” (Westwick, 2007). JPL’s culture afterwards featured increased oversight with continued pressure to reduce costs (Leising, 2004). JPL at that time was focusing on the mission-oriented process to Develop New Products (DNP)—where mission and system development for space projects occur—to further establish its subsystem-level processes and procedures as “best practices” for employees (Linick & Briggs, 2014).

In 2004, JPL launched the Systems Engineering Advancement (SEA) initiative to improve its systems engineering practices and organizational capabilities for flight projects and ground support (Jansma & Jones, 2006). As defined by (Jansma & Jones, 2006), the scope of systems engineering (SE) work in SEA encompasses the work carried out “in all three dimensions of a program, project, or task: (1) the full life-cycle, e.g.., concept through the end of operations, (2) the full depth, e.g., Program, Project, System, Subsystem, Element (SE Levels 1 to 5), and (3) the full technical scope, e.g., flight, ground and launch systems, avionics, power, propulsion, telecommunications, thermal, etc.”

Figure 3 shows the three key aspects of change according to the SEA approach: people, process, and technology, with the initiatives associated with each (Jansma & Jones, 2006). *Figure 4* further expands on these three aspects, laying out the details on each of the three axes for JPL's competency model (Jansma & Jones, 2006). These axes include details on (1) key JPL technical domains and disciplines, (2) key personal behaviors of systems engineers from leadership, attitude, and communication skills, in addition to technical acumen, and (3) key JPL systems engineering processes such as "systems architecture, requirements management, interface definition, technical resource management, system design and analysis, system verification and validation, risk management, technical peer reviews, design process management, and systems engineering task management" (Jansma & Jones, 2006).

Since then, JPL has continued to evolve its management style, adapting to the highly dynamic and challenging environment of space exploration. These changes include adapting Agile Development software implementations in some groups, promoting flexibility and rapid iteration (Streiffert, Starbird, & Grenander, 2006), in addition to establishing formal partnerships with various academic and private partners. JPL's decade forward since then has featured a series of successes including the Mars Science Lab and Mars 2020 missions.

In 2020, one important challenge for JPL was during and post the covid-19 pandemic and its impact on the lab as it struggled "with how best to balance onsite and offsite work following the post-COVID societal changes", as was pointed out in the Psyche mission review report (NASA, 2022).

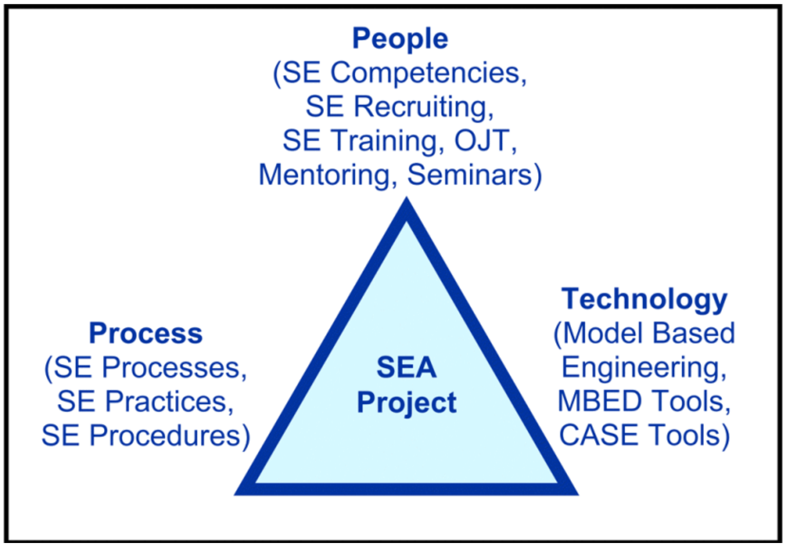


Figure 3. How the SEA Project Addresses the Three Key Aspects of Change. *(Jansma & Jones, 2006)*

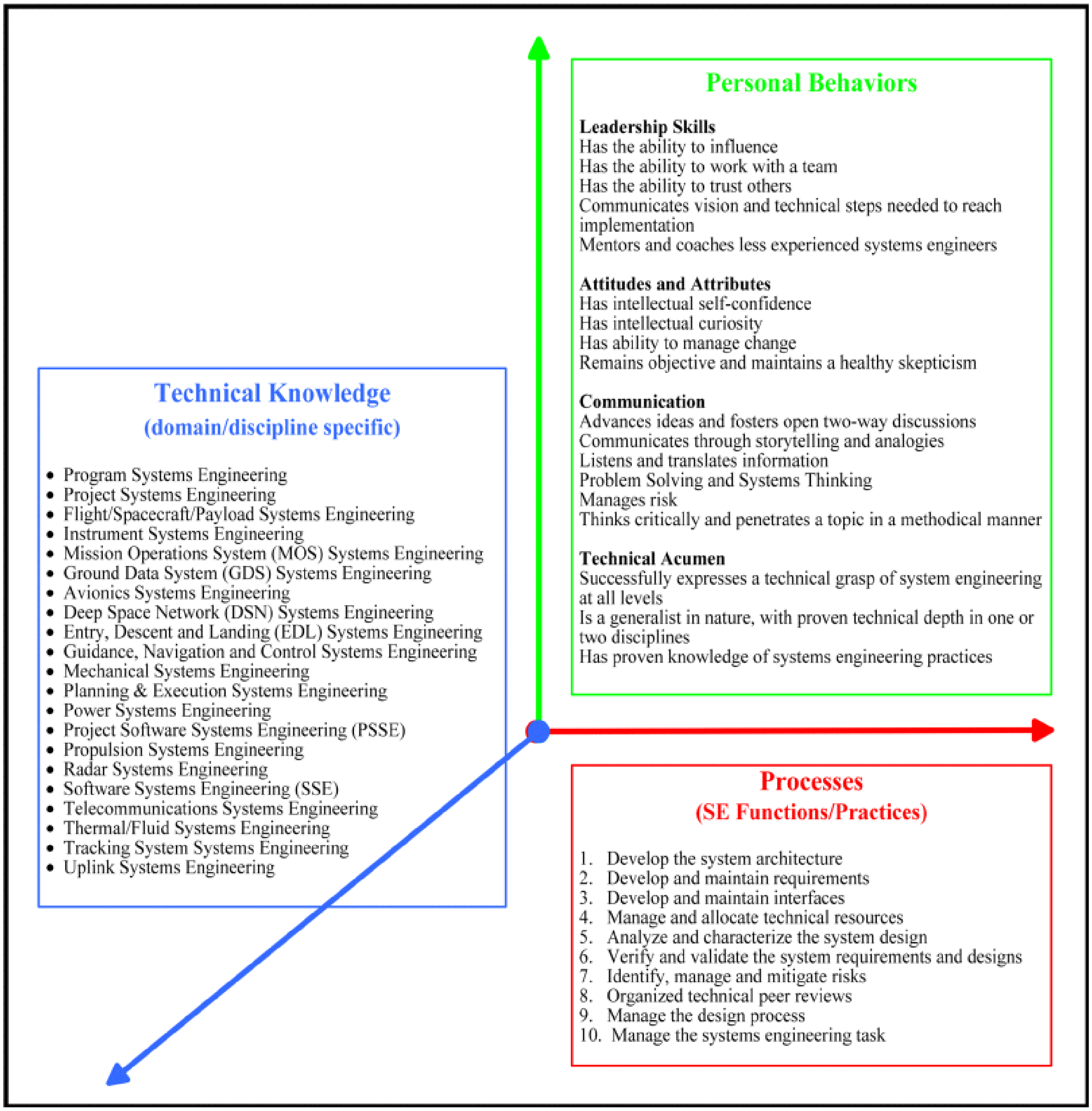


Figure 4. The Three Axes of the JPL Systems Engineering Competency Model. *(Jansma & Jones, 2006)*

1.1.1.5 Handbooks, Metrics, Programs, and Initiatives

1.1.1.5.1 NASA Systems Engineering and Project Management Handbooks

NASA has a set of handbooks that codify guidelines, standards and best practices for the management and execution of the projects and missions that the agency undertakes. These handbooks are interdependent and interconnected in their guidance. Some examples are that are most relevant for this research are:

- NASA's Software Engineering and Assurance Handbook that provides guidance on software engineering best practices to implement the requirements of NPR 7150.2, NASA Software Engineering Requirements, and the implementation of the NASA Software Assurance and Software Safety requirements in NASA-STD-8739.8 (NASA-HDBK-2203, 2020; NPR 7150.2D, 2022; NASA Office of Safety and Mission Assurance (OSMA)).

- NASA's Cost Estimating Handbook (CEH) that provides guidance for cost estimates of flight projects at NASA using a 12-step cost estimating process covering the project definition, cost methodology, and cost estimate (CEH Ver 4.0, 2015)

- NASA's Risk Management Handbook that provides guidance for systems engineers, risk managers, and risk analysts on risk management (RM) best practices for applying the requirements of NPR 8000.4A, based on both the qualitative Continuous Risk Management (CRM) and the more rigorous quantitative Risk-Informed Decision Making (RIDM) processes (Dezfuli, et al., 2011; Dezfuli, Stamatelatos, Maggio, Everett, & Youngblood, 2010; NID 8000-108, 2016).

- NASA's Project Planning and Control (PP&C) Handbook that provides guidance on project control practices in the functional areas of "PP&C Integration, Cost Estimation/Cost Assessment, Resource Management, Scheduling, Acquisition and Contract Management, Risk Management, and Configuration Management/Data Management" (NASA/SP-2016-3424, 2016).

- NASA's Systems Engineering Handbook that provides general guidance on the systems engineering process at the agency and is a companion document to NPR 7123.1, Systems Engineering Processes and Requirements, as well as the systems engineering handbooks and directives developed at each specific NASA center (NASA SP-2016-6105 Rev2, 2016; NPR 7123.1C, 2020).

- NASA's Space Flight Program and Project Management Handbook that incorporates the "corporate knowledge" at NASA and the implementation guidance on for NASA Procedural Requirements (NPR) 7120.5, the NASA Space Flight Program and Project Management Requirements (Osborne, 2022; NPR 7120.5F, 2021). NASA's Science Mission Directorate (SMD) has also created a policy document on "Standard Mission Assurance Requirements (MAR) for Payload Classification D". D-MAR tailors the cumbersome requirements of higher-class payloads (A, B, C) to a more cost-effective process for class D, emphasizing insight as opposed to oversight (SMD Policy Document SPD-39, 2021). Lastly, NPR 7120.8, the NASA Research and Technology Program and Project Management Requirements is another critical guiding document at NASA for project management (NPR 7120.8A, 2018).

Figure 5, taken from NASA's Project Planning and Control (PP&C) Handbook, provides an overview of how PP&C, systems engineering, and project management activities fall within the context of one another at NASA (NASA/SP-2016-3424, 2016).

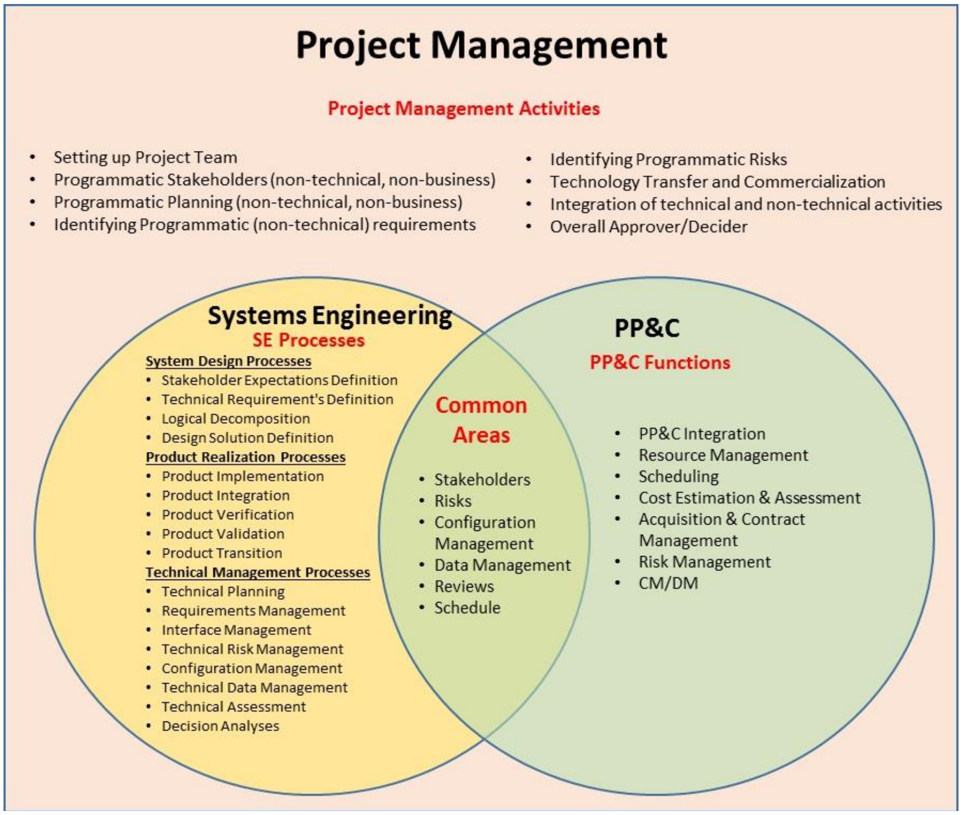


Figure 5. PP&C and Systems Engineering Activities in the Context of Project Management.
(NASA/SP-2016-3424, 2016)

In addition to complying to the NASA handbooks, two of JPL's main guiding documents are the JPL Flight Project Practices and the JPL Design Principles. These two documents are internal to JPL and not publicly available, but they were developed to codify JPL's processes, procedures, and best practices as presented in *Figure 6* (Linick & Briggs, 2014). In a presentation by Charles Leising at the Space Telescope Science Institute Technical Colloquium in 2004 on "JPL's Approach for Helping Flight Project Managers Meet Today's Management Challenges", Leising showed a snippet overview of these two documents as presented in *Figure 7* and *Figure 8* (Leising, 2004).

The Flight Project Practices mainly covers management, engineering, and mission assurance processes that represent top level implementation practices (Leising, 2004). The Design Principles, on the other hand, covers the mission, design, components of the system, hardware, software, and mission operations (including interface documents, margins, subsystem designs, etc.) (Leising, 2004). Lastly JPL additionally uses compliance matrices attached to implementation plans where any "deviations must be justified and approved" (Leising, 2004).

Figure 9 presents the project lifecycle at JPL, with the required deliverables and reviews at each phase. At each of these gates, the Flight Project Practices invoke "over 100 products" for planning, cost, and technical issues, such as "project plans, mission scenarios, system requirements, cost estimates, flight designs, verification results, interface documentation, command dictionaries, flight rules, etc." (Leising, 2004).

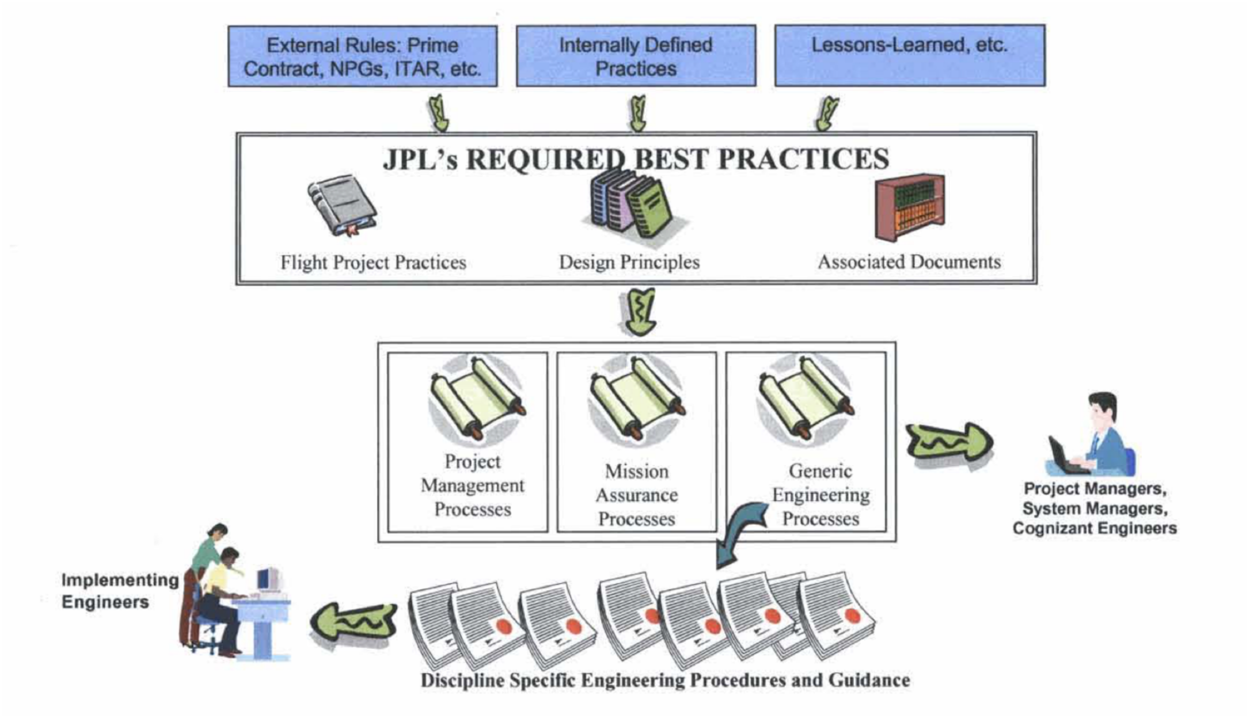
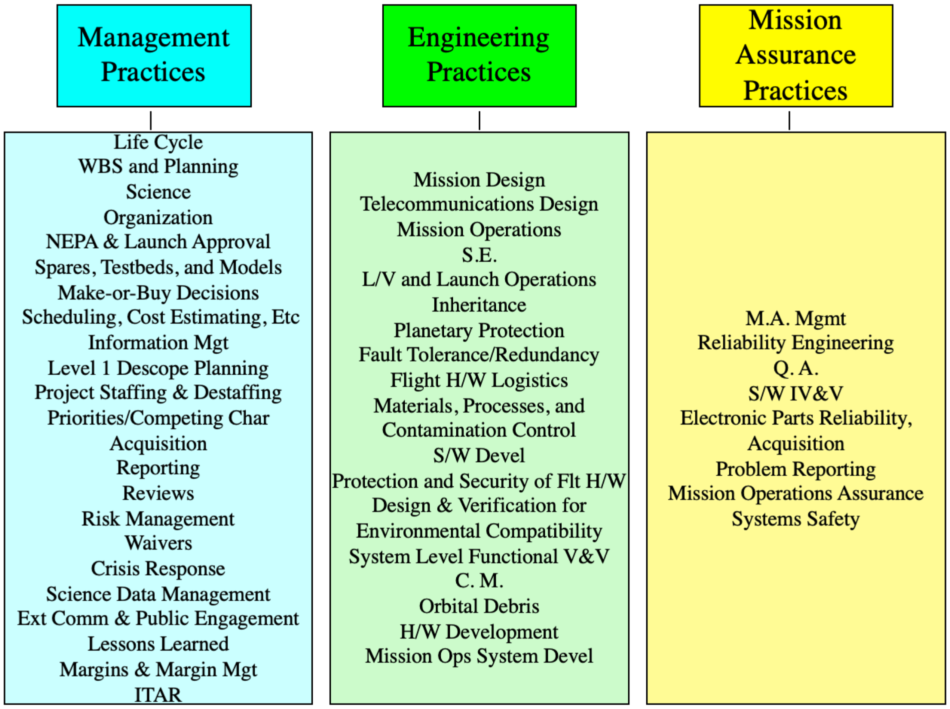


Figure 6. Flow of Requirements to Processes at JPL. (Linick & Briggs, 2014)



Management Practices

Life Cycle
WBS and Planning
Science
Organization
NEPA & Launch Approval
Spares, Testbeds, and Models
Make-or-Buy Decisions
Scheduling, Cost Estimating, Etc
Information Mgt
Level 1 Descope Planning
Project Staffing & Destaffing
Priorities/Competing Char
Acquisition
Reporting
Reviews
Risk Management
Waivers
Crisis Response
Science Data Management
Ext Comm & Public Engagement
Lessons Learned
Margins & Margin Mgt
ITAR

Engineering Practices

Mission Design
Telecommunications Design
Mission Operations
S.E.
L/V and Launch Operations
Inheritance
Planetary Protection
Fault Tolerance/Redundancy
Flight H/W Logistics
Materials, Processes, and Contamination Control
S/W Devel
Protection and Security of Flt H/W
Design & Verification for Environmental Compatibility
System Level Functional V&V
C. M.
Orbital Debris
H/W Development
Mission Ops System Devel

Mission Assurance Practices

M.A. Mgmt
Reliability Engineering
Q. A.
S/W IV&V
Electronic Parts Reliability, Acquisition
Problem Reporting
Mission Operations Assurance
Systems Safety

Figure 7. JPL Flight Project Practices. (Leising, 2004)

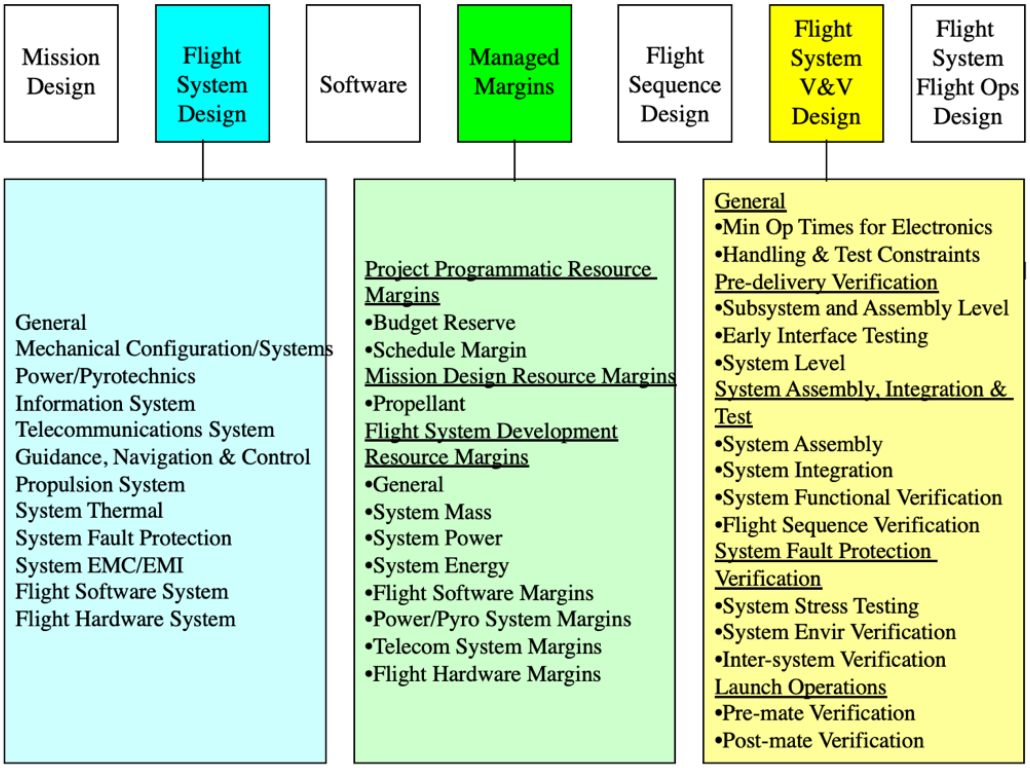


Figure 8. JPL Design Principles. *(Leising, 2004)*

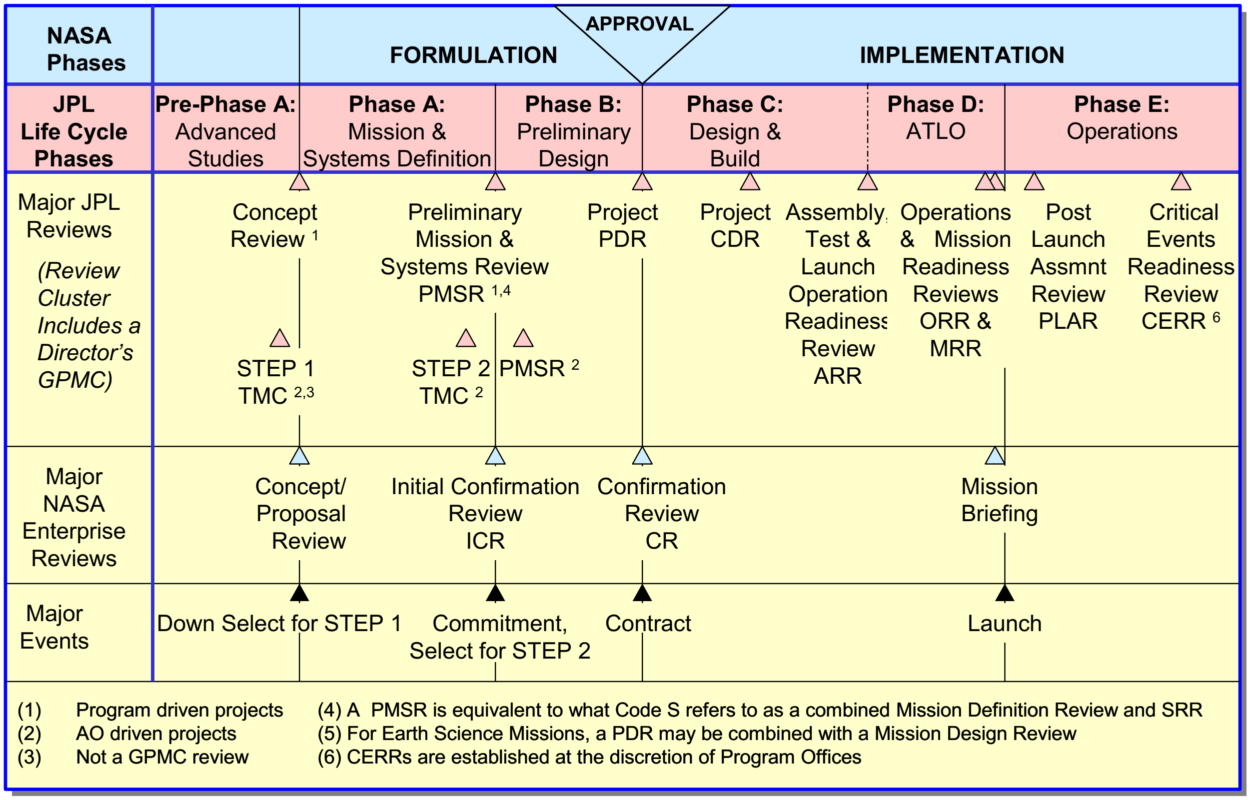


Figure 9. JPL Project Lifecycle. *(Leising, 2004)*

1.1.1.5.2 NPR 7120.5, NPR 7120.8, and D-MAR

This section takes a deeper dive into NASA's project management handbooks, NPR 7120.5, NPR 7120.8, and D-MAR to create a solid foundational understanding of these documents.

NPR 7120.5, the NASA Space Flight Program and Project Management Requirements, is the main guiding document that uniformly establishes "the requirements by which NASA formulates and implements space flight programs and projects" (Osborne, 2022; NPR 7120.5F, 2021). NPR 7120.5 has gone through dramatic changes throughout the years, from its first revision 7120.5A in 1996 to 7120.5F in 2021, reflecting changes in NASA's policies, procedures, and best practices (Hoffman (Ed.) & Lawbaugh (Ed.), 1998; NPR 7120.5F, 2021).

The first revision 7120.5A in 1996 was in alignment with NASA's Strategic Management System at the time, that aimed to improve the agency's planning, approval, execution, and evaluation of missions and projects. As described by (Hoffman (Ed.) & Lawbaugh (Ed.), 1998):

> "An Agencywide team has spent thousands of hours developing the NASA Program and Project Management Processes and Requirements- NPG 7120.5A. We have created significant flexibility, authority and discretion for the program and project managers to exercise and carry out their duties and have delegated the responsibility and the accountability for their programs and projects".

7120.5A provided a "process-based approach" with a "tailoring capability" to offer flexibility and meet the different needs for the different NASA centers. The process comprised of four subprocesses: Formulation, Approval, Implementation, and Evaluation, as seen in the Provide Aerospace Products and Capabilities (PAPAC) process in *Figure 10* and expanded on in *Figure 11*. Formulation deals with the project's requirements and concepts, Approval refers to the Program Management Council process, Implementation is the execution phase, and Evaluation as both a customer and independent assessment (Hoffman (Ed.) & Lawbaugh (Ed.), 1998).

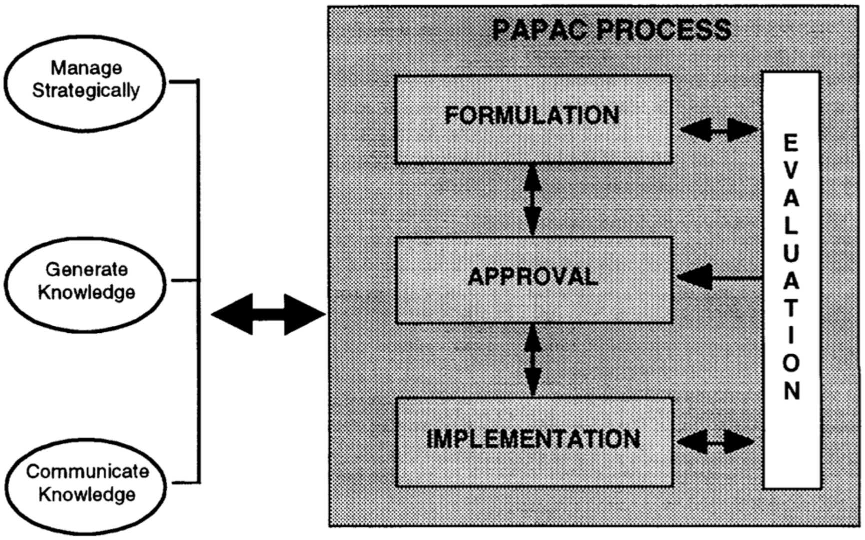


Figure 10. The "Provide Aerospace Products and Capabilities" (PAPAC) Process. *(Hoffman (Ed.) & Lawbaugh (Ed.), 1998)*

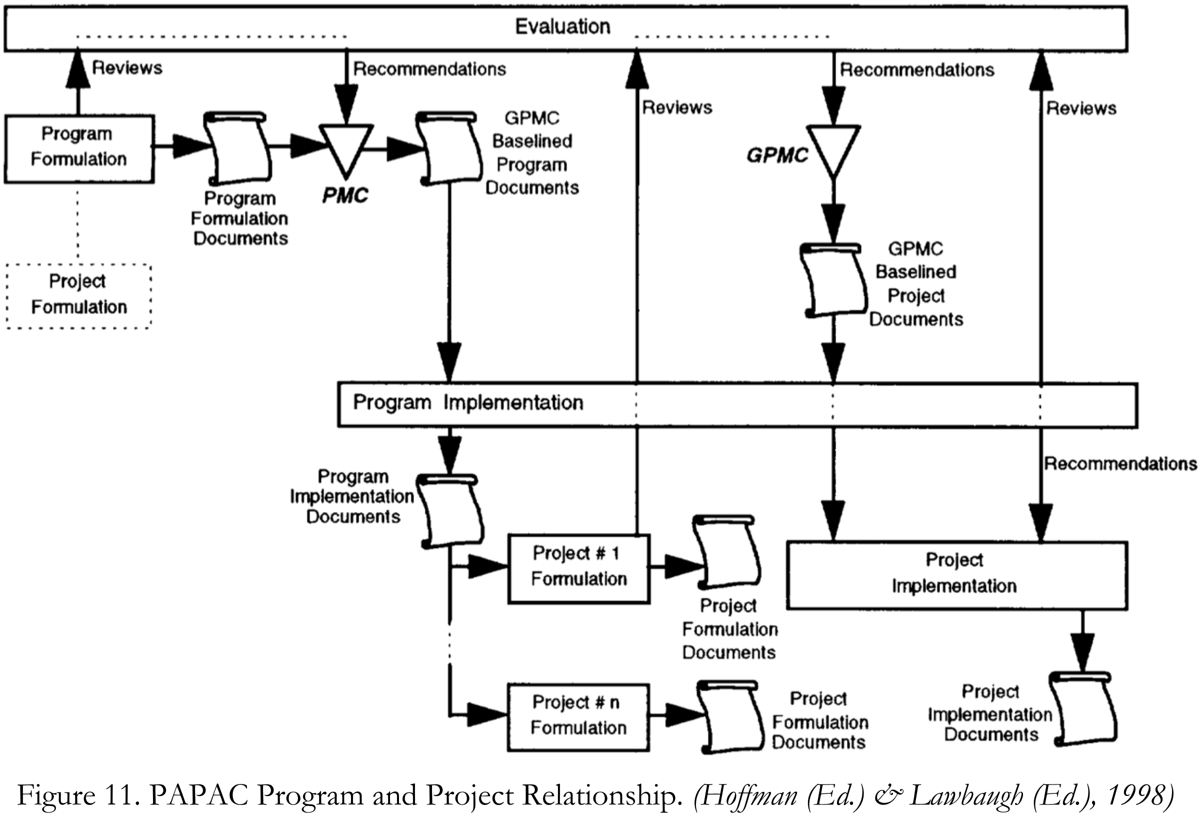


Figure 11. PAPAC Program and Project Relationship. *(Hoffman (Ed.) & Lawbaugh (Ed.), 1998)*

Starting from 7120.5B in 2002, a comprehensive definition of cost, schedule, and content commitments was required, incorporating NASA Customers and Stakeholders to the PAPAC process, with a clear emphasis on the "safety first", specifically saying (AE/Office of Chief Engineer, 2002),

> "NASA will conduct its programs and projects with safety as the first priority. Safety and reliability will be an integral part of the total design, development, and operations. Processes will be in place to uncover potential failures throughout the life cycle. Decisions will be made on programs and projects consistent with NASA safety principles. These principles include safety to the public, astronauts and pilots, the NASA workforce, and high-value equipment and property".

Fast forwarding throughout all the revisions C through F in 2021, NASA's 7120.5F reflected major changes in comparison to the initial revision (NPR 7120.5F, 2021). Management requirements became more detailed and bureaucratic over time, due to the need for a more robust and comprehensive management, intended to promote safety, quality, and efficiency, to minimize risks, and to ensure the success of NASA's missions.

NPR 7120.5F distinguishes between programs and projects, as shown in *Figure 12* (NPR 7120.5F, 2021). Programs are divided into four types and projects into three categories (defined in *Table 2*). The definitions of these types and categories, verbatim from (NPR 7120.5F, 2021), are as follows:

- Program— "Programs are a strategic investment by Mission Directorates or mission support offices with a defined architecture and/or technical approach, requirements, funding level, and a management structure that initiates and directs one or more projects. A program implements a strategic direction that the Agency has identified as needed to accomplish Agency goals and objectives".
    - "a. Single-Project: These programs (e.g., James Webb Space Telescope) tend to have long development and operational lifetimes and represent a large investment of Agency resources. Multiple organizations or agencies contribute to them. Single-project programs have one project and implement their program objectives and requirements through one of two management approaches: (1) separate program and project structures or (2) a combined structure. The requirements for both programs and projects apply to single-project programs as described in this NPR.

    - b. Uncoupled: These programs (e.g., Discovery Program) are implemented under a broad theme (like planetary science) and/or a common program implementation mechanism, such as providing flight opportunities for formally competed cost-capped projects or Principal Investigator (PI)-led missions and investigations. Each project in an uncoupled program is independent of the other projects within the program.

    - c. Loosely Coupled: These programs (e.g., Mars Exploration Program) address specific objectives through multiple space flight projects of varied scope. While each project has an independent set of mission objectives, the projects as a whole have architectural and technological synergies and strategies that benefit the program. For example, Mars orbiters designed for more than one Mars year in orbit are required to carry a communication system to support present and future landers.

- d. Tightly Coupled: These programs have multiple projects that execute portions of a mission or missions. No single project is capable of implementing a complete mission. Typically, multiple NASA Centers contribute to the program. Individual projects may be managed at different Centers. The program may also include other agency or international partner contributions”.

- Project— “Space flight projects are a specific investment identified in a Program Plan having defined requirements, a life-cycle cost, a beginning, and an end. A project also has a management structure and may have interfaces to other projects, agencies, and international partners. A project yields new or revised products that directly address NASA’s strategic goals”.

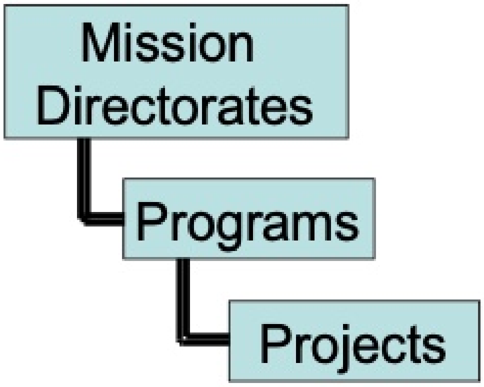
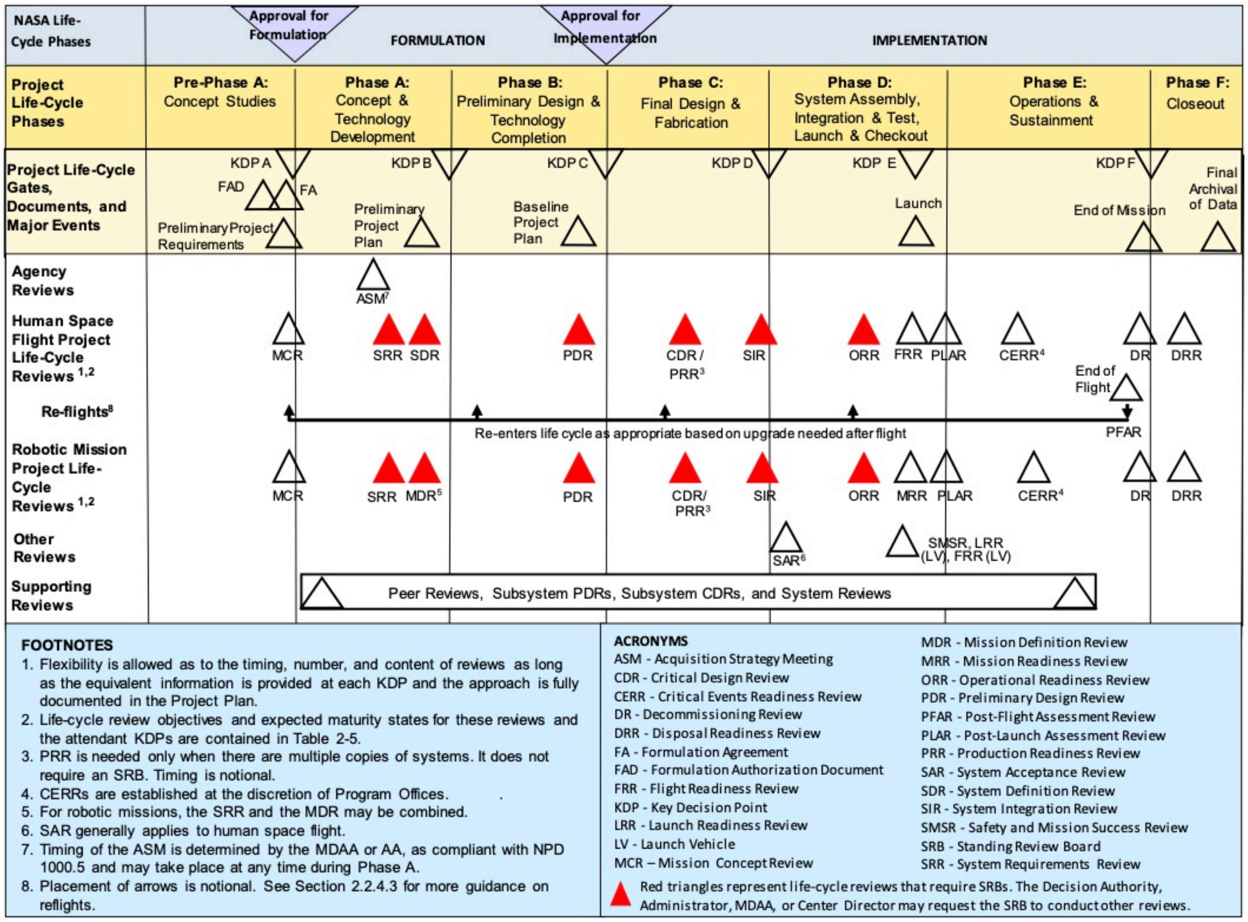


Figure 12. Programmatic Authority Organizational Hierarchy. *(NPR 7120.5F, 2021)*

Table 2. Project Categorization Guidelines in 7120.5F. Adapted from *(NPR 7120.5F, 2021)*

Project Categorization Guidelines			
Priority Level	**Project life-cycle cost (LCC) < $365M**	**$365M ≤ LCC ≤ $2B**	**LCC > $2B, significant radioactive material, or human space flight**
High	Category 2	Category 2	Category 1
Medium	Category 3	Category 2	Category 1
Low	Category 3	Category 2	Category 1

NPR 7120.5F also provides a detailed life cycle for each of its program types and projects, with “emphasis to the use of Leading Indicators in life-cycle reviews (LCRs) and Key Decision Points (KDPs)” (NPR 7120.5F, 2021). An example of the cycle for projects is presented in *Figure 13* and Table *3*.



FOOTNOTES

1. Flexibility is allowed as to the timing, number, and content of reviews as long as the equivalent information is provided at each KDP and the approach is fully documented in the Project Plan.
2. Life-cycle review objectives and expected maturity states for these reviews and the attendant KDPs are contained in Table 2-5.
3. PRR is needed only when there are multiple copies of systems. It does not require an SRB. Timing is notional.
4. CERRs are established at the discretion of Program Offices.
5. For robotic missions, the SRR and the MDR may be combined.
6. SAR generally applies to human space flight.
7. Timing of the ASM is determined by the MDAA or AA, as compliant with NPD 1000.5 and may take place at any time during Phase A.
8. Placement of arrows is notional. See Section 2.2.4.3 for more guidance on reflights.

ACRONYMS

ASM - Acquisition Strategy Meeting
CDR - Critical Design Review
CERR - Critical Events Readiness Review
DR - Decommissioning Review
DRR - Disposal Readiness Review
FA - Formulation Agreement
FAD - Formulation Authorization Document
FRR - Flight Readiness Review
KDP - Key Decision Point
LRR - Launch Readiness Review
LV - Launch Vehicle
MCR – Mission Concept Review
MDR - Mission Definition Review
MRR - Mission Readiness Review
ORR - Operational Readiness Review
PDR - Preliminary Design Review
PFAR - Post-Flight Assessment Review
PLAR - Post-Launch Assessment Review
PRR - Production Readiness Review
SAR - System Acceptance Review
SDR - System Definition Review
SIR - System Integration Review
SMSR - Safety and Mission Success Review
SRB - Standing Review Board
SRR - System Requirements Review

▲ Red triangles represent life-cycle reviews that require SRBs. The Decision Authority, Administrator, MDAA, or Center Director may request the SRB to conduct other reviews.

Figure 13. NASA Project Life Cycle. Adapted from *(NPR 7120.5F, 2021)*

Table 3. Expected Maturity State Through the Life Cycle of Projects and Single-Project Programs Adapted from *(NPR 7120.5F, 2021)*

Key Decision Point (KDP) Review	**Associated Life-cycle Review**	**LCR Objectives**	**Overall Expected Maturity State at KDP**
KDP A	Mission Concept Review (MCR)	To evaluate the feasibility of the proposed mission concept(s) and its fulfillment of the program's needs and objectives. To determine whether the maturity of the concept and associated planning are sufficient to begin Phase A.	Project addresses critical NASA need. Proposed mission concept(s) is feasible. Associated planning is sufficiently mature to begin Phase A, and the mission can likely be achieved as conceived.
KDP B	System Requirements Review (SRR)	To evaluate whether the functional and performance requirements defined for the system are responsive to the program's requirements on the project and represent achievable capabilities.	Proposed mission/system architecture is credible and responsive to program requirements and constraints, including resources. The maturity of the project's mission/system definition and associated plans is sufficient to begin Phase B, and the mission can likely be achieved within available resources with acceptable risk.
	Mission Definition Review (MDR) or System Definition Review (SDR)	To evaluate the credibility and responsiveness of the proposed mission/system architecture to the program requirements and constraints, including available resources. To determine whether the maturity of the project's mission/system definition and associated plans are sufficient to begin Phase B.	

KDP C	Preliminary Design Review (PDR)	To evaluate the completeness/consistency of the planning, technical, cost, and schedule baselines developed during Formulation. To assess compliance of the preliminary design with applicable requirements and to determine if the project is sufficiently mature to begin Phase C.	Project's planning, technical, cost, and schedule baselines developed during Formulation are complete and consistent. The preliminary design complies with its requirements. The project is sufficiently mature to begin Phase C, and the cost and schedule are adequate to enable mission success with acceptable risk.
KDP D	Critical Design Review (CDR)	To evaluate the integrity of the project design and its ability to meet mission requirements with appropriate margins and acceptable risk within defined project constraints, including available resources. To determine if the design is appropriately mature to continue with the final design and fabrication phase.	Project is still on plan. The risk is commensurate with the project's payload classification, and the project is ready for AI&T with acceptable risk within its ABC.
	Production Readiness Review (PRR)	To evaluate the readiness of system developer(s) to produce the required number of systems within defined project constraints for projects developing multiple similar flight or ground support systems. To evaluate the degree to which the production plans meet the system's operational support requirements.	

	System Integration Review (SIR)	To evaluate the readiness of the project and associated supporting infrastructure to begin system AI&T, evaluate whether the remaining project development can be completed within available resources, and determine if the project is sufficiently mature to begin Phase D.	
KDP E	Operational Readiness Review (ORR)	To evaluate the readiness of the project to operate the flight system and associated ground system(s) in compliance with defined project requirements and constraints during the operations/sustainment phase of the project life cycle.	Project and all supporting systems are ready for safe, successful launch and early operations with acceptable risk within ABC.
	Mission Readiness Review (MRR) or Flight Readiness Review (FRR)	To evaluate the readiness of the project and all project and supporting systems for a safe and successful launch and flight/mission.	
KDP En (applies only to Single-Project Programs)	Program Implementation Review (PIR)	To evaluate the program's continuing relevance to the Agency's Strategic Plan, assess performance with respect to expectations, and determine the program's ability to execute the implementation plan with acceptable risk within cost and schedule constraints.	Program still meets Agency needs and is continuing to meet Agency commitments, as planned.

Non-KDP Reviews	Post-Launch Assessment Review (PLAR)	To evaluate in-flight performance of the flight system early in the mission and determine whether the project is sufficiently prepared to begin Phase E.	PLAR Expected State: Project is ready to conduct mission operations with acceptable risk within ABC.
	Critical Events Readiness Review (CERR)	To evaluate the readiness of the project and the flight system for execution of a critical event during the flight operations phase of the life cycle.	Mission CERR Expected State: Project is ready to conduct critical mission activity with acceptable risk.
	Post-Flight Assessment Review (PFAR)	To evaluate how well mission objectives were met during a human space flight mission and to evaluate the status of the returned vehicle.	PFAR Expected State: All anomalies that occurred in flight are identified. Actions necessary to mitigate or resolve these anomalies are in place.
KDP F	Decommissioning Review (DR)	To evaluate the readiness of the project to conduct closeout activities including final delivery of all remaining project deliverables and safe decommissioning of space flight systems and other project assets. To determine if the project is appropriately prepared to begin Phase F.	Project decommissioning is consistent with program objectives and project is ready for safe decommissioning of its assets and closeout of activities, including final delivery of all remaining project deliverables and disposal of its assets.
Non-KDP Disposal Readiness Review	Disposal Readiness Review (DRR)	To evaluate the readiness of the project and the flight system for execution of the spacecraft disposal event.	Mission DRR Expected State: Project ready to conduct disposal activity with acceptable risk.

NASA's Science Mission Directorate (SMD) has also created a policy document on "Standard Mission Assurance Requirements (MAR) for Payload Classification D". D-MAR tailors the cumbersome requirements of higher-class payloads (A, B, C) to a more cost-effective process for class D, emphasizing insight as opposed to oversight (SMD Policy Document SPD-39, 2021). According to (SMD Policy Document SPD-39, 2021), the DMAR policy document,

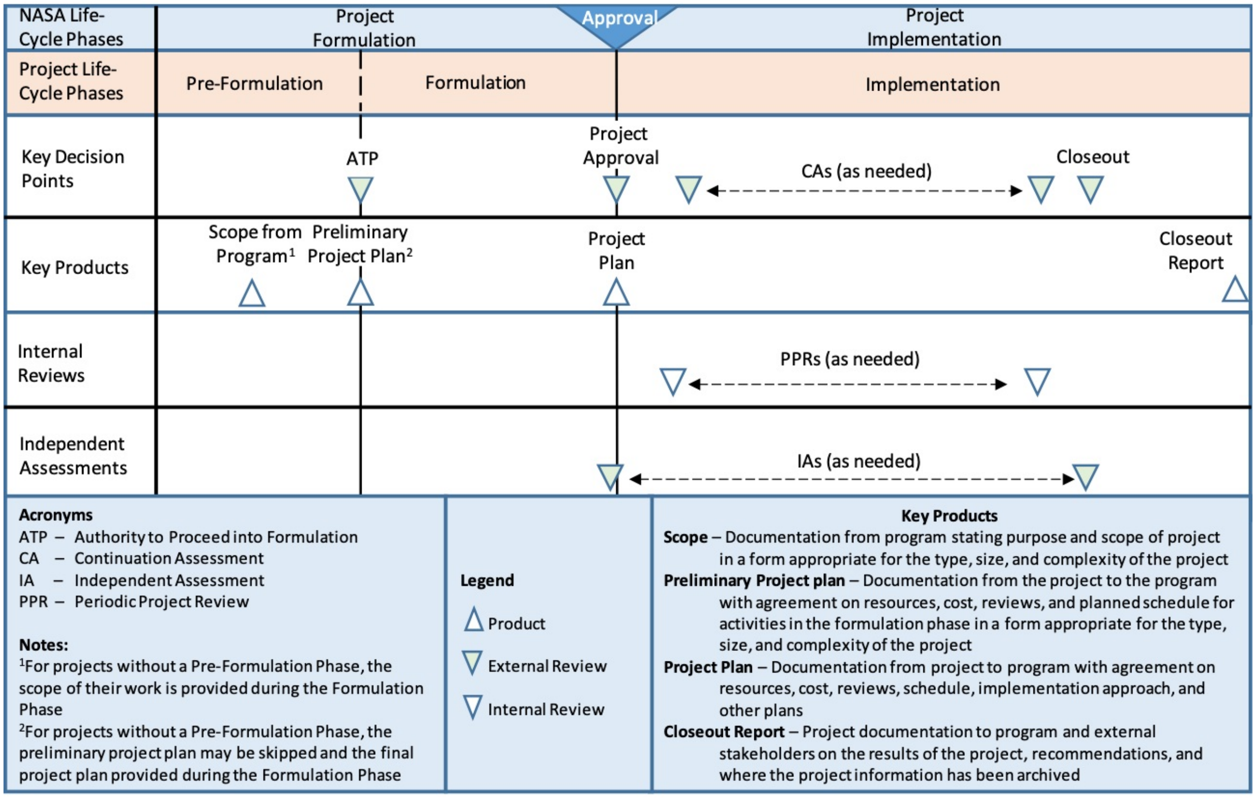
> "[D-MAR] takes a different tact from past Program-level MARs typical of NASA; in this case, the emphasis is on implementing developer practices that have been proven successful, using teamwork between NASA and the Developer to assure mission success, and driving efforts based on characterization and management of risk than enforcement of broad, but prescriptive, requirements. This approach by no means encourages ignoring risks, but on the contrary, emphasizes using rigorous understanding of risk to guide development and testing efforts".

The other critical guiding document at NASA for project management, NPR 7120.8, the NASA Research and Technology Program and Project Management Requirements, is distinct from NPR 7120.5, focusing on Research and Technology (R&T) programs and projects. NPR 7120.8 has a detailed definition for technology development (TD) projects and research projects, distinguishing them from each other (NPR 7120.8A, 2018):

- "Technology Development (TD) projects: TD projects characterize or enhance performance and mature a technology or set of related technologies. These projects attempt to solve a specific problem or address a practical need. They advance investigations, experiments, and prototyping to higher level of maturity. This should typically be a point at which a decision to continue into a new project task or cease investment can be made based on performance. The most mature R&T projects advance to the point where the technology is at its final pre-production version, and where the prototype design has been fully developed, tested, and verified. TD projects typically focus their activities on fully establishing their approach and techniques, answering all pertinent questions on the theory or hypothesis, developing the simulations, prototypes, and models that demonstrate the capability, and testing, verifying and validating the capability with the intended customer or beneficiary. These activities reduce the risk associated with the new technology to the point where it is ready for use by a customer or beneficiary. Usually, TD projects have an identified or targeted beneficiary who is the intended user of the technology being developed and who is involved throughout the development process."

- "Research projects: Research projects perform either basic research or applied research. Basic research addresses the need for knowledge through investigation of fundamental principles and interactions. In the early stages, it may take the form of theory development, or scientific and/or technical investigations as to the feasibility of an idea. The activity at this stage is generally driven by a principal investigator. As the basic research evolves, hypotheses may be formed, or scientific testing may proceed to evaluate the theories. Research papers, presentations or articles are the typical outcomes of this phase. For applied research, once an idea is defined enough to start thinking about practical application, single prototypes can be designed and tested, or a simulation or model developed to demonstrate the potential of the research. Basic and applied research is directly tied to the Agency's vision and mission, as defined by NPD 1001.0. The results of this basic or applied research may provide fundamental discoveries, expand the knowledge base, provide scientific and technological breakthroughs that are immediately applicable, or evolve into more advanced technology development. Research projects are characterized by unpredictability of outcome. Funding may be at a fixed level on a yearly basis."

As explained in the policy document, "Due to the wide range of activities, this NPR does not standardize their development into a single process, but rather provides a minimum management requirement set for R&T programs and projects that is tailorable to suit their type and complexity. This NPR then establishes the management processes and practices available for NASA R&T activities and identifies the Decision Authority (DA) responsible to select the appropriate process" (NPR 7120.8A, 2018). *Figure 14* shows the project life cycle according to (NPR 7120.8A, 2018).



Acronyms
ATP – Authority to Proceed into Formulation
CA – Continuation Assessment
IA – Independent Assessment
PPR – Periodic Project Review

Notes:
[1] For projects without a Pre-Formulation Phase, the scope of their work is provided during the Formulation Phase
[2] For projects without a Pre-Formulation Phase, the preliminary project plan may be skipped and the final project plan provided during the Formulation Phase

Key Products
Scope – Documentation from program stating purpose and scope of project in a form appropriate for the type, size, and complexity of the project
Preliminary Project plan – Documentation from the project to the program with agreement on resources, cost, reviews, and planned schedule for activities in the formulation phase in a form appropriate for the type, size, and complexity of the project
Project Plan – Documentation from project to program with agreement on resources, cost, reviews, schedule, implementation approach, and other plans
Closeout Report – Project documentation to program and external stakeholders on the results of the project, recommendations, and where the project information has been archived

Figure 14. R&T Project Life Cycle. *(NPR 7120.8A, 2018)*

1.1.1.5.3 Technology Readiness Assessment and Levels

NASA currently uses the Technology Readiness Assessment (TRA) process to evaluate the maturity of a particular technology, throughout its process of development, identifying its potential risks and areas for improvement, and determining if it is ready for use in a flight. The process is used to assess the maturity of technologies at different stages of development, from basic research to flight-ready hardware. Throughout TRA, NASA assigns the so-called Technology Readiness Levels (TRL) to various technologies. As defined by (Kimmel, et al., 2020), "The TRL describes the state of a given technology and provides a baseline from which maturity is gauged and advancement defined."

The goal of TRA and TRL is to have an accurate, consistent, and standardized evaluation during the entire process of technology development that could increase opportunities for technology infusion, through understanding the level of risk that a technology poses. The process claims to support innovation because "a firm grasp of the risks balanced against benefits supports an environment where innovation is nurtured, rather than avoided" (Kimmel, et al., 2020).

Figure 15 presents the "thermometer" TRL scale, ranging from 1 to 9 based of the maturity of a technology, with 1 representing basic technology research and 9 representing a flight-proven system. The bracket between TRL 1-3 holds the technology conception phase, which then transitions into development and demonstration between TRL 4-6. TRL 6 is an important milestone because it qualifies the technology to the Preliminary Design Review (PDR). Following TRL 6, *Figure 16* presents the two paths for technologies to flight. Most common operational mission technologies pass through the TRL 8-9 path, skipping TRL 7. What this path means is that "building and testing an engineering unit, detailed analysis, and detailed drawings" would be required, leading to the Critical Design Review (CDR). TRL 8 then would verify the flight qualification of the technology at the "subsystem and system level", leading to TRL 9 at which point the technology is "flight proven" and successfully operated (Kimmel, et al., 2020).

The other path after TRL 6, however, is that of technology demonstrations for new technologies where TRL 7 is not skipped. This added step requires the development of a representative "high-fidelity prototype" whose demonstration would be critical for risk reduction, but, as (Kimmel, et al., 2020) explains, "not necessarily a "build-to-print" unit that might be used on a specific future operational space flight mission".

Aside from, but associated with the TRL and TRA concepts, are important categoric terminologies for flight systems: new technology, standard engineering, or heritage as shown in *Figure 17*. These categories have an impact on demonstration and integration procedures (Kimmel, et al., 2020).

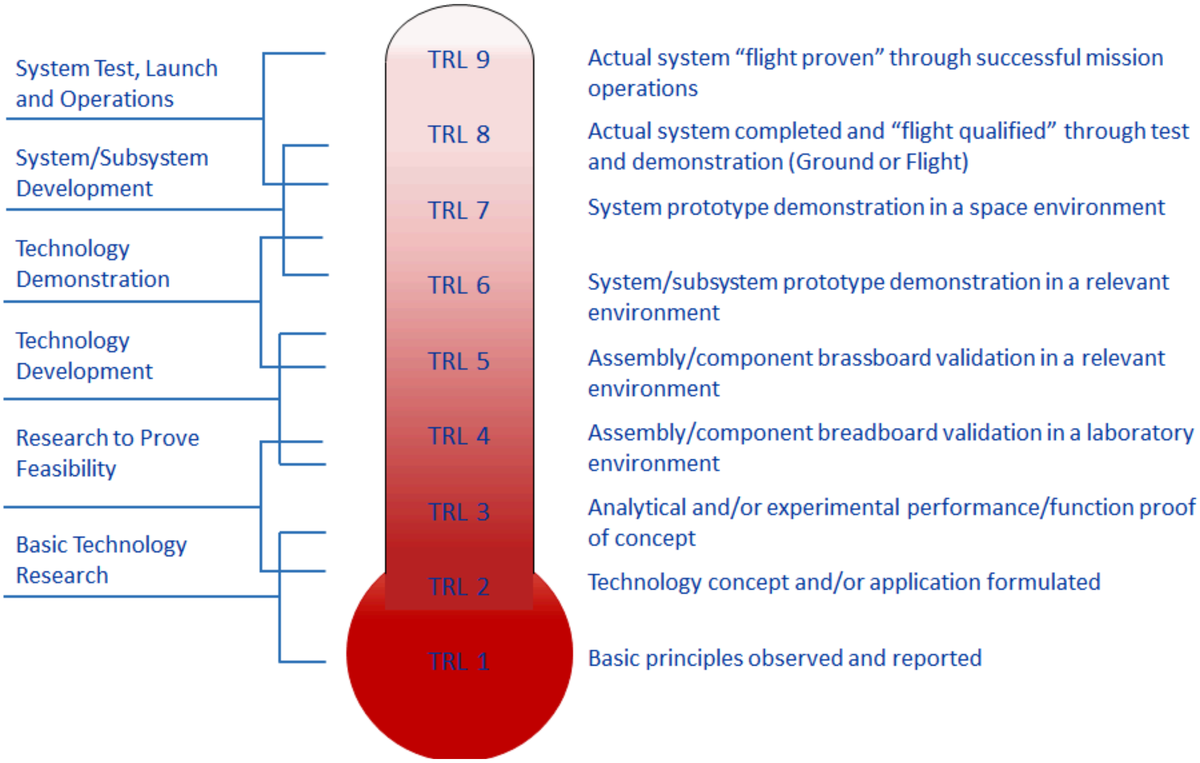


Figure 15. Thermometer Scale for NASA's Technology Readiness Levels. (Kimmel, et al., 2020)

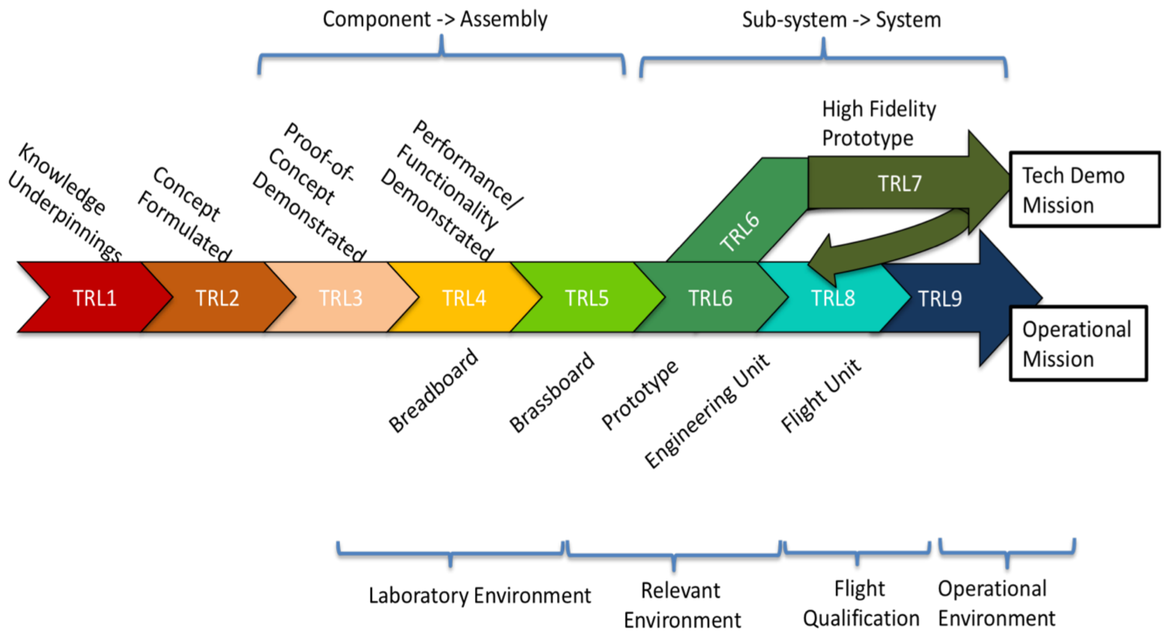


Figure 16. TRL Paths to Flight. (Kimmel, et al., 2020)

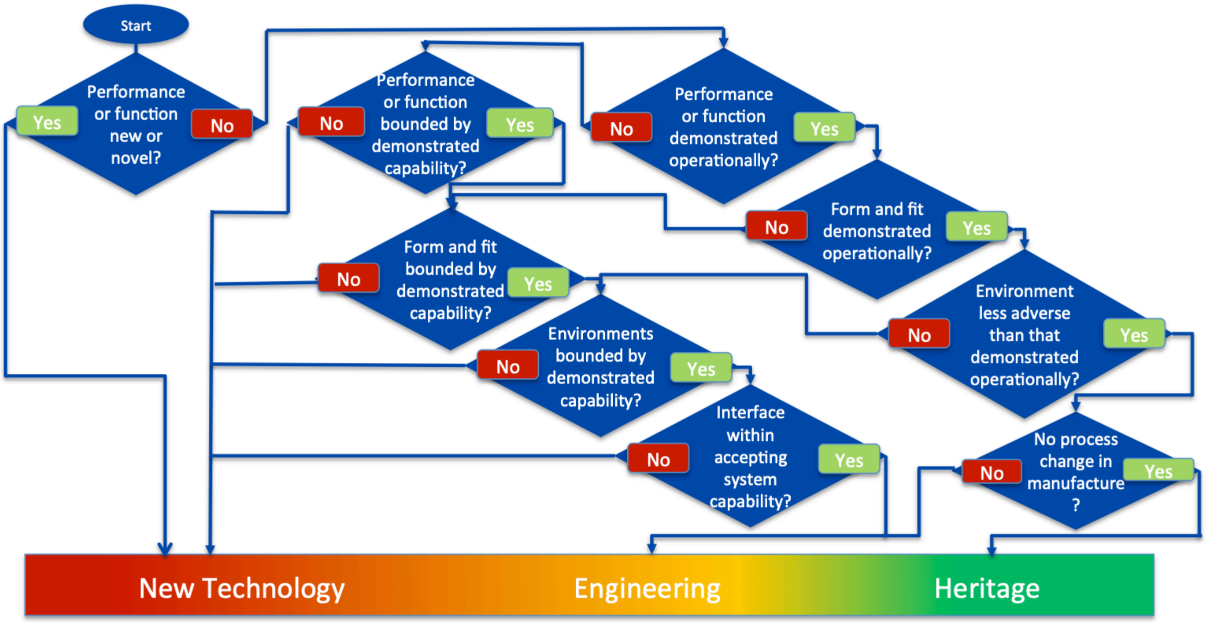


Figure 17. Flight System Categories: New Technology, Standard Engineering, or Heritage. *(Kimmel, et al., 2020)*

1.1.1.5.4 SMD

Within SMD, there exists multiple programs and initiatives for technology development and infusions, three of which are expanded on below: the Small, Innovative Missions for PLanetary Exploration (SIMPLEx), the Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO), and the Maturation of Instruments for Solar System Exploration (MatISSE) programs.

1.1.1.5.4.1 SIMPLEx

SIMPLEx is a program that supports the goals of the Planetary Science Division (PSD) through advancing small, cost-effective, and low-risk spacecraft (including CubeSats) that investigate high-priority science questions for any Solar System body aside from the Earth and Sun (SOMA LaRC, 2018; Mercer, 2019). The SIMPLEx process begins with a Stand-Alone Missions of Opportunity Notice (SALMON) Announcement of Opportunity (AO) from SMD to collect PI-led proposal submissions. Proposals that pass the compliance checklist are sent for evaluation by several panels. The Science Evaluation Panel evaluates the "intrinsic science merit", the "experiment science implementation merit", and the "feasibility" of the proposed investigation. (SIMPLEx SALMON-3 PEA J Evaluation Plan, 2018).

The Technical, Management, and Cost (TMC) Evaluation Panel, on the other hand, is led by an Acquisition Manager who works for the NASA Science Office for Mission Assessments (SOMA) at the Langley Research Center (LaRC). SOMA reports to NASA Headquarters and is separate from the rest of LaRC. The panel's evaluators are a combination of contractors, consultants and civil servants who are experts in their relevant areas and are chosen specifically to avoid any conflicts of interest (SIMPLEx SALMON-3 PEA J Evaluation Plan, 2018). Proposals are then evaluated according to several factors including the "adequacy and robustness of the instrument implementation plan, design and plan for operations, flight systems. the management approach and schedule, including the capability of the management team, and the cost plan, including cost feasibility and cost risk" (SIMPLEx SALMON-3 PEA J Evaluation Plan, 2018).

SIMPLEx-1, the first planetary science CubeSat PSD solicitation in 2014, capped mission proposal to \$5.6M for the full mission lifecycle of the mission and limited the size to 1U, 2U, 3U, or 6U for launch (Mercer, 2019). The two selected proposals in 2015 were the CubeSat Particle Aggregation and Collision Experiment (Q-PACE) and the Lunar Polar Hydrogen Mapper (LunaH-Map) (NSPIRES NASA PRS, 2015; Hardgrove, 2016; Genova & Dunham, 2017; Colwell, Brisset, Dove, Jarmak, & Q-PACE team, 2019). The cost cap for SIMPLEx, however, drastically increased to \$55M along with the mass limit increase to 180 kg in the 2017 PSD SIMPLEx solicitation— "an order of magnitude higher than those given under SIMPLEx-1, but […] an order of magnitude less than PSD's Discovery program" (Mercer, 2019). The three selected proposals in 2019 out of this solicitation were Lunar Trailblazer, Janus asteroid mission, and Escape and Plasma Acceleration and Dynamics Explorers (EscaPADE) (Foust, NASA to continue Lunar Trailblazer despite cost overrun, 2022). Lunar Trailblazer has already exceeded its cost cap by 30%, reaching \$72M in its development, and the latter two missions have both encountered problems delaying their launch that was originally slated, then removed, as part of NASA's Psyche mission (Foust, NASA to continue Lunar Trailblazer despite cost overrun, 2022). With these cost increases, the 2022 planetary science decadal survey recommended increasing the SIMPLEx cost cap from \$55M to \$80M (Canup & Christensen, 2022).

In addition to the previously mentioned missions, NASA has also launched the JPL directed CubeSat Mars Cube One (MarCO) on the InSight mission to Mars and the partnered Light Italian CubeSat for Imaging of Asteroids (LICIA) secondary payload on NASA's Double Asteroid Redirection Test (DART) mission (Mercer, 2019; Sternberg, 2019; Handal, Surowiec, & Buckley, 2022).

1.1.1.5.4.2 PICASSO and MatISSE

The other two programs for technology development and maturation within SMD are PICASSO and MatISSE that were established in 2013 at NASA (Voytek, 2023). As shown in *Figure 18,* these two programs are meant to mature technologies throughout TRL 1-3 then 4-6 respectively. PICASSO is a no-due-dates (NoDD) program where proposals for a of specific proposal opportunity on new planetary and astrobiology science instrumentation and technology can be submitted at any time. The program supports the development of early-stage, innovative instrument "feasibility studies, concept formation, proof of concept instruments, and advanced component technology development" to mature the proposed technology to TRL 3 where it can be passed on to the MatISSE program (Voytek, 2023).

Aimed at maturing technologies between TRL 4 and 6, MatISSE address the so-called "valley of death" in technology development. This program supports the development of advanced technologies and instruments that address specific scientific objectives for future planetary spacecraft and missions. With an entry of TRL 4, the goal of MatISSE is to develop these instruments to approximately TRL 6, where they can be ready to be proposed for future planetary flight opportunity announcements (Voytek, 2023).

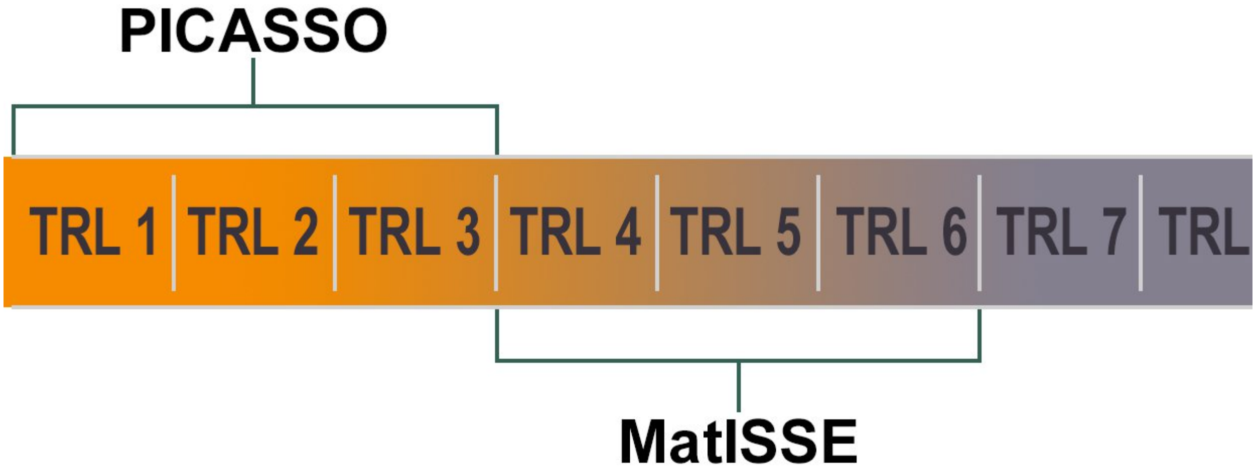


Figure 18. PICASSO and MatISSE Instrument Development Programs. *(Voytek, 2023)*

1.1.1.5.5 STMD

STMD has a series of programs and initiatives for technology development and infusion that target different stages of technologies from early-stage innovation and partnerships at a low TRL, to mid-level TRL programs such as Small Business Innovation Research (SBIR), Small Business Technology Transfer (STTR), and technology maturation, all the way up to higher-TRL-targeted technology demonstration programs (Space Technology Mission Directorate, 2022).

1.1.1.5.5.1 Early-Stage Innovation and Partnerships

At the low TRL early-stage of technologies, STMD offers several opportunities and programs, including the following:

- The Space Tech Research Grants (STRG) Program that targets academic researchers with a range of graduate students to tenured faculty members to "examine the theoretical feasibility of ideas and approaches that are critical to making science, space travel, and exploration more effective, affordable, and sustainable" (Hall L. , STMD: Space Tech Research Grants, 2021). STRG solicitations fund activities that include NASA Space Technology Graduate Research Opportunities (NSTGRO) (up to $80K per year), Early Career Faculty (ECF) (up to $200K per year), Early Stage Innovations (ESI) (up to $200K per year), Lunar Surface Technology Research Opportunities (LuSTR) (up to $2M for 2 years), and Space Technology Research Institutes (STRI) (up to $3M for 5 years (Hall L. , STMD: Space Tech Research Grants, 2021).

- The Center Innovation Fund (CIF) is two-component program that aims to stimulate creativity and innovation at NASA centers. CIF provides annual funding for emerging technology development and new center initiatives for each NASA center and partnerships among centers or with academia and/or the commercial industry is encouraged. The second component of the program is the Early Career Initiative (ECI) targeted at early-career NASA researchers to train them and give them the opportunity to "lead hands-on technology development projects" (Hall L. , STMD: Center Innovation Fund, 2022). Note that as an FFRD, JPL is not eligible for submitting or leading proposals but can participate in ongoing proposals.

- Prizes, Challenges & Crowdsourcing are other opportunities that STMD also offers. In fiscal year 2021, NASA ran over 65 crowdsourcing projects and competitions with prizes over $9M in total (NASA STEM Engagement Highlights , 2021). Some examples include NASA's Big Idea Challenge, The Deep Space Moon Challenge, NASA's Break the Ice Lunar Challenge, Cube Quest Challenge, and CO_2 Conversion Challenge (NASA Solve).

- NASA Innovation Advanced Concepts (NIAC) is another program that specifically aims to foster visionary, radical, untraditional, and innovative ideas and technically credible advanced breakthrough concepts that could have a significant impact on future NASA missions. The NIAC process is divided into three phases: (I) 9 months focused on concept definition and initial analysis with up to $175K of funding, (II) 2 years focused on development, mission analysis, and spin offs with up to $600K of funding, and (II) the last 2 years focused on strategically transitioning the project to the highest impact for NASA with up to $2M of funding (Hall L. , NIAC Overview, 2022). Successful examples include the Ingenuity helicopter and the MarCO first interplanetary CubeSat mission.

- NASA's Technology Transfer program includes a variety of opportunities such as Technology Transfer University for student entrepreneurs with NASA's patent portfolio, Technology Transfer Expansion Initiative working with FedTech Startup Studio that uses NASA technology for entrepreneurial training, and the Tech Center Research Park Accelerator Network Program which targets minority and under-represented entrepreneurs and focuses on globally-impactful innovations (NASA's Technology Transfer Program).

1.1.1.5.5.2 SBIR/STTR Programs

At the mid TRL technology stage, two of the STMD opportunities are the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. The two programs provide partnership opportunities between small businesses and research institutions and NASA to develop technologies in focus areas of NASA's interest. The main difference between the two is that SBIR is targeted for small business of under 500 employees, while STTR is targeted for small business of under 500 employees "that is partnering with a non-profit research institution such as a university or a research laboratory" (NASA SBIR/STTR Program Support Office, 2022). *Figure 19* presents the three phases of the SBIR and STTR programs starting with idea generation, to prototype development, all the way up to the infusion or commercialization phase, with up to $1.15M in funding during the first three years.

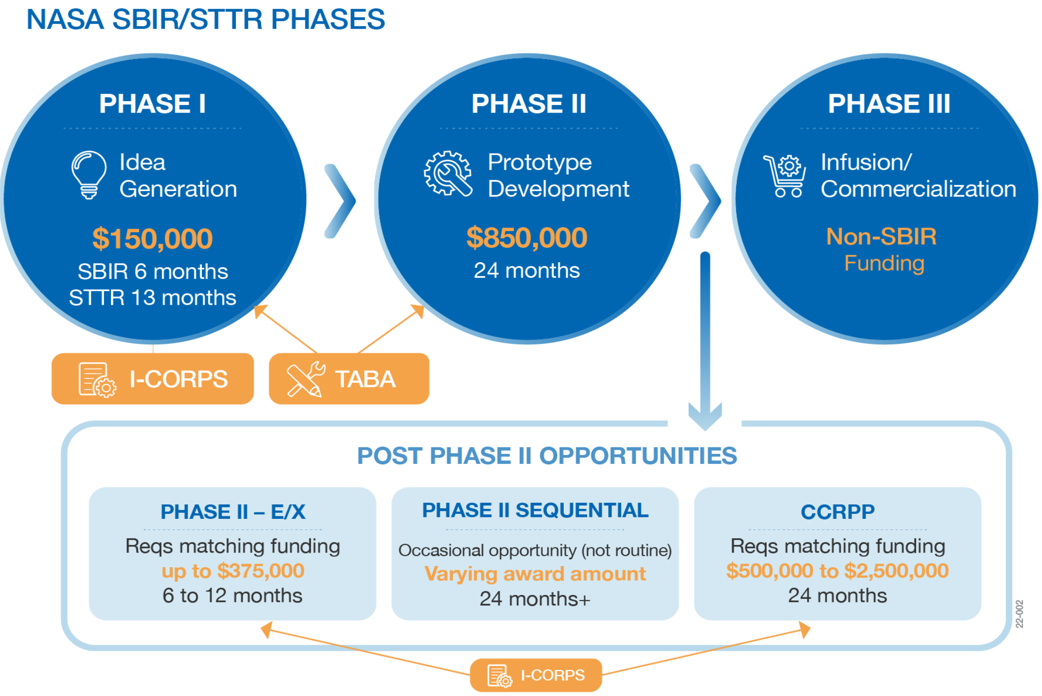


Figure 19. NASA SBIR/STTR Phases *(NASA SBIR/STTR Program Support Office, 2022).*

1.1.1.5.5.3 Technology Maturation

Technology Maturation is the other path for mid TRL (3-5/6) technology stage at STMD. The two main programs for that purpose are the Game Changing Development (GCD) (Vitug, 2022) and the Lunar Surface Innovation Initiative (Hall L. , Lunar Surface Innovation Initiative, 2020).

Game Changing Development (GCD) invests in advancing innovative technologies, proposed by academia, industry, NASA, and other agencies, that could enable space missions and the Artemis program. GCD matures the conceptual stage of technologies rapidly throughout "analytical modeling, ground-based testing and spaceflight demonstration of payloads and experiments" (Vitug, 2022).

The Lunar Surface Innovation Initiative is the other technology development portfolio that specifically targets the lunar activities, implemented through a combination of NASA and commercial partnerships. Among the top interests of this program are technologies such as in-situ resource utilization that enable life and exploration on the Moon (Hall L. , Lunar Surface Innovation Initiative, 2020).

1.1.1.5.5.4 Technology Demonstration

At the highest TRL stage of technologies, STMD offers multiple programs for technology demonstrations that aims to "bridge the gap between needs and means" in technologies (Mohon, 2021). These programs include Technology Demonstration Missions (TDM), the Small Spacecraft Technology Program, and various Flight Opportunities.

STMD's Technology Demonstration Missions (TDM) target "cross-cutting technologies with strong customer interest that meet the needs of NASA and industry by enabling new missions or greatly enhancing existing ones" (Mohon, 2021). Throughout ground and flight tests, TDM allows technologies to gain the "heritage" needed to be a lower risk for infusion in future NASA missions. Some examples of TDM technologies are the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) on the Mars 2020 Perseverance rover, the Deep Space Atomic Clock, and the Deep Space Optical Communications (DSOC) that is "piggybacking" on the Psyche mission (Mohon, 2021).

The other technology demonstration opportunity throughout STMD is the Small Spacecraft Technology program (SSTP). SSTP focuses on using small spacecraft as "platforms for testing and demonstrating technologies and capabilities that might have more general applications in larger-scale spacecraft and systems" (Hall L. , STMD: Small Spacecraft Technology, 2022). SSTP-executed projects are diverse between NASA centers, the commercial sector, or academia.

Flight Opportunities are the other route for technology demonstration. NASA leverages commercial capabilities for testing technologies on rocket-powered suborbital vehicles, high-altitude balloons, and parabolic aircraft—opportunities that provide technologies the "relevant environment" needed for their maturation or demonstration, whether that environment is suborbital space, certain altitudes, or conditions such as microgravity, radiation, extreme temperatures, vacuum, etc. (FS-2019-03-102 AFRC).

1.1.1.5.6 CLPS

The Commercial Lunar Payload Services (CLPS) initiative is one of NASA's commercial programs that aim to leverage the capabilities and expertise of the private sector specifically for the delivery of scientific and other payloads to the surface of the Moon (Dunbar, 2023). Starting with nine companies in 2018, the program increased its number of contracts to 14 a year later. In its selection process, NASA reviews and evaluates the technical feasibility, schedule, and price in each of the vendor bids, providing "indefinite delivery, indefinite quantity contracts with a combined maximum contract value of $2.6 billion through November 2028" (Dunbar, 2023). Some examples of CLPS contractor companies are Astrobotic Technology, Draper, Firefly Aerospace, and Intuitive Machines. Among the initially selected vendors, OrbitBeyond backed out of its offer and Masten Space Systems had critical financial struggles including filing for bankruptcy in 2022 (Foust, 2022).

CLPS is a higher risk initiative, and NASA is aware that not all the missions would be successful. Each CLPS mission will be carrying several different payloads, however, one mission of particular interest is Astrobotic's launch in late 2024 that will carry NASA's Volatiles Investigating Polar Exploration Rover (VIPER) (Chen, 2022). VIPER has cost NASA nearly half a billion dollars and thus been requiring additional testing and additional cost for Astrobotic CLPS task to ensure risk reduction (Foust, 2022).

1.1.2 Objectives

Modern enterprises are complex systems that operate in an increasingly global and interconnected environment. Treating an enterprise as an organic whole as opposed to focusing on its isolated elements provides a better understanding of the evolution and potential of the enterprise in an ever-changing domain. Part I of this thesis uses multiple technology case studies to study NASA's enterprise architecture and its technology investment, development, and maturation frameworks, through different eras, and to identify the current management and program challenges for efficient development and infusion of innovative planetary technologies that the agency faces.

This research then focuses on the systematic pain points for NASA's Jet Propulsion Laboratory (JPL), aiming to use key system architecting tools and delve into this chosen enterprise via extensive interviews and a literature review. The research uses architectural thinking, ecosystem frameworks, and alternative architecture design and evaluation to offer advice on transformations needed to restart JPL as a "60-year-old startup".

1.2 Research Questions and Motivation

This research discusses the questions outlined below:

(1) What are the current management and program challenges for efficient development and infusion of innovative planetary technologies at NASA?

(2) How to restart JPL as a "60-year-old startup"?

Question (1) uses multiple technology case studies to study NASA's enterprise architecture and its technology investment, development, and maturation frameworks, through different eras, and to identify the current management and program challenges for efficient development and infusion of innovative planetary technologies that the agency faces.

Question (2) focuses on the systematic pain points for NASA's Jet Propulsion Laboratory (JPL) and proposes needed enterprise architectural changes to restart JPL as a "60-year-old startup".

Note that a portion of the research in Question (2) was done as part of the MIT 16.855 "Systems Architecting Applied to Enterprises" class in Spring 2019, with some collaborating efforts from colleagues Becca Browder, Dylan Muramoto, and Lydia Zhang.

The main motivation behind this work stems from the critical importance of ensuring a path forward for innovation in planetary technologies to provide technology with which to constantly push the boundaries of our understanding in space, despite all the existing challenges. The research systematically studies this topic, focusing on NASA's challenges in planetary innovation and takes a deep dive into NASA's leading center on that front, JPL, to propose potential paths forward, from institutional, strategic, and policy vantage points.

Chapter 2: Literature Review, Gaps and Contributions

This literature review draws on sources from management, knowledge management and reuse, and innovation literatures, in addition to published studies and reports on technology roadmapping and governmental NASA assessments, to present the previous work relating to management and program challenges for efficient development and infusion of innovative planetary technologies at NASA. The review also considers the enterprise architecture literature to scope out relevant studies on architectural changes that promote innovation in response to identified challenges in an enterprise.

2.1 Literature Review

Understanding and assessing technology innovation has been a topic of extensive research in various fields and domains. However, research studies on applications in the space industry, and at organizations such as NASA, have been more limited. Despite the importance of non-space related work in understanding the broader context of the innovation landscape and its relevance in some facets to space applications, the space industry remains challenging. This industry presents major differences in its budgets, organizational relationships, partnerships, market structures, and level of complexity of technological innovation.

This research uses the definition of innovation by (Szajnfarber, 2009) that draws from various sources that tackled the definition of innovation, including (OECD, 1992; Fagerberg, Mowery, & Nelson Eds., 2005; Anderson & Tushman, 1990; Christensen, 2003; Henderson & Clark, 1990; Utterback & Abernathy, A Dynamic Model of Process and Product Innovation, 1975; Utterback, Mastering the Dynamics of Innovation, 1994; Thomke & Hippel, 2004; Schumpeter, 1934).

> "**Spacecraft Innovation:** A measure of how performance outcomes (as defined by the user), normalized by resource constraints (as experienced by the producer), changes over time. This can equivalently involve: a) generating a wholly new capability; or b) reducing the resources required to achieve an existing capability (e.g., making the system cheaper or lighter)" (Szajnfarber, 2009).

One relevant area of research to this work is that of risk management. On this topic in 2008, Cooper tackled "how project teams conceive of and manage pre-quantitative risk" (Cooper, 2008). This study focused on the individual then the team perception of risk and concluded with the ways teams manage risk from outcome and uncertainty manipulation to team management and work processes" (Cooper, 2008). This work is important because it shed light on an under-studied phase in risk management that impacts how innovation is viewed at NASA. There exists a number of risk quantification and assessment tools and methods, including Probabilistic Risk Assessment (PRA), Failure Mode, Effects & Criticality Analysis (FMECA), Fault Trees, and Risk Matrices—the latter of which is incorporated in NASA's Risk Management Procedures and Guidelines (Dezfuli, et al., 2011; Dezfuli, Stamatelatos, Maggio, Everett, & Youngblood, 2010; NID 8000-108, 2016). Cooper's research unraveled the mental models in teams before that statistical and quantitative risk phase, showing that project teams follow neither a rational nor a recognition-based decision-making process while perceiving risk, incorporating a number of utilities, heuristic shortcut, and mental simulation of what-if scenarios. This process is also not carried out linearly, but rather through a "messy process that was spread over time and multiple meetings and involved a shifting set of decision makers" (Cooper, 2008). Having this background is important while thinking of current management and process challenges at NASA that hinder innovative technologies.

In another study on risk management, (Reeves, Eveleigh, Holzer, & Sarkani, 2013; Reeves Jr., 2013) have also taken a deeper dive into the risk identification biases and trends in space system development, specifically for systems engineers and risk managers. Despite NASA's standardized risk identification methodologies, (Reeves, Eveleigh, Holzer, & Sarkani, 2013; Reeves Jr., 2013) concluded that "there may still be biases within risk identification efforts that marginalize external and other low likelihood events that could potentially cause disruption to cost and schedule plans".

In 2018, (Ellyin, 2018) extended the previous studies, focusing on creating a technology infusion decision model for robotic space exploration. The goal of this model was to "help prioritize investment opportunities toward the development of novel pieces of technology ensuring the evaluation of innovative concepts in an impartial manner" (Ellyin, 2018). Acknowledging the shortcomings of the TRL scale in quantifying the potential of a technology, (Ellyin, 2018)'s model calculated a score for each technology based on a set of weighted parameters that included "the TRL of a specific piece of technology; the time required to develop the technology; the cost associated with developing the technology; the determination as to whether the technology was enabling or enhancing; the risk posture of the flight project; and considerations of whether the technology happened to be cross cutting or not" (Ellyin, 2018). This quantitative tool has not yet been implemented and still requires further research to study how well it predicts the success or failure of infused technologies.

Knowledge management and knowledge reuse for innovation are another relevant area of study to innovation challenges at NASA. Cooper has previously studied the topic of the application of "experience" as knowledge in a new product development team (Cooper, 2010). Throughout studying "experience exchanges" in the meetings of a case study team in the formulation phase of a highly innovative robotic science mission to Mars (Hecht & Saunders, CryoScout: A descent through the Mars polar cap, 2003), Cooper's research addressed how work processes were influenced by team members' experiences and how to "effectively enable the application of experiences as knowledge" (Cooper, 2010). Cooper built on previous work that tackled how knowledge is captured and transferred based on job length, industry, repeated experiences, skill level, and previously experiencing success, failure, or accidents (Klein, 2003; Kolb, 1984; Rentsch, Heffner, & Duffy, 1994; Salomon & Martin, 2008; Weiss, Lurie, & Macinnis, 2008; Nguyen, 2008; Abele, Rupprecht, & Wojciszke, 2008; Niza, Silva, & Lima, 2008; Argote, 1999; Kogut & Zander, 1992).

Two of the main relevant conclusions from Cooper's research are on the topics of (1) integrating experiences and (2) functional diversity (Cooper, 2010):

- "Integrating experiences requires knowledge of the individual experiences, models of information needs, an understanding of the project context, and an understanding of the vulnerabilities associated with the process."

- "When forming teams, organizations should strive for a combination of shared and divergent experiences. Conversely, as teams develop and discover knowledge gaps, a common set of reference experiences can help integrate new members."

This research was also extended by Majchrzak, Cooper, & Neece, adding additional case studies of varying degree of innovation at NASA JPL to "better understand the knowledge reuse process when radical innovation is expected", such as for technologies that prepare for future human exploration of Mars, for example (Majchrzak, Cooper, & Neece, 2004). The research identified a reuse-for-innovation process across its case studies, based on the following actions: "reconceptualize the problem and approach, including deciding to search for others' ideas to reuse; search-and-evaluate others' ideas to reuse; and develop the selected idea" (Majchrzak, Cooper, & Neece, 2004). In the JPL specific context, Majchrzak, Cooper, & Neece also confirmed the reusers' balancing of "the paradox of identifying a nontraditional untested conceptual approach to the problem against the need for risk reduction by picking only those approaches in which they had some confidence that someone, somewhere, would have a relevant idea" (Majchrzak, Cooper, & Neece, 2004).

One additional important aspect of innovation in technologies is in managing a project's legacy—its contributions to its home organization's knowledge, on the product, process, and people levels (Cooper, Hecht, & Majchrzak, 2003). Despite the importance of focusing on meeting project goals to create new knowledge, there exists a gap "between the act of creating this new knowledge, which is necessary for the project to accomplish its goals, and the act of capturing this knowledge for the explicit purpose of future reuse, which is important for the organization" (Cooper, Hecht, & Majchrzak, 2003). In the context of an innovative research and development (R&D) institution like JPL, (Cooper, Hecht, & Majchrzak, 2003) argue for "expanding the role of the organization in this process and tying it to strategic goals", providing the needed resources to facilitate the project legacy process. This legacy-based approach was applied in multiple pilot sessions, providing NASA an alternate to "lessons learned sessions – an approach that relied on current socio-cognitive theory on transactive memory systems in groups" (Cooper, Majchrzak, & Faraj, 2005).

In 2009, Szajnfarber studied "how innovation can, and should, happen in the space sector", creating an empirical measure of spacecraft innovation, specifically based on the quantitative analysis of communication satellite history (Szajnfarber, 2009). Szajnfarber specifically raised an important question based on the United States General Accounting Office (GAO) reports at the time that mostly recommended using mature and proven technologies to avoid overruns in NASA programs (Szajnfarber, 2009),

> "[the recommendation] seems intuitively true. It also raises an important question, are billions of public funds being allocated to government space projects so that they can play it *safe*? Where is the boundary between pushing limits and controlling costs?"

In 2011, Szajnfarber also studied the innovation pathways at NASA, creating an "Epoch-Shock" model that demonstrated how the classic "Stage-Gate" process used by NASA per its systems engineering heritage, where concepts linearly pass through a series of sequential gates or key decision points to be progressively matured at each, does not capture the "decentralized, probabilistic nature of key interactions" for innovative ideas (Szajnfarber, 2011). Previous studies have also backed the conclusion that the sequential "Stage-Gate" process does not represent the reality of the innovation process (Rothwell & Zegveld, 1994).

Another perspective that is popular in policy that Szajnfarber integrated is that of the "windows of opportunity". This approach does not stage and compartmentalize the process, but rather suggests that "separate problem streams and solution streams exist independently. Progress occurs when a window of opportunity opens, allowing a problem and a solution stream to combine and yield a new status quo" (Szajnfarber, 2011; Kingdon, 1984; Stone, 2012). (Kingdon, 1984) describes that anticipation for windows to be used, "*like surfers waiting for the big wave*". (Szajnfarber, 2011), however, argued that this approach “oversimplies and de-emphasizes the importance of structure in the pre-window development for technology-intensive solutions”. This argument emphasized that the “windows of opportunity” perspective neglects the path dependency and its involved investments for technology development—dynamics that are very different in the space sector’s “monopsony markets characteristic” as compared to those of a competitive market context, as many enabling space technologies do not have near-term commercial viability (Szajnfarber, 2011; Adams & Adams, 1972; Szajnfarber, Richards, & Weigel, Challenges to Innovation in the Government Space Sector, 2011; Peck & Scherer, 1962; Sherwin & Isenson, 1967).

Another angle of literature that drives Szajnfarber’s “Epoch-Shock” model is that of mutiple studies on the shock requirement—in the form of fear, foreign policy, prestige, military necaessity, etc.—for change in bureaucratic organizations that are designed to resist change (Rosen, 1994; Posen, 1984; Beard, 1976; Launius & McCurdy, 1997; McDougall, 1985).

The last angle of Szajnfarber’s “Epoch-Shock” model as applied to NASA involved that of sustained performance, balancing both exploration and exploitation efforts, with the tension that occurs between these “mutually contradictory and self-reinforcing pursuits” (Szajnfarber, 2011; Greve, 2007; March, 1991; O'Reilly & Tushman, 2007). In order to combine and balance these exploration and exploitation efforts, two strategies exist in literature: ambidexterity and punctuated equilibrium—the former of which is the closest to NASA’s structure and strategies, albeit some differences at the working level. The concept of ambidexterity promotes the integration of exploration and exploitation through the use of loosely connected sub-units within an organization, overseen by top management (Tushman & Smith, 2002; Smith & Tushman, 2005). In contrast, the theory of punctuated equilibrium proposes that the conflicting functions of exploration and exploitation can be balanced through a temporal sequence, such as alternating periods of exploration with longer periods of exploitation (Tushman & Romanelli, 1985; Brown & Eisenhardt, 1998; Burgelman, 2002; Van de Ven, Polley, Garud, & Venkataraman, 1999).

Combining these difference lenses and approaches, (Szajnfarber, 2011) developed the so-called “Epoch-Shock” model to frame the innovation pathway at NASA, capturing throughout that the “informal mechanisms and micro-behaviors” that affect innovation. This model is presented in *Figure 20* in comparision to the “Stage-Gate” approach (Szajnfarber, 2011).

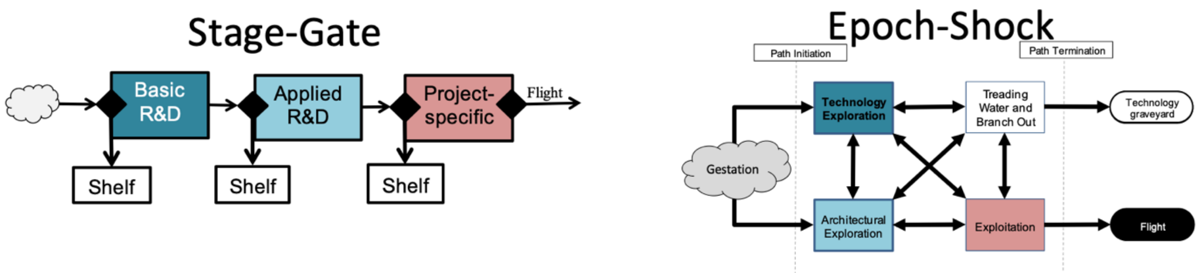


Figure 20. Comparison of Stage-Gates and Epoch-Shocks. Figure from *(Szajnfarber, 2011)*

Szajnfarber’s work is a critical baseline for this thesis. However, despite the relevance of some of its results, that research is outdated as there has been various changes in innovation pathways at NASA after the creation of STMD, in addition to the other “low-cost” programs at NASA such as CLPS and SIMPLEx. Moreover, Szajnfarber’s focus was on the innovation structure and pathway, rather on the idenitification of challenges for innovation at NASA within that structure. The latter is where this research's focus is on.

There is ongoing technology roadmapping work by (de Weck, 2021) on the "Advanced Space Technology Roadmapping Architecture (ASTRA)" project that aims to perform technology investment portfolio valuation, optimization, and selection at NASA. ASTRA draws from (de Weck, 2022) integrates modeling, simulation, and Markowitz portfolio theory in its methodology and build on previous data such as NASA's technology roadmaps and the 2018 Commercial Space Technology Roadmaps document (de Weck, et al., 2018). ASTRA, however, does not tackle the current program and management challenges that hinder technology innovation at NASA, nor the enterprise architectural changes needed, but it rather provides insight on technology portfolio construction at NASA.

The most relevant existing studies to this thesis work, however, are the yearly reports created by the United States General Accounting Office (GAO) and Office of Inspector General (OIG) on NASA's management and program challenges. In the 2022 OIG report (Office of Inspector General, 2022), seven main challenges were identified for NASA:

- Challenge 1: Returning Humans to the Moon
- Challenge 2: Improving Management of Major Programs and Projects
- Challenge 3: Sustaining a Human Presence in Low Earth Orbit
- Challenge 4: Managing and Mitigating Cybersecurity Risks
- Challenge 5: Improving Oversight of Contracts, Grants, and Cooperative Agreements
- Challenge 6: Attracting and Retaining a Diverse and Highly Skilled Workforce
- Challenge 7: Managing NASA's Outdated Infrastructure and Facilities

For each of these challenges, the OIG report provides seven sections: (1) Why This Is a Challenge, (2) Progress in Addressing the Challenge, (3) Key Implemented Recommendations, (4) Work Remaining to Address Challenge, (5) Key Unimplemented Recommendations, (6) Ongoing and Anticipated Future Audit Work, and (7) Relevant OIG Reports.

For example, for Challenge 1: Returning Humans to the Moon, the 2022 OIG report (Office of Inspector General, 2022) acknowledges that NASA has implemented some of the previous recommendations such as "Codify the remaining governance structure such as the Federated Boards and Joint Directorate Program Management Council", "Develop an acquisition strategy for the next-generation spacesuits that meets the needs of both the ISS and Artemis programs", and "For new acquisitions of SLS deliverables, develop a cost accounting model that separates each deliverable into its own contract line item number for tracking costs, performance, and award fees". However, the report points out that NASA hasn't yet implemented things like "Issue policy guidance to reinforce current Federal Acquisition Regulation and NASA FAR Supplement regulatory guidance for stopping or withholding payments to a contractor for significant deficiencies in business systems, such as the Earned Value Management (EVM) System", "Develop an Artemis-wide cost estimate, in accordance with best practices, that is updated on an annual basis", or "Develop a Human Exploration and Operations Mission Directorate policy that establishes a reasonable amount of recommended schedule margin by phase of program or project" (Office of Inspector General, 2022).

Challenges 2 and 5 in (Office of Inspector General, 2022) are of particular interest to this research. On Challenge 2: Improving Management of Major Programs and Projects, the 2022 OIG report points out NASA's historical record of cost and schedule overruns, stating that, "According to GAO, NASA plans to invest more than $80 billion over the life cycle of its portfolio of major programs and projects, 21 of which are currently in development. However, 15 of those programs and projects have already experienced a cumulative cost growth of about $12 billion and 28 years of delay since original cost and schedule baselines were established" (Office of Inspector General, 2022). The report however applauds NASA's progress in developing best practices, adding requirements, and adding external cost and schedule monitoring, including NASA's Program Planning and Control training curriculum and establishing the Chief Program Management Officer in 2022 who is responsible for "strengthening the Agency's oversight, management, and implementation of program management policies, processes, and best practices" (Office of Inspector General, 2022).

The 2022 OIG report points out the list of recommendations below to be the only unimplemented ones by NASA, and thus remaining a challenge (Office of Inspector General, 2022):

- "Estimate, track, and report ongoing production costs for all major programs, such as SLS and Orion, as development costs (Phases C and D) and not as Operations and Sustainment (Phase E) costs.
- Establish procedural requirements to ensure compliance with the Title 51 requirement to report full life-cycle cost and schedule for all major programs should NASA elect to estimate, track, and report baseline costs for major programs or activities that exceed $250 million by component rather than by mission.
- Update NASA Procedural Requirements 7120.8 to require major acquisition projects that cost over $250 million to complete a Joint Cost and Schedule Confidence Level analysis.
- Update NASA Procedural Requirements 7120.8 to require major acquisition projects that cost over $250 million to implement EVM.
- Review Human Exploration and Operations Mission Directorate and NASA program management policies, procedures, and Agency Baseline Commitment reporting processes to provide greater visibility into current, future, and overall cost and schedule estimates for the SLS Program and other human space flight programs."

On Challenge 5: Improving Oversight of Contracts, Grants, and Cooperative Agreements, the 2022 OIG report (Office of Inspector General, 2022) emphasized NASA's $19.3 billion spent in FY2021 on contracts, grants, and agreements for research and development, services, supplies, and equipment, in addition to the public-private partnerships and alternative acquisition methods to reduce costs and speed up the development of new technologies, especially for Artemis. However, the report still highlights NASA's struggle to "develop more realistic cost and schedule estimates and temper its culture of optimism with respect to contract oversight". (Office of Inspector General, 2022) suggests that the list of recommendations below remains unimplemented by NASA (Office of Inspector General, 2022):

- "Ensure acquisition officials minimize the availability of award fees when contract modifications and value increases are the result of shortcomings in contractor performance and require documentation of the rationale for any award fees granted.
- Finalize and fully implement the performance metrics dashboard to measure acquisition performance.
- Document contract assignments to contracting officers, contracting officer's representatives, and program and project managers in a centralized system for inclusion in the performance metrics dashboard."

The recommendations in these reports are critical, but they do not particularly focus on the ongoing challenges for efficient development and infusion of innovative planetary technologies and technology demonstrations, nor do they pose recommendations on any enterprise architectural changes needed to instill innovation at the agency. This focus area at NASA is what this thesis targets.

For the case of NASA's Jet Propulsion Laboratory (JPL), there has been few previous studies that tackled the NASA Lessons Learned Information System (Maya, et al., 2005), systems engineering (Jansma & Jones, 2006), and risk management at JPL (Rose, 2002). However, given their published dates, these studies are not fully up to date with the ongoing challenges at JPL, and none of them conducted an enterprise architectural analysis for the laboratory, nor did they offer proposed architectural changes for instilling more innovation.

2.2 Gaps and Conflict Summary

In summary, despite the many challenges facing NASA that could stifle innovation and limit the agency's ability to explore and understand the solar system and beyond, there exists a lack of an up-to-date evaluation and identification of the current innovation challenges in NASA's planetary program, specifically for innovative technologies and technology demonstrations, to guide any institutional or process changes. This gap in literature continues to create a split at NASA between the implementers, who run space projects, and the technologists who develop technologies but rarely get beyond the hump to get new technologies into space.

Moreover, for the specific case of JPL, there has been no major up-to-date research efforts that involve a deep dive into the laboratory's enterprise architecture nor that propose architectural changes needed to improve innovation, responding to the more recent pain points faced.

2.3 Research Contributions Summary

As a summary, after identifying the gaps and inadequacies in existing literature, this research examines NASA's enterprise architecture and its technology investment, development, and maturation frameworks across different eras by analyzing multiple technology case studies. The first contribution of this research is the creation of an up-to-date evaluation of the management and program challenges that the agency is facing for efficient development and infusion of innovative planetary technologies. The second contribution of this research is focusing on and studying NASA's Jet Propulsion Laboratory (JPL)'s enterprise architecture and proposing alternative architectural transformations needed to further instill innovation at the laboratory as a "60-year-old startup".

Chapter 3: Research Design and Methods

3.1 Research Design Overview

3.1.1 Research Question #1

In Research Question #1, this thesis creates an up-to-date evaluation of the management and program challenges that the agency is facing for efficient development and infusion of innovative planetary technologies. This was done through exploratory work examining a series of case studies of innovative NASA missions and technologies across different eras. Due to the complexity of NASA as an enterprise and its increasingly global and interconnected environment, this research treated the agency as an organic whole, looking at its everchanging systems and processes, with a focus on its planetary technology program.

The research design used (Langley, 1999)'s process tracing methods in addition to (Eisenhardt, 1989; Yin, 1984)'s process of building theory from case studies as a guide for the data collection and analysis and for the identification of challenges in NASA's planetary program. For each of the case studies, data was collected through a series of interviews, in addition to documentation and archival reviews (Yin, 1984). On the sampling depth vs. breadth tradeoff and the number of case studies, this research follows (Eisenhardt, 1989)'s recommendation of 4-10 cases to achieve the right balance between depth and breadth in data collection, synthesis, and analysis. The research used six case studies for a retrospective and longitudinal process study.

The selected qualitative methods have been extensively used in management literature, specifically for understanding the root causes of problems or technical failures (Glaser & Strauss, 1967; Langley, Strategies for Theorizing from Process Data, 1999; Locke, 2001; Mintzberg, 1979; Pettigrew, 1990). The methods were also used in comparative politics (Collier & Collier, 1991), organizational science (Langley & Truax, 1994; Nutt, 1984; Sonenshein, 2010), and military innovation studies (Lindsay, 2006; Sapolsky, 1972).

Szajnfarber & Gralla explored the qualitative research process and its importance in application to systems engineering contexts stating that, "Systems engineering needs qualitative methods because as systems grow increasingly complex, and the behavior of human designers, operators, and users becomes increasingly important in understanding system behavior, qualitative methods may be the only way to gain certain kinds of understanding of the system" (Szajnfarber & Gralla, 2017).

For purposes of Research #1, these qualitative approaches provide a key advantage of allowing a deep understanding of innovation challenges in NASA's planetary program—a phenomena of complex causality (Hall P. A., 2003; Buthe, 2002). Process tracing and building theory from case studies are particularly useful in this case for understanding the dynamics of organizational change at NASA, throughout studying the experiences and perspectives of individuals and groups involved in these case studies and derive insights into the challenges and opportunities that arose during these processes. As (Falletti, 2006) states, these methods "explain the outcomes of interest by going back in time and identifying the key events, processes, or decisions that link the hypothesized cause or causes with the outcomes". Chapters 3.2 Data Collection and 3.3 Data Analysis Methods outline the details of the data collection and analysis methods introduced in the research design above.

3.1.2 Research Question #2

Building on the data collected and results obtained in Research Question #1, Research Question #2 of this thesis focuses on identifying systematic pain points at JPL and recommending the needed enterprise architecture changes to restart the laboratory as a "60-year-old startup". The phrase "60-year-old startup" is internal jargon that JPL uses to describe itself (James, 2019) per its reputation for being agile, innovative, and willing to take calculated risks. The research for this question was done through the ARchitecting Innovative Enterprise Strategy (ARIES) method discussed in Chapter 3.3 Data Analysis Methods.

The main pain points addressed in the transformation include communications, financial architecture, and cybersecurity. Specifically, there were three communication channels that need improvement: internal communications between divisions and organizations; external communications with NASA Headquarters, commercial entities, and academia; and lastly, digital communication for data sharing and digital engineering. In terms of the financial architecture update, the research focused on designing the right financial structure and incentives to drive change. In generating alternative architectures, cybersecurity was always kept in mind.

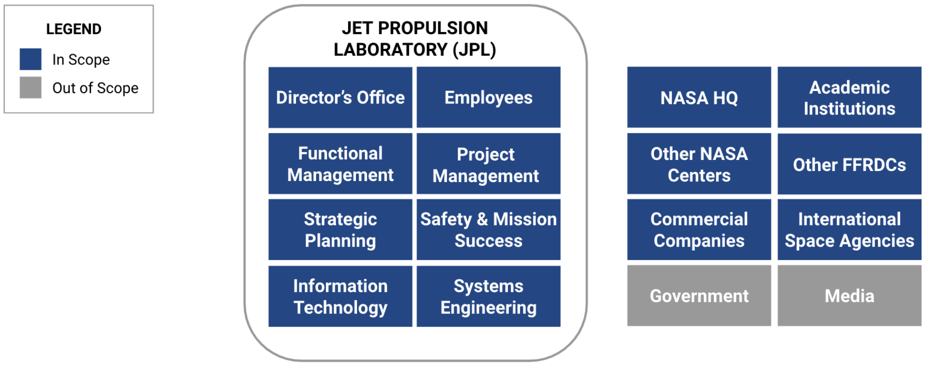


Figure 21. Scope of the Project.

JPL interacts with many organizations and is made up of various subgroups, as shown in *Figure 21*. For this research, the scope was tailored not to include the government and the media, focusing on internal relationships within JPL and on JPL's relationships with external partners. Including the government and the media introduces additional topics such as politics and public relations that could be material for future research, as these are significant stakeholders in JPL's operations as well.

3.2 Data Collection

3.2.1 Research Question #1

In this research, data was collected and analyzed from six case studies of innovative planetary missions associated with SMD, STMD, and Jet Propulsion Laboratory (JPL). These missions were selected from a larger pool of potential cases identified throughout an initial set of interviews that the research conducted with NASA senior leadership. The cases were outlined chronologically over NASA's different eras and classified according to the mission class and number of innovative instruments and technologies that they each carry onboard. Following (Eisenhardt, 1989)'s recommendation for number of cases for theory building, this research selected six case studies at which point theoretical saturation was achieved. *Table 4* presents the chosen missions and program case studies, chronologically covering various eras at NASA, since FBC onwards, and covering a variety of mission classifications. *Table 4* also includes what instruments or technologies that this research particularly focused on in each of the cases, if applicable.

Table 4. Summary of Case Studies.

	Case Study #	**Name**	**Classification**	**Launch Year/ Program Start Date**	**Instruments/ Technologies Considered (If applicable)**
Missions	1	Deep Space 1	New Millennium	1998	Ion Propulsion
	2	Phoenix	Mars Scout Program	2007	Thermal and Evolved Gas Analyzer (TEGA)
					Microscopy, Electrochemistry, and Conductivity Analyzer (MECA)
	3	Perseverance	Flagship	2020	Terrain Relative Navigation (TRN)
					Fast Traverse
					Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE)
					Ingenuity
	4	Psyche	Discovery	2023 (planned)	Solar Electric Propulsion (SEP)
					Deep Space Optical Communications (DSOC)
Programs	5	Small, Innovative Missions for PLanetary Exploration (SIMPLEx)	"low-cost" SMD	2014	N/A
	6	Commercial Lunar Payload Services (CLPS)	"low-cost" commercial	2018	

As a retrospective and longitudinal process study (Rogers, 1983), this research collected data on the case studies through a series of semi-structured interviews and detailed document review in a process focused on developing a detailed timeline for each case, with triangulation in sources. A minimum of three interview sources were used per each studied case. The documents reviewed included instrument proposals, announcements of opportunity (AO), publications, presentations, reports, press releases, and notes.

Approximately 80 hours of semi-structured interviews were conducted with 58 interviewees, who constitute a wide representation of NASA leadership, scientists, technologists, engineers, managers, STMD, SMD, JPL, Goddard, Headquarters, Academia, etc. Only two of the interviews were done in person, while the rest were virtually recorded via Zoom and transcribed afterwards. Note that 13 of these interviews were done as part of the MIT 16.855 "Systems Architecting Applied to Enterprises" class in Spring 2019, with some collaborating efforts from colleagues on the team (*Becca Browder, Dylan Muramoto, and Lydia Zhang*). The rest of the interviews were carried out in the 2021-2023 period. Interviews started by introducing the general thesis topic, asking the interviewee about their role, then diving into the details of the program, mission, or instrument of interest, including the challenges that happened along the way. Because multiple interviewees were asked about the same case studies, there were reported differences between the received answers in some cases. These differences were shared with the interviewees to further explain and refer to documentation for evidence. All interviewees were anonymized afterwards. *Table 5* presents a summary of the interviewees and their relevant functional titles.

Throughout this process so far, the research aligns with (Eisenhardt, 1989)'s recommended steps as follows:

(1) Getting started: Definition of research question; possibly a priori constructs.

- Two research questions were defined, and literature was reviewed for a priori constructs.

(2) Selecting Cases: Neither theory nor hypotheses; specified population; theoretical, not random, sampling.

- Six case studies of innovative planetary missions associated with SMD, STMD, and Jet Propulsion Laboratory (JPL) were selected. These missions cover various eras at NASA, since FBC onwards, and a variety of mission classifications.

(3) Crafting Instruments and Protocols: Multiple data collection methods; qualitative and quantitative data; multiple investigators.

- Data on the case studies was collected through a series of semi-structured interviews and detailed document review (instrument proposals, announcements of opportunity (AO), publications, presentations, reports, press releases, and note). A minimum of three interview sources were used per each studied case, and interviewees had a wide representation of NASA leadership, scientists, technologists, engineers, managers, STMD, SMD, JPL, Goddard, Headquarters, Academia, etc.

(4) Entering the field: Overlap data collection and analysis, including field notes; flexible and opportunistic data collection methods.

- Interviews were verbatim transcribed right afterwards, and notes were added to the case studies' database to confirm any additional information needed.

(Eisenhardt, 1989)'s recommended steps 5-8 focus on data analysis and are discussed in Chapter 3.3.1 Research Question #1.

Table 5. Research Summary of Interviewees.

Interviewee Code #	**(Relevant) Functional Title**	**Case Study**
I1	NASA Senior Leadership	General, JPL
I2	NASA Senior Leadership	JPL
I3	Systems Engineer	JPL
I4	Strategic Integration	JPL
I5	Enterprise Architect	JPL
I6	Enterprise Architect, Engineer	JPL
I7	Mission Formulation	JPL
I8	Program Manager	JPL
I9	Mechanical Engineer	JPL
I10	Mechanical Engineer	JPL
I11	Engineer	JPL
I12	Technologist	JPL
I13	Mechanical Engineer	JPL
I14	Principal Investigator/Project Manager	Multiple
I15	Principal Investigator/Project Manager	Multiple
I16	University Professor – Aerospace Engineering	General
I17	Systems Engineer	General, Phoenix
I18	University Professor – Engineering Systems	General
I19	Project Manager/Systems Engineer	Perseverance
I20	Program Executive/Technology Strategy	General/Perseverance
I21	Technologist	General/Deep Space 1

I22	NASA Senior Leadership	General/Perseverance
I23	NASA Senior Leadership	General/Multiple
I24	Systems Engineer	General
I25	Program Executive	Perseverance
I26	Technology Infusion	General
I27	Policy Analyst	General
I28	NASA Senior Leadership	General
I29	Scientist	Perseverance
I30	System Engineer	Phoenix
I31	System Engineer	Multiple
I32	Project Manager	Multiple
I33	Project Manager	General
I34	Program Executive	General/SIMPLEx
I35	Principal Investigator	Phoenix
I36	Instrument Manager	Perseverance
I37	NASA Senior Leadership	General
I38	Director	Multiple/STMD
I39	Flight System Manager	General/Deep Space 1
I40	Life Support Systems Engineer	General
I41	Architect	General/STMD
I42	Payload Manager	Perseverance
I43	Principal Investigator	General/Psyche
I44	NASA Senior Leadership	General
I45	Engineer	Multiple
I46	Payload Manager	Phoenix
I47	NASA Senior Leadership	General
I48	NASA Senior Leadership	General
I49	Systems Engineer	Psyche
I50	Program Manager/System Engineer/ Review and Advisory	General/Pscyhe
I51	Director	General/STMD

I52	Manager/Telecommunications Engineer	Perseverance
I53	Technology Coordinator	Perseverance
I54	Supervisor/ Senior Technical Staff	Perseverance
I55	Robotics Systems Engineer	Perseverance
I56	University Professor – Aerospace Engineering	General
I57	Systems Integration	CLPS
I58	Program Manager	CLPS

3.2.2 Research Question #2

This research question used the same data collected in Research Question #1, but it focused on JPL-related documents and interviews done with current and former JPL employees. Interviewees were deliberately chosen to represent a variety of groups across the enterprise hierarchy to capture different perspectives within the organization and identify key pain points.

3.3 Data Analysis Methods

3.3.1 Research Question #1

To analyze the collected data, the research follows (Eisenhardt, 1989)'s recommended steps 5-8 (following on the former steps 1-4 that are discussed in Chapter 3.2.1 Research Question #1).

(5) Analyzing data: Within-case analysis; Cross-case pattern search using divergent techniques.

- On the within-in case analysis recommendation, an event database (Van de Ven, Angle, & Poole, 2000) was created for each of the selected cases, where data from different sources was added to construct an analytical chronology of the sequence of events (Pettigrew, 1990). Each of the interview sources was codified, and each of the document sources used was cited. All facts were triangulated throughput this process. As iteration between data collection and analysis was ongoing (Glaser & Strauss, 1967; Yin, 1984), this database was critical in maintaining traceability for the next step of cross-case pattern search. Databases for each of the case studies were compared to identify the emerging pattern of challenges at NASA.

(6) Shaping hypotheses: Iterative tabulation of evidence for each construct; replication not sampling logic across cases; search evidence for "why" behind relationships.

- Throughout the process of database construction and cross-case analysis done, evidence was studied, and new cases were added based on identified patterns.

(7) Enfolding literature: Comparison with conflicting literature; comparison with similar literature.

  - During the analysis of each of the case studies, notes and initial results were compared with existing literature, including governmental reports and scientific publications.

(8) Reaching closure: Theoretical saturation when possible.

  - The research stopped adding additional cases studies or iterating in results after six cases, where theoretical saturation was concluded, and the identified results were matching to the evidence in the collected data as a whole.

3.3.2 Research Question #2

For Research Question #2, this thesis uses the ARchitecting Innovative Enterprise Strategy (ARIES) approach for data analysis. After the initial spread of systems engineering practices in the 1950s, the concept of systems architecting started coming into life with (Goode & Machol, 1957)'s publication: System Engineering: An Introduction to the Design of Large-Scale Systems, where issues of system complexity and structure were implicitly discussed (Goode & Machol, 1957; Emes, et al., 2012).

The term "systems architecture" has had a broad range of interpretations in literature over the years. A study by (Emes, et al., 2012) based on sources from (ISO/IEC/IEEE 42010:2011, 2011-12; Ministry of Defence, 2012; Maier, 2009) showed that,

> "One model sees systems architecting as simply a rebranding of systems engineering to broaden its appeal with no change in content. Another model sees systems engineering restricted to its traditional processes, with systems architecting adding to systems engineering through external processes. The final model, and the most popular among the systems engineering community surveyed, sees systems architecting addressing shortcomings in traditional sequential lifecycle models by stretching the content of systems engineering to include new elements under the banner of systems architecting".

Applying systems architecture practices to enterprises, however, is critical to achieve fundamental change and transformation for gaining competitive advantage (Rouse, 2005). As shown in Figure *22*, the ARchitecting Innovative Enterprise Strategy (ARIES) framework by (Nightingale & Rhodes, 2015) incorporates an Enterprise Element Model, an Architecting Process Model, and Analysis Techniques.

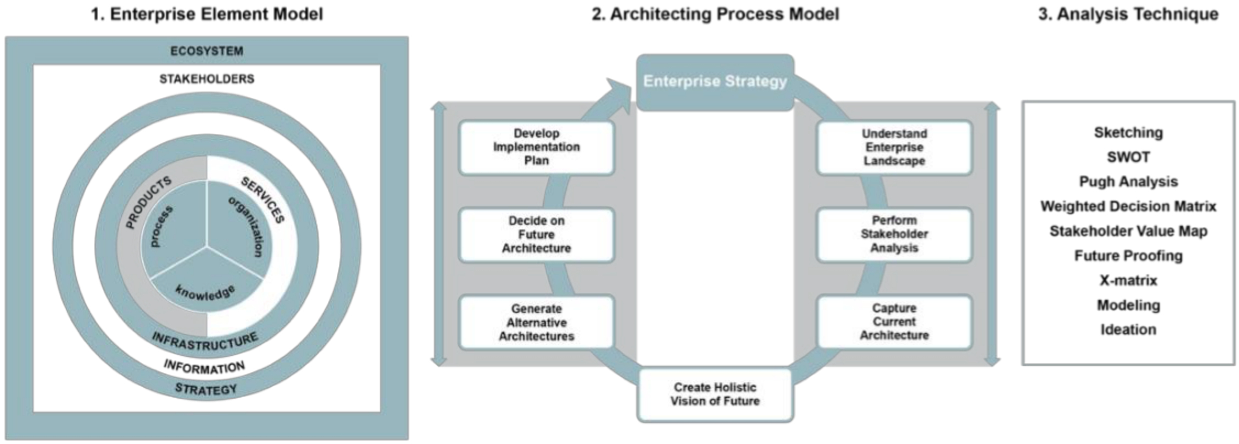


Figure 22. ARIES Framework. *(Nightingale & Rhodes, 2015; Lee, Lin, Rudnik, & Rhodes, 2021)*

The Enterprise Element Model presents ten enterprise elements for enterprise understanding: Ecosystem, Stakeholders, Strategy, Information, Infrastructure, Products, Services, Process, Organization and Knowledge (Nightingale & Rhodes, 2015). These elements are important to understand the enterprise's boundaries, its relationship with its ecosystem, and the value-exchange ongoing within the enterprise.

The Architecting Process Model presents seven architecting imperatives for performing the architecting process:

- Make architecting the initial activity in transformation.
- Develop a comprehensive understanding of the enterprise landscape.
- Understand what stakeholders value and how that may change in the future.
- Use multiple perspectives to see the whole enterprise.
- Create an architecting team suited to the transformation challenges.
- Engage all levels of leadership in transformation.
- Architect for the enterprise's changing world.

For the stakeholder analysis, the research refers to (Mitchell, Agle, & Wood, 1997)'s work on stakeholder salience, where stakeholders are classified into Dormant, Discretionary, Demanding, Dominant, Dangerous, Dependent, Definitive, or Nonstakeholder based on each of their attributes of Power, Legitimacy, and Urgency as shown in Figure *23*. According to (Mitchell, Agle, & Wood, 1997), Power is defined as "the authority or influence of the stakeholder on the enterprise", Legitimacy as "the genuineness of involvement of the stakeholder in the enterprise", and Urgency as "the degree to which stakeholder requirements call for immediate attention by the enterprise". Stakeholder salience is also dynamic and could change over time.

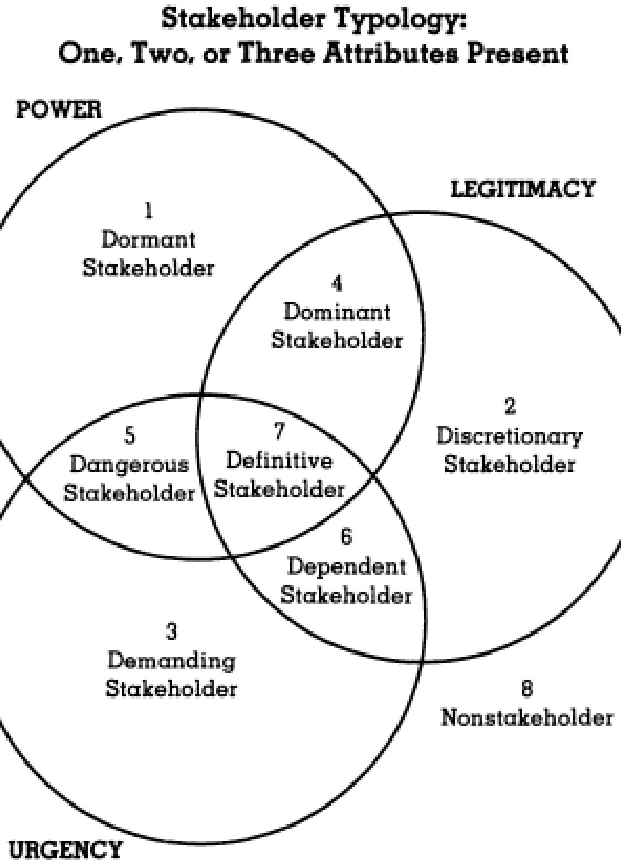


Figure 23. Stakeholder Typology. *(Mitchell, Agle, & Wood, 1997)*

The last part of the ARIES framework shown in *Figure 22* is the Enterprise Analysis Techniques. Among the presented tools, this research used the following:

- Stakeholder Classification Venn Diagram for stakeholder analysis.

- SWOT—strengths, weaknesses, opportunities, and threats—analytical approach for analyzing proposed architectures.

- Pugh Analysis for scoring and downselecting proposed architectures for implementability using criteria of Cultural Acceptance, Flexibility, Responsiveness, Affordability, Innovation/Creativity, Strategy, and Mission Readiness.

- X-Matrix assessment process: where grids in each corner of the matrix represent potential interaction between the row and column they connect strategic objectives, enterprise metrics, enterprise processes, and stakeholder values, as shown in Figure *24*. This process is helpful for identifying strong and weak relationships within the enterprise architecture. The process of filling out that matrix is by starting in the upper left quadrant and move around the matrix in Figure *24* in a counter-clockwise direction. For each row and column intersection, the relationship can be determined as strong, weak, or no interaction, and color coded accordingly, based on the answer to these four questions: (1) Is this strategic objective measured by this metric? (2) Does this metric measure performance of this process? (3) Does this process contribute to delivering this stakeholder value? And (4) Is this stakeholder value represented by this strategic objective? The color coding refers to each of these relationship classifications. For example, the yellow boxes here can keep count of the number of weak relationships, the blue boxes of the strong relationships, and the white one of the no interaction category.

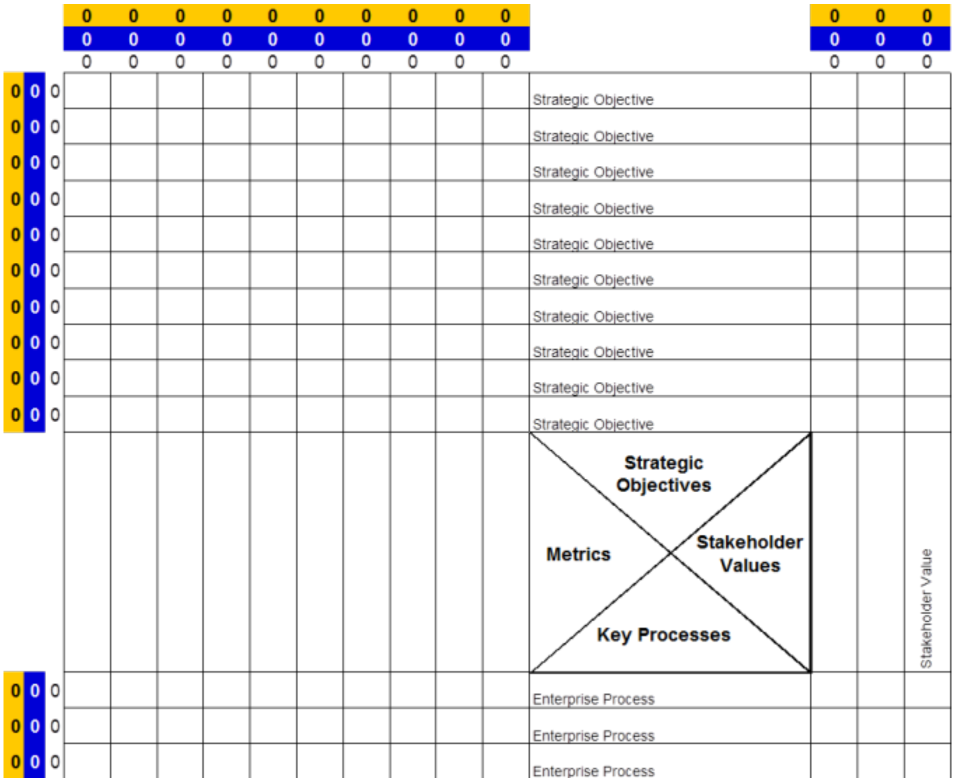


Figure 24. X-Matrix assessment process.

Finally, the research looks at the implementation plan, including its steps and epochs, for implementing the downselected architecture, in addition to performing future proofing analysis to test the adaptability of that architecture to different future scenarios.

Chapter 4: Results and Discussion

4.1 Research Question #1

This chapter presents the detailed analysis and results for each of the six case studies in this retrospective and longitudinal process study. The presented results incorporate the information collected throughout the conducted series of interviews, in addition to documentation and archival reviews, to create an up-to-date evaluation of the management and program challenges that the agency is facing for efficient development and infusion of innovative planetary technologies.

4.1.1 New Millennium – Deep Space 1

Launched on Oct. 24, 1998, the Deep Space 1 (DS1) Flyby mission was the first flight of the New Millennium program at NASA—a program whose flights were "intended to validate the technologies required for future deep space and Earth orbiting science missions" (Nelson, Stofan, Raymond, & Rayman, 1997). DS1's primary mission was devoted to such technology demonstrations that were enabling for science, but too risky to devote a full mission to [I21, I31], with its payload of 12 technologies for testing and evaluation (Rayman, 2002; Rayman, Varghese, Lehman, & Livesay, 2000). After successfully completing its primary technology demonstration mission, DS1 also conducted a successful bonus encounter with asteroid (9969) Braille in 1999 and ended with its encounter with comet 19P/Borrelly in 2001 (see *Figure 25*).

Figure 25. Artist's Concept of Deep Space 1 Encounter with Comet Borrelly. *(NASA/JPL, 2001)*

According to (Rayman, Varghese, Lehman, & Livesay, 2000), DS1's criteria for "complete mission success" criteria, as agreed to by NASA Headquarters and JPL, were:

> "1) Demonstrate the in-space flight operations and quantify the performance of the following 5 advanced technologies:
>
> - Solar electric propulsion (SEP)
> - Solar concentrator arrays
> - Autonomous navigation
> - Miniature camera and imaging spectrometer
> - Small deep space transponder
>
> and any 3 of the following 6 advanced technologies:
>
> - Ka-band solid state power amplifier
> - Beacon monitor operations
> - Autonomous remote agent
> - Low power electronics
> - Power actuation and switching module
> - Multifunctional structure
>
> 2) Acquire the data necessary to quantify the performance of these advanced technologies by September 30, 1999. Analyze these data and disseminate the results to interested organizations/parties by March 1, 2000.
>
> 3) Utilize the on-board ion propulsion system (IPS) to propel the DS1 spacecraft on a trajectory that will encounter an asteroid in fiscal year 1999.
>
> 4) Assess the interaction of the IPS operations with the spacecraft and its potential impact on charged particle, radio waves and plasma, and other science investigations on future SEP-propelled deep space missions."

The first criteria leaves out one of the 12 total technologies demonstrated— a miniature integrated ion and electron spectrometer—because albeit being eventually successful, it was added late to the mission, that "even six weeks before launch, it was uncertain whether the device would be ready" (Rayman, Varghese, Lehman, & Livesay, 2000).

DS1 was the original and probably one of the most successful of the Deep Space New Millennium program missions. One of the unique aspects of DS1 is that it was also the "last larger mission, where the price point was still low enough that even though it was not required to do science, it did some science. So that was considered an equitable trade" [I39]. This advantage was not available for later Deep Space missions, like Deep Space 3, where the cost kept increasing into "the several hundreds of millions of dollars", becoming "a value proposition for astrophysics—it was not going to do science that was considered worthy of spending that much of the astrophysics budget", despite the understanding of the need to validate the Deep Space 3 technologies [I39].

With the DS1 goal of getting technologies to fruition, the solar electric propulsion (SEP) was perhaps the key technology carried onboard and providing the primary needed delta-V for the mission [I21, I31, I39]. SEP was an "enabling technology" that had not been yet demonstrated at the time, whose successful demonstration on DS1 opened the doors to its wide use afterwards [I31]. Electric propulsion had been previously proposed several times in Discovery class proposals, but not selected because "while it had been used for station keeping around the Earth, in telecom applications, up until that point, it was enabling missions in science, but there were concerns that it could not be used reliably, or that the ionization would affect the science measurements" [I39]. In DS1, it was critical to demonstrate the ability to use electric propulsion to continuously or near continuously get somewhere, and that science measurements, not degraded by spacecraft charging or something similar, could still be collected [I39].

The NASA SEP Technology Application Readiness (NSTAR) program was a collaboration between JPL, NASA's Glenn Research Center, Hughes Electron Dynamics, Spectrum Astro, Moog, and Physical Science, Inc. The program aimed to validate low-power ion propulsion as a means of significant mass savings for future deep-space and Earth-orbiting spacecraft (Rayman, Varghese, Lehman, & Livesay, 2000). As explained by (Rayman, Varghese, Lehman, & Livesay, 2000), the ion propulsion system (IPS) on the DS1 spacecraft worked by using a hollow cathode to generate electrons that convert the xenon gas into a charged particle (ion) called Xe+. These ions were then propelled out of the spacecraft through a 30-cm thruster, which had a pair of molybdenum grids to help with the emission. In addition to the ion beam, a separate electron beam was produced to create a neutral plasma beam. This process is shown in the NSTAR Ion Engine and the IPS functional diagrams in Figure *26* and Figure *27* (JPL Publication 00-10, 2000). The IPS's power processing unit can accept up to 2.5 kW and produce a peak thrust of 92 mN (Rayman, Varghese, Lehman, & Livesay, 2000).

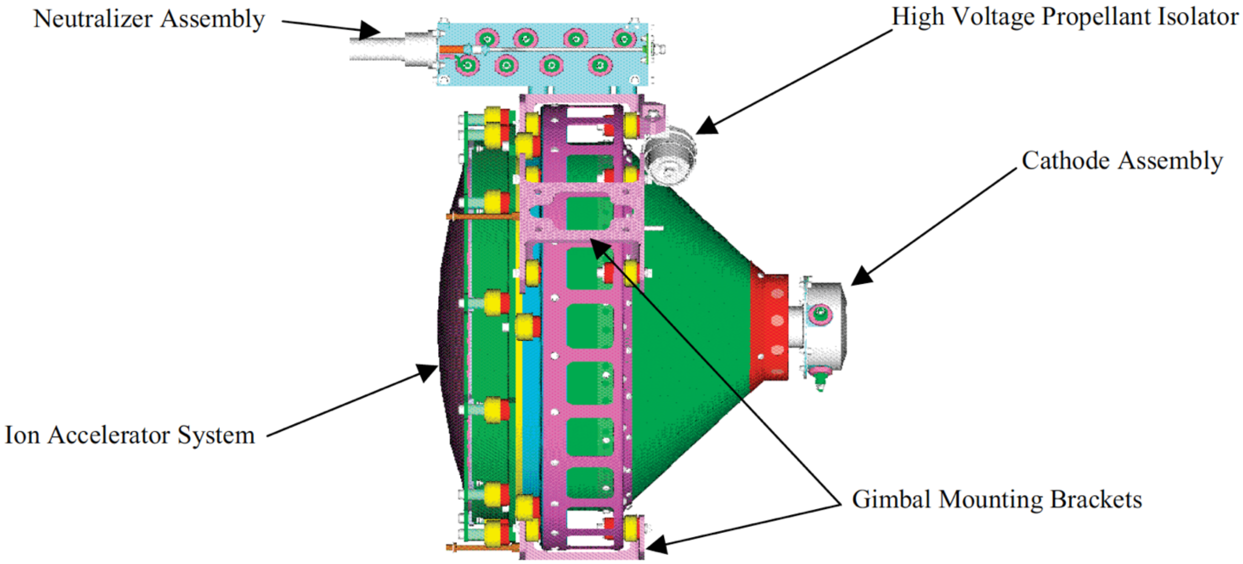


Figure 26. Diagram of the NSTAR Ion Engine. *(JPL Publication 00-10, 2000)*

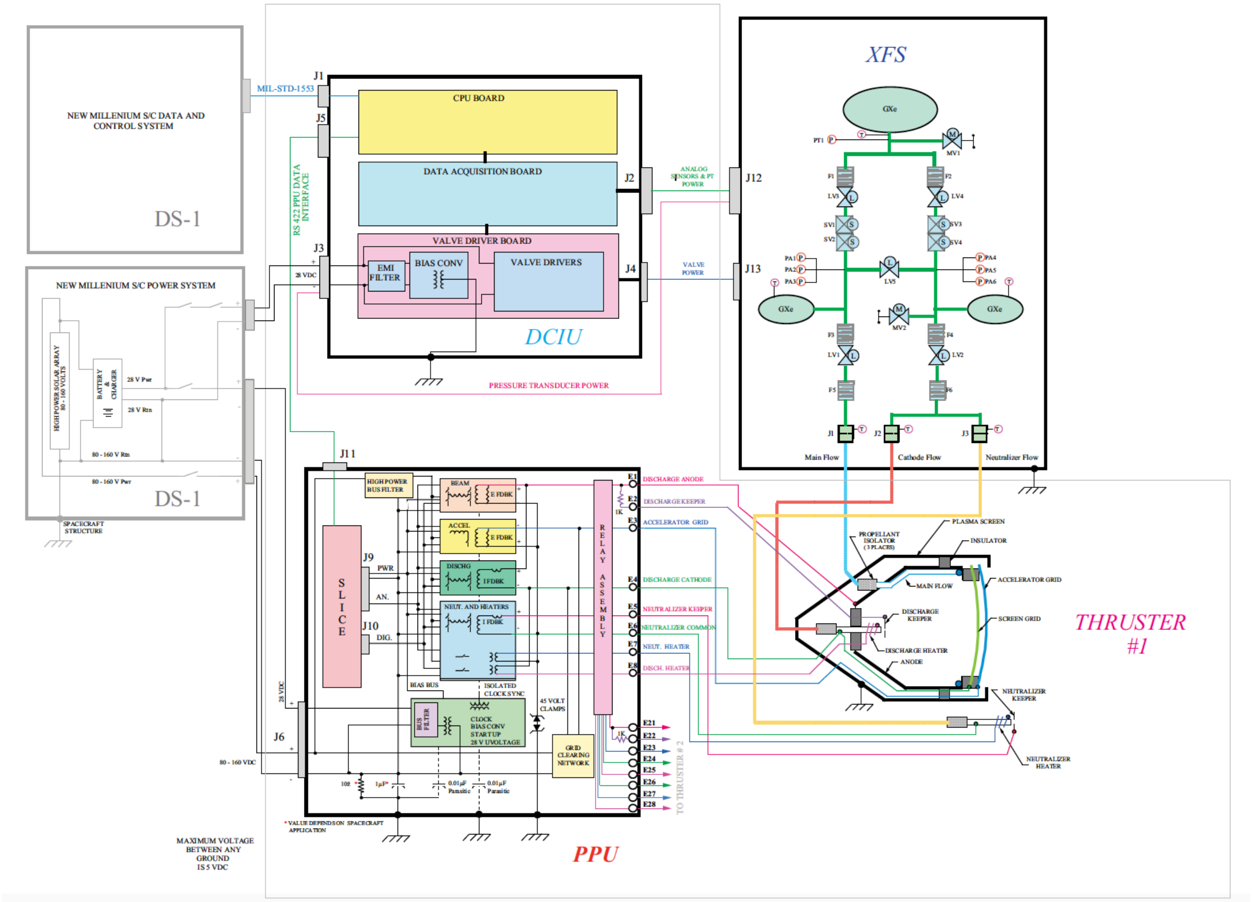


Figure 27. Functional Block Diagram of the NSTAR Ion Propulsion System. *(JPL Publication 00-10, 2000)*

The IPS was tested on DS1 and operated for nearly 1800 hours by June 30, 1999, during which a comprehensive diagnostic system was used to quantify the interactions of the IPS with the spacecraft and validate models of those interactions (Rayman, Varghese, Lehman, & Livesay, 2000). Before flight testing, NSTAR also conducted an extensive ground-testing to validate the ion propulsion technology. This validation effort was mainly focused on "demonstrating that the NSTAR thruster design had sufficient total-impulse capability and reliability to accomplish deep-space and near-Earth-space missions of near-term interest", but it was also partly targeting the IPS interdependency on the other DS1 subsystems (JPL Publication 00-10, 2000). These subsystems include the solar array, the spacecraft power subsystem, thermal control, attitude control, communications, science instruments, command & control, and navigation (JPL Publication 00-10, 2000).

The NSTAR ground testing used a total of four engineering-model thrusters (EMT) build by NASA Glenn Research Center (GRC), in addition to two flight model thrusters fabricated by Hughes, Electron Dynamics (HED). The test series included four major tests (NSTAR Project Tests NPT1—NPT4), along with three other series of development tests (DTs), engineering development tests (EDTs), and characterization tests (CTs). NSTAR also conducted a series of long duration tests on the IPS to "identify unexpected failure modes, characterize the parameters that drive known failure mechanisms, and determine the effect of engine wear on performance" (JPL Publication 00-10, 2000). These tests resulted in multiple design changes to the thrusters to address the identified failure mechanisms, followed by a post-test thruster inspection to confirm that such failure mechanisms have been eliminated (JPL Publication 00-10, 2000).

In the DS1 development process, the team tried to do things very differently, streamlining tasks and "inventing the way" they did things, such as not having PDR and CDR, but an ODR, Only Design Review, for some instruments, for example [I21]. With most of JPL's focus and attention being on the Cassini mission at the time, the DS1 team had some ability to "operate in a semi-skunk works mode and make decisions locally", with a "very, very streamlined review process" [I39].

DS1 had a remarkably good and dedicated team. The team featured a good skill mix, with many technologists on board, who were getting the support from the flight team for any areas of less expertise. This mix of skill sets for DS1 was critical for the mission's price point, as one team member describes, "you can't afford everybody to be senior at those budgets, you just can't. But you need a few senior people to make that happen. Those teams need to be collocated" [I39]. This team structure enabled quick decision-making by experienced members who possessed greater insight into which risks to take and which to avoid. As one technologist described the team [I21],

> "The people I had on my team are outstanding. We had an incredible system engineer, we had incredible people working a job and people worked very long hours. People work long hours on most projects, especially towards the end."

In addition to the DS1 team structure, one of the key factors for the success of this technology-driven mission was an underlying premise of having a "safety net" based on testing. Testing was key to avoid "skimping things" and to ensure that possible oversights in the process were identified through to ultimately prevent potential issues in the future [I21, I39].

However, despite its success in completing its mission success criteria, DS1 suffered from several challenges along the way of its development [I39], causing it to be "very difficult" and "not terribly successful" from a management perspective [I21]:

- **Spacecraft Provider Selection:** The spacecraft provider was decided by the program office, downselected after a competition between various other providers. However, the contractor selected was a "very small company that had not had that much experience" [I39]. As one DS1 engineer described, "[the contractor] was at fifty people, when DS1 was selected, and it grew, during the time of the DS1, to around three hundred and fifty or four hundred people, so tremendous growth in a small amount of time" [I39].

  This spacecraft provider choice was partly done as a quicker and more efficient way of doing things in the "faster, better, cheaper" era because of the idea that JPL was "just an old dinosaur that only knew how to do the flagships" [I39]. However, in the end, the spacecraft had to be brought back in-house to JPL "largely untested and finished that testing at JPL"—it was clear to DS1 team at JPL that they "could not get that [spacecraft provider] team to get that job completed without having a little bit more direct control and oversight over it" [I39, I21].

- **Instrument Selection:** One of the main challenges that occurred in the process of instrument selection was that "the technologies were selected almost independent of one another, and they were primary systems on the spacecraft" [I39]. For example, two of the technologies that were on

DS1 were the ion engine and the concentrator solar array. The ion engine had multiple throttle levels and needed power to be able to do that, but the concentrator solar array required very tight pointing to get those power levels. Hence, those two technologies would not be normally planned together [I39].

The other example was that of 3D Flight Computer and the autonomous remote agent software. Since both the technologies were new, the DS1 team did not have the compute technology to be able to test with the software early enough in the life cycle. The development timeframes of these two technologies were "out of phases for a project need for them to be primary systems on the mission" [I39].

- **Oversight & Review Structure:** Despite the positive aspects of the DS1 team's ability to utilize streamlined review processes and "operate in a semi-skunk works mode", that structure hurt the projects in some ways too. A better review structure might have helped the team in finding issues earlier, particularly for the science instruments. As one engineer explains, "for the Plasma Experiment for Planetary Exploration (PEPE), in particular, as well as for the avionics and the 3D stack, a better review structure would have helped us come to decisions earlier" [I39].

  Despite being a contributor to DS1's launch delay [I21], not operating within the formal structure at JPL was however mainly because "it is very hard for a small technology demonstration mission to do that and still maintain its cost point" [I39].

- **Future Use:** As a technology demonstration mission, one of the main questions to ask is whether this mission was able to mature the technologies enough for their next generation to be happily flown on a billion dollar or a two-billion-dollar mission, for example. As this engineer explained [I39],

  > "You do have to look at is that enough of a leap? Can I make the transition now from what I am demonstrating here to that very expensive, could be several billion dollars, next generation? Am I convinced enough that the risk is manageable? And that is the real thing that must be looked at besides the ability to do it for the small mission in dollars."

  In the case of electric propulsion, the answer was yes. After DS1, electric propulsion was flown on NASA's Dawn mission, as the first proposal to get through the Discovery competition, and will be flown on NASA's Psyche mission, largely because of the successful DS1 demonstration. DS1 retired a list of key risks that include adequate engine life, Guidance, Navigation and Control of an SEP spacecraft, mission-operation costs, spacecraft contamination by the SEP system, SEP impacts on science instruments, SEP impacts on communication, and Electromagnetic compatibility (EMC) of the SEP system with the spacecraft (JPL Publication 00-10, 2000).

  However, there was a lot of work left to do between DS1 and Dawn, creating a mismatch in expectations about the technology status for the next generation. Such remaining tasks included testing multi-engine SEP systems, instead of the single-engine system used on DS1 and significantly enhancing the "engine-throughput capability, operation at higher power levels per engine, and operation at higher specific impulses" (JPL Publication 00-10, 2000). The main challenge there was that "at a one hundred million dollars, you are not getting a set of flight qualified documentation that you can just go out and build to print, at that lower price point. You

> get the existence proof of the technology demonstration. And I think that the Dawn folks thought they were getting the qualified instrument" [I39].

In summary, despite its low budget (totaling under $150 million (in year 2022 dollars) for development, launch, and operations in its primary mission, including payload integration) and its aggressive schedules, the DS1 mission was a successful precursor to many future NASA missions that have incorporated the advanced technologies demonstrated on this mission, especially the ion propulsion system. However, throughout the development of this mission and its technologies, various challenges were faced by the team in term of the spacecraft provider, the independent instrument selection with out of phase development timeframes, the streamlined review structure, and the price point constraint for preparing technologies for their next generations.

4.1.2 Mars Scout Program – Phoenix

As previously discussed, the Mars Scout Program was a NASA program that ended in 2010 and got incorporated within the Discovery program. The Mars Scout missions, analogous to Discovery missions, were PI-led, price-fixed missions that specifically targeted the Mars program's science goals that were "not otherwise covered in the baseline Mars plan" (Matousek, 2001). Mars Scout missions were also intended to "allow more risky technologies and approaches to be applied in the investigation of Mars" (Shotwell, 2005). The first of these missions was the Phoenix lander that landed in 2008 on the surface of Mars (Phoenix, 2022).

The Phoenix Mars Lander was a University of Arizona driven activity, with JPL and Lockheed Martin as the implementing organization [I50]. Phoenix came after a series of previous Mars surface robotics missions, including the Pathfinder mission and its Sojourner rover that landed on Mars in 1997 (Mars Pathfinder), the Mars Polar Lander that was lost on arrival in 1999 (Mars Polar Lander/Deep Space 2), and the twin Mars Exploration Rovers Spirit and Opportunity that landed in 2004 on the surface of Mars (Mars Exploration Rovers).

One critical mission in the discussion of the Phoenix lander is the Mars Surveyor 2001 lander that was cancelled as part of the review and restructuring of NASA's Mars Exploration Program. This mission was based on the lost '98 Mars Polar Lander, and it was supposed to carry the Athena precursor experiment (APEX) package comprised of "the Mars Descent Imager (MARDI), the Mars Radiation Environment Experiment (MARIE), designed to study the radiation environment at the surface, a Panoramic Camera (PanCam), a small Thermal Emission Spectrometer (Mini-TES), the Mars Environment Compatibility experiment (MECA), designed to measure the toxicity to humans of Martian soil and dust, the Mars In-situ Propellant production experiment (MIP), and a robotic arm and camera" (Williams D. R., 2022).

Throughout these series of robotics missions, NASA featured a "change at heart" when it comes to developing instruments, as one project manager described [I35]. For example, a more "engineering-centric" premise was observed in the Pathfinder era, where adding instruments such as the cameras were not given as much priority, as the focus was on testing the landing system [I35].

When the Phoenix mission was proposed, the Mars Surveyor 2001 lander was already "a spacecraft in a box" at Lockheed Martin. To win against the other received proposals, the team's idea was, "if we use the spacecraft in the box, as it is in the box and use its instruments and its robotic arm, we could have the cheapest mission of anybody since it is already built, we just need to fly it" [35]. The mission's science theme in its winning proposal revolved around the theme of "low cost, great science, high reliability" [I35, I17], by taking the already built spacecraft straight into the test phase.

During that time, the 2001 Mars Odyssey had just gone into orbit and was starting to return some measurements, specifically regarding finding ice surrounding the polar cap, all the way down to ~50 degrees latitude, up to 50% water by weight in the subsurface layer (NASA JPL, 2002). The Phoenix team thus proposed "following the water", by landing in the north of Mars and using the robotic arm to dig up the soil and put it in the MECA instrument and the Thermal and Evolved Gas Analyzer (TEGA) instrument (Garcia & Fujii, 2007). Since the robotic arm and the instruments already exist, that would allow a low cost, high science opportunity to do "something exciting" [I35]. Phoenix was a proposal for a small mission without individual instrument proposals, only sections describing them. The instrument costs were folded into the overall mission costs as well.

Eventually, after being selected, several changes were made in comparison to the original proposal. The previously built spacecraft had to undergo a series of modifications that included replacing hardware taken by other projects such as the Mars Reconnaissance Orbiter (MRO), responding to Return to Flight recommendations, and accommodating an updated mission design (Garcia & Fujii, 2007; Shotwell, 2005). The updated mission design occurred due to the change of the Earth/Mars opportunity (JPL Document D-16303, 1999) and the change of the landing site latitude from the previous mission's equatorial landing site to the Martian arctic (Garcia & Fujii, 2007).

Phoenix's main target questions were: (1) Can the Martian arctic support life, (2) What is the history of water at the landing site, and (3) How is the Martian climate affected by polar dynamics? (Garcia & Fujii, 2007). To explore and conduct the scientific in-situ and remote sensing investigation for these questions, Phoenix had a series of instruments, mostly with heritage from the Mars Surveyor 2001 lander and the Mars Polar Lander. These instruments included a Robotic Arm (RA) responsible for excavating soil to reveal ice samples for analysis by the Thermal and Evolved Gas Analyzer (TEGA) and the Microscopy, Electrochemistry, and Conductivity Analyzer (MECA). Phoenix also had a Meteorological Station (MET) to measure daily weather and exceptional imagining systems thanks to the Surface Stereo Imager (SSI) that captured high-resolution stereoscopic images of the Martian terrain, in addition to the Mars Descent Imager (MARDI) and an Atomic Force Microscope (AFM) inside MECA (Garcia & Fujii, 2007).

Phoenix had the following set of minimum and full mission success criteria (Garcia & Fujii, 2007):

- **Minimum Mission Success Criteria:**

  1. "Land successfully on the surface of Mars and achieve a power safe state.
  2. Acquire a partial 120° monochromatic panorama of the landing site.
  3. Provide samples of the surface soil as well as samples from one depth beneath the surface to either TEGA or MECA wet chemistry.
  4. If TEGA, analyze at least 2 soil samples to create a profile of H_2O (in the form of hydrated minerals, adsorbed water, or possibly ice at the deepest level) and mineral abundances near the surface. It shall also analyze an atmospheric sample in its mass spectrometer.
  5. If MECA, analyze the wet chemistry of 2 soil samples.
  6. Document all non-atmospheric samples and their collection locations with images."

- **Full Mission Success Criteria:**

    1. "Land successfully on the surface of Mars and achieve a power safe state.
    2. Acquire a true color (RGB), 360° panorama of the landing site
    3. Obtain calibrated optical spectra of at least 3 locations that include both rocks and soil.
    4. Provide temperature and pressure measurements throughout landed surface operations at a frequency that determines key atmospheric properties.
    5. Provide samples of the surface soil, and samples from two depths beneath the surface, to both TEGA and MECA.
    6. Use TEGA to analyze at least 3 soil samples to create a profile of H2O (in the form of hydrated minerals, adsorbed water, or possibly ice at the deepest level) and mineral abundances near the surface. It shall also analyze an atmospheric sample in its mass spectrometer.
    7. Use MECA to analyze the wet chemistry of at least 3 soil samples. It shall also analyze 3 additional samples in its microscopy station.
    8. Document all 9 non-atmospheric samples and their collection locations (before and after sampling) with images."

Phoenix had a remarkable team, with a high technical background and a mix of senior and junior levels of expertise. The team structure fostered creative conflict and conversations that consistently resulted in design-involved risk management [I46]. Despite the convincing proposal and the final mission success, Phoenix faced several challenges in its implementation and development, both on a mission and at an instrument level [I35, I46, I50, I14, I15]:

- **Misconceived Requirements in Science:** When mission and instrument requirements were in the process of being defined, the team worked hard to develop a set of Level 3 (Subsystem Level) engineering requirements that were implementable by the engineering teams without "handcuffing engineering" in terms of developing the instruments, but still got the PI's what they wanted [I46]. This process allowed the PI's to more freely "operate in their sandboxes", but it was also a challenge as it required a "lot of arguments, I mean *a lot* of arguments to get that to that place", as one payload manager explained [I46].

  Enforcing that early conversation on requirements allowed the PI's and teams to do their jobs and keep moving in the direction of get the instruments built to the requirements that had been agreed on. However, in addition to the set of arguments that took place throughout the development process of the set of requirements, there has also been some misconceived requirements between the language of science versus engineering. One such example was the pressure and temperature data collection frequency. The mission was very energy-limited on the surface, and the "energy-balance dance" was critical [I46]. During the requirements discussion, there was a requirement for collecting pressure and temperature measurements over diurnal cycles at a Nyquist frequency. The science team agreed to that requirement, but there was a miscommunication there that what was meant by Nyquist frequency was collecting data twice a day. After the mission landed, the team suddenly realized that the scientists had wanted a continuous around-the-clock pressure and temperature data. Given the power and energy limitations on the surface, this was impossible and forced the team to continuously make decisions between surface digging versus collecting pressure and temperature data [I46].

- **Instruments vs Spacecraft:** Because Phoenix was going to land on Mars using thrusters, and it was same sister spacecraft as the Mars Polar Lander that had just crashed, the NASA administrators and the managers did not want to "crash the same spacecraft at the same planet—it just does not look good" [I35]. At the same time, JPL was getting ready for the Curiosity Rover, which was going to land with thrusters too, although in a different way. JPL wanted to show the world that they had the total experience necessary to land safely on Mars, that "nobody else could do it as well as they could do it" [I35]. What these concerns meant was that Phoenix *had to* land safely [I35, I46, I50]. As the team was building the spacecraft, they were looking for additional fatal flaws that could have killed the Mars Polar Lander to fix them in the sister spacecraft used for Phoenix. As they started to find these flaws, they realized there were a more than they were hoping for—any of which could have easily killed the mission. One example was the release cable for landing between the orbital stage and the entry stage that was only tested at room temperature, instead of the temperature it was going to be released at [I35]. As they fixed each of the discovered fatal flaws, new ones kept appearing, "we had a plot that showed when each fatal flow is found versus time, and what you want to see is that steep slope rolling over to an asymptote. That's not what we were seeing. There was a straight line." [I35].

  JPL's efforts and oversight, thus, mainly focused on the risk reduction for landing safely. As whether the instruments worked, that was all different question [I50]. This dynamic left the instrument teams with less resources and attention. As two managers explained [I35, I46],

  > "When it comes to instruments, JPL was not very interested. They obviously wanted the instruments to work, particularly the camera, but they were willing to take substantial risk for the other instruments. However, when it came to landing safely on Mars, that is where the oversight came in." [I35]

  > "The system needed to land. Without the landing, everything else would be dead. That was the highest priority thing in terms of how the review board dealt with us all the way through, and the instruments were held to probably not the same bar, but they still had to be a Class C development process. Instruments still had to go through the same gates, while everybody was worried about the landing system. As soon as the landing was over, all eyes went to the instruments. And it is always a joke that '*everybody is class A at the pad*', and that means that everybody says they are willing to take the risk and then, all of a sudden, the risk is not acceptable as you get closer and closer to launch." [I46]

  Occurring at the pivot point of JPL's process evolution of its design principles and flight practices after the Mars Polar Lander failure, Phoenix was at an intersection of additional processes at JPL to increase the safety next, but a carried over flexibility from the faster, better, cheaper (FBC) era. That environment forced Phoenix to have a "very different DNA from the top down", so it was implemented differently, still allowing for "failures to occur at some level" [I50]. The team had a lot of flexibility on an instrument level, as one project manager described [I35],

  > "People only talk to you once a month. You have 30 people working on the project every day, so once a month, you tell them what you're doing. There's a lot of flexibility to do what you want, because you have to meet a schedule, and those schedules are looked at once a month.

> As far as the instruments are concerned, there was a lot of flexibility. The spacecraft was a little different. It was looked at more carefully and very much more daily basis.
>
> […] When it came to the spacecraft and the parts of the spacecraft that have to work if you're going to get down to Mars, that was given tremendous oversight, and the budget was float out the door for any problems that we encountered over there. But when it came to instruments, they were being held to their original prices, and it was like pulling teeth to get extra money for the instruments. So that was disappointing."

The team overall also tried to make changes to save money for the science—tailoring parts of the MECA instrument and picking the donated Canadian-built meteorological station's lidar, for example [I46]. However, despite such efforts, JPL's interest was in focusing the money spent on risk reduction. Such efforts opposed the initial team's theme of "low cost, great science" where they planned to use the spacecraft and instruments as they were, without the costs of redesigning and rebuilding. The team was pushed towards higher costs of reliability engineering, especially for the spacecraft [I35, I46, I14, I15].

Aside from the spacecraft, there was also a differential distribution of efforts between the instruments themselves. For example, a lot of resources were pushed towards the development of a new robotic arm from scratch, after the team realized the inadequacy of the robotic arm from the 2001 Mars Surveyor Lander [I46]. This differential distribution of resources between instruments created disagreements on which instrument was to be considered more important. Some people argued that resources and efforts had to go to the robotic arm, since without it, getting samples to TEGA or MECA would not be possible [I46].

Moreover, the team had to upgrade the 2001 Mars Surveyor Lander development program, that fell under the Faster, Better, Cheaper (FBC) era, to increase reliability. The team ran a true class C development program, where they went through the parts list of the electronics that existed, upgraded where possible, did testing where it was not previously done, and conducted full analyses across the development program. These analyses included worst case analyses on all the electronics, in addition to full-part stress analyses which were not properly done, nor verified by mission assurance, for the 2001 mission [I46].

This distribution of resources and oversight between the instruments themselves and between the instruments and the spacecraft created the typical conflict between the flight system and the payload. As one manager explained [I46],

> "Flight systems are trying to protect their resources and their reserves. Payloads are fighting like crazy to get as much as they can. We did a lot of work within a payload system to live within the resources that we were provided, including not only that the power available, but the current available. However, there was *a lot of clawing and scratching* to get the resources we needed to do what we needed to do."

- **Instrument-Specific Challenges:** Despite the general mission success, including the successful camera system, microscope, and lidar, several instruments on Phoenix faced challenges along the way in their development and operations. The next two sections focus on the instrument-specific challenges for two of Phoenix's instruments: the Thermal and Evolved Gas Analyzer (TEGA) and The Microscopy, Electrochemistry, and Conductivity Analyzer (MECA).

4.1.2.1 TEGA

The Thermal and Evolved Gas Analyzer (TEGA), shown in *Figure 28*, was a Phoenix instrument consisting of two main components: two main components: the thermal analyzer (TA) designed and constructed by the University of Arizona Lunar and Planetary Laboratory, and the evolved-gas analyzer (EGA), a mass spectrometer, designed and constructed by the University of Texas at Dallas Physics Department (Hoffman, Chaney, & Hammack, 2008). Combining a high-temperature furnace and mass spectrometer, TEGA was responsible for analyzing eight unique Martian ice and soil samples delivered by the robotic arm into its eight small ovens— "the size of an ink cartridge in a ballpoint pen" (NASA, 2008; Hoffman, Chaney, & Hammack, 2008). A scanning calorimetry process was then used to monitor the temperature and power required for heating the sample in each oven, as the materials in each sample transition from solid to liquid to gas. The streams of vaporized evolved gases from the sample volatile material would then be transported to the mass spectrometer for the scientific analysis of the "chemical character of the soil and ice" (NASA, 2008; Hoffman, Chaney, & Hammack, 2008). The mass spectrometer can detect molecules and atoms in the sample at a level as low as 10 parts per billion, which critical for scientists to determine the ratios of various isotopes of hydrogen, oxygen, carbon, and nitrogen and gain insights into the origin of volatile molecules and biological processes that may have occurred in the past (NASA, 2008; Hoffman, Chaney, & Hammack, 2008).

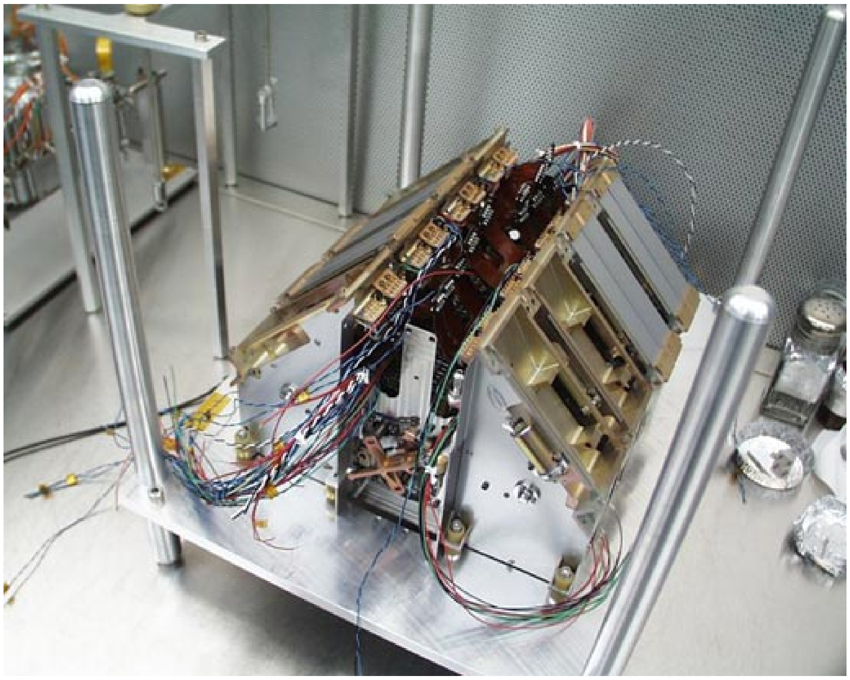


Figure 28. Thermal and Evolved Gas Analyzer (TEGA) built by the University of Arizona and University of Texas, Dallas. *(NASA, 2008)*

TEGA was initially built for the lost Mars Polar Lander mission, where it was similarly composed of two separate but closely coupled components: a Differential Scanning Calorimeter (DSC) and an Evolved Gas Analyzer (EGA) (Boynton, et al., 2001). However, many changes and redesigns had to implemented between the initial instrument and its Phoenix next generation, including its cover and the addition of pulse width modulation for its ovens [I46].

Eventually, TEGA's results included detecting water at temperatures "that may indicate the presence of phyllosilicates, Fe-oxyhydroxides, and possibly hydrous carbonates, and/or hydrous sulfates" (Sutter, et al., 2009). However, despite these results, TEGA faced a problematic journey during its development and operations on the surface of Mars. Some of its main challenges were the following [I50, I15, I35, I46]:

- **Instrument Team Expertise and Facilities:** As TEGA was being developed by the two university teams, it became clear to the Phoenix team that the instrument team was "not well equipped to build the instrument" [I50]. Despite the good instrument idea in mind, the physical implementation inside the universities presented "really poor processes" [I50, I15] and left the instrument "close to not working" on Mars [I50, I15]. During visits from external engineering experts, especially for the analyzer development at University of Texas, Dallas, multiple issues were constantly pointed out, including the lack of proper facilities and processes for contamination control. As one system engineer described, "They didn't have the requisite skill to do it. It was evident, and as a result, it was very amateurly done, and they were lucky to have it work" [I50]. Without the needed support and oversight throughout the instrument development, a tiger team had to be pulled towards the end to fix problems and get the instrument to work. A key reason behind these issues was that TEGA was a younger team, with less expertise, and thus needed a larger safety net that should have been recognized earlier in the instrument development process.

- **Oversight and Poor Processes during Redesign:** After redesigning TEGA for the Phoenix lander, many parts of the instrument did not work on the surface of Mars [I15]. One of the main problems that happened was with the sampling system, where TEGA had a door opening anomaly. TEGA had a set of cells arranged "in 2 rows on either side of the instrument with 4 cells apiece", where each cell was equipped by a pair of spring-loaded protective doors released by a pin puller device (JPL, 2009). Two sets of commands were sent to open the doors of the cells, the first of which for Cell #4 was sent in early June 2008, and the second was sent for Cell #5 in mid-June. The first command resulted only in a partial door opening, and the second command resulted in a 25 degrees marginal opening (JPL, 2009). Failure investigations showed that a mechanical interface had happened due to the configuration of TEGA and the stiffeners on the doors impeding the door opening—the root cause of which was to a "breakdown in the design, verification, and validation processes" (JPL, 2009). That failure mode had been already revealed in the testing of the cover release and door opening of an Engineering Qualification Model (EQM), but it was not properly modified nor documented. As summarized by JPL in NASA's Lessons Learned System (JPL, 2009),

  > "A mechanical interference, attributed to inadequate processes and procedures for instrument design, verification, and validation, prevented the full opening of a set of instrument doors following the landing of Mars Phoenix. The problem was attributed to the instrument contractor's inadequate documentation of the anomaly, and failure to adequately communicate

> a redlined design change to a subcontractor. The anomaly also represents a violation of the "test-as-you-fly" principle".

This anomaly was specifically reported in NASA's Lessons Learned System as follows (JPL, 2009),

> "The instrument contractor failed to implement a rigorous design process:
>
> 1. No failure report, inspection report, or other control paperwork was processed for the mechanical interference design issue discovered on the EQM.
> 2. The stiffener modification, as redlined on the sketch, was not provided to the fabrication subcontractor.
> 3. The flight unit was accepted without all the stiffener modifications due to improper configuration control.
> 4. Modifications to the EQM for the subcontracted hardware were made by the customer (i.e., the instrument developer) instead of by the contractor.
> 5. Because the fix was implemented only on the EQM, and the EQM was used to verify the door functionality, the intent of having identical EQM and flight units was not met."

This challenge that TEGA faced was critical to the instrument [I15], uncovering the poor processes [I50] and mistakes that took place [I46], causing an anomaly that could have been completely avoidable had it been dealt with before launch [I46]. TEGA was left in idle for around a month, out of a three-month mission, waiting to get their sample and trying to recover their instrument [I15]. What this anomaly also unveiled, however, relates back to NASA's focus on the spacecraft instead of instruments in their oversight, budgets, and other resources. Teams like TEGA's had "too much autonomy" [I35] and required additional help and oversight, even if they had not asked for it [I35, I50, I15]. Such lack resources, financially and otherwise, taxed the already not-so-equipped team members with many additional challenges, as one project manager explained [I35],

> "Every part of the instrument seemed to fail, and it was just so difficult to work with the group. They had too much autonomy. They had not given an honest price for the instrument. They underbid it, so they kept trying to do things just by working extra hours. They almost killed the team trying to get the thing working. And as you might guess under those conditions, you can make a lot of mistakes, and that is what happened."

In conclusion, TEGA faced a series of challenges in its development including the inadequate team expertise and facilities, in addition to the poor processes implemented and the deficit oversight and resources. However, as one system engineer pointed out, "The answer for TEGA is not the answer for today" [I50]. The reason has to do with the diminishment of actual capabilities among many of the existing scientific groups due to retirements and loss of people, which created a situation where an even bigger safety net is now needed than what was needed in the Phoenix era.

4.1.2.2 MECA

The Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) was another key instrument on the Phoenix lander. Like TEGA, MECA was also not specifically designed for Phoenix, but rather for the Mars Surveyor 2001 lander that was cancelled after the Mars Polar Lander loss [I35, I30, I15]. Originally sponsored by NASA's Human Exploration and Development of Space (HEDS) Office, MECA was short for the "Mars Environmental Compatibility Assessment" on the 2001 lander before getting renamed on Phoenix (Shirbacheh, Hecht, Bell, & Mogensen, 2005).

For its original mission in 2001, MECA was supposed to analyze soil-water mixtures and provide microscopic images of Martian soil. The instrument's primary goal was to "evaluate potential geochemical and environmental hazards that may confront future Martian explorers, and to guide HEDS scientists in the development of high-fidelity Mars soil simulants" (Hecht, et al., 1999). MECA was a suite of instruments that included a wet-chemistry laboratory, a microscopy station, an electrometer, and arrays of material patches "to study the abrasive and adhesive properties of soil grains" (Hecht, et al., 1999). The wet-chemistry laboratory was supposed to perform extensive analysis of the solution using ion-selective electrodes and related sensors. The microscopy station and the electrometer were supposed to combine optical and atomic-force microscopy to image dust and soil particles and address the electrostatics of the soil and its environment, respectively (Hecht, et al., 1999).

Supporting the MECA activities was the Robotic Arm that was going to help by collecting surface and subsurface soil samples (at a depth of up to 50cm) in its scoop and depositing them into the wet chemistry cells and microscope port. The Arm was going to also place the soil samples onto the MECA material patch plates for imaging and measuring properties such as "soil particle wear, hardness, and adhesion" (Bonitz, Nguyen, & Kim, 2000).

Moreover, MECA was going to assess the Martian soil for any potential hazards for "human explorers and their equipment", in addition to "providing information on the composition of ancient surface water environments, observing microscopic evidence of geological (and biological?) processes, inferring soil and dust transport, comminution and weathering mechanisms, and characterizing soil horizons that might be encountered during excavation" (Hecht, et al., 1999).

After cancelling the 2001 Mars Surveyor Lander, MECA was later revived for the Phoenix lander—looking close to what was originally proposed, but with few modifications [I46, I35, I30, I14, I15]. The Phoenix MECA instrument suite included a Wet Chemistry Laboratory (WCL), a Microscopy Laboratory consisting of an Optical Microscope (OM) and an Atomic Force Microscope (AFM), and a Thermal and Electrical Conductivity Probe (TECP) (Shirbacheh, Hecht, Bell, & Mogensen, 2005).

MECA featured a series of academic and commercial collaborations outside of the core team responsible for its project management at NASA JPL, including the University of Arizona, collaborators from the Max Planck Institute, Tufts university for the electrochemistry, in addition to several academic institutions and companies that were responsible for building the electrochemistry sensors, the accelerator assembly, and the soil conductivity analyzer [I30].

The Phoenix lander was physically at Lockheed Martin's facilities in Colorado, where the main integration and testing program, in addition to launch, cruise, and landing operations were run [I30]. The surface mission operations were handed to the University of Arizona, where the principal investigator of the mission worked out of [I30]. As the spacecraft integration took place at Lockheed Martin, the individual pieces were sent over there once they were ready to be integrated, along with personnel to build the integration and perform the system operations test in Thermal-Vac [I30].

MECA was proposed as an almost TRL six instrument on Phoenix, because it was previously developed. Phoenix MECA had to be "low cost, low risk", so it integrated a lot of lessons learned from its first development cycle [I15, I17]. That second iteration, after being put on a shelf, allowed MECA to have a full-scale system integration twice [I17].

Since most of MECA's hardware and electronics had been already developed, MECA's suite of instruments mainly underwent modifications, "tweaks", and fine-tuning for reliability for the Phoenix mission [I46, I15], replacing "a couple of elements with equivalent things" [I30]. One major change was excluding the arrays of material patches that was part of the 2001 Mars Surveyor Lander because Phoenix MECA was a Science Mission Directorate (SMD)-sponsored, not a human exploration, instrument anymore [I17, I15]. A new soil conductivity probe replaced the electrometer that was for the original development, while everything else was to be "more or less the same" [I30], except for MECA's original electrochemistry experiment. That experiment had sensors (originally built by an outside vendor) with a shelf life that had been exceeded by the time of the Phoenix mission, so they had to be rebuilt [I30]. That original vendor had "kind of lost the process" [I15, I30], but they had a good relationship with the MECA team to admit the challenges they were facing in redoing that work for the electrochemistry experiment, even if they had done it for the 2001 mission before [I15]. A tiger team, with experts on materials, had to be then brought to help in addressing that rebuild for the chemical cells, troubleshooting the leaks that were going on [I15, I30]. Other tweaks were in rebuilding and improving the electronics boards for the chemistry cells and improving the mechanicals on the atomic force microscope [I15].

MECA's team was highly technical and majorly composed of technologists—a category of JPL employees that was close to experimental scientists [I14]. That team composition was critical for MECA's success because despite not all having flight engineering experience, all these technologists had previously developed instrumentation and were able to learn what was needed for flight [I14].

Despite few hiccups, and at a total of ~ $13 million in its two phases of development, MECA was overall very successful—producing impressive microscopic pictures [I35] and a wealth of scientific findings [I14, I15]. One of its main scientific results was discovering calcium carbonate in the soil and soluble chlorine in the form of perchlorate, revealing an alkaline environment in contrast to that found by the Mars Exploration Rovers (Hecht, et al., 2009).

However, despite its success, MECA faced a few challenges during its development and operations on the surface of Mars. Some of its main challenges were the following [I14, I15, I30, I35, I46, I17]:

- **Budget and Oversight:** As previously discussed in the challenges that faced the Phoenix lander overall, MECA also fell at that pivot point between the faster, better, cheaper (FBC) and the modern eras at NASA [I30]. However, because the Phoenix mission and its instruments were largely billed as having a hardware on the shelf that "you would basically just recondition and fly" [I30], there were some carryovers from the better, faster cheaper era, but with an expectations of following NASA's new more rigorous guidelines. As one system engineer explained,

> "The instrument had been sold under sort of the better, faster cheaper framework, but it was then having to try to comply with NASA guidelines in a post better, faster, cheaper world. In other words, there was greater oversight from quality assurance in-house and other various rules, yet the budget has not been increased to account for that. That basically meant that there are a lot of folks working a lot of unbilled overtime hours to try to get everything ready in time to ship." [I30]

During the FBC era of MECA for the 2001 Mars Surveyor lander, NASA's first 7120.5a version was starting. Teams had to submit project implementation plans, but guidelines were "all hand wavy and about tailoring" [I14] leaving it to the teams themselves to make up the rules after the FBC era had "ripped up the rulebook" [I15]. In its original proposal at that time, MECA was proposed as a "low-cost, fast-reaction investigation implemented in JPL's "soft projectization" mode, a management structure designed to optimize performance". As described in an interview in 2003 with MECA's Project Manager and co-investigator (Hecht, 2003), "MECA was a very unusual project. We were below the radar, if you will, so we could be a little more relaxed."

NASA's new procedures, however, required significantly more paperwork overhead and more involvement from quality assurance for the assembly— "Every screw that was turned, every adjustment that was made needed a procedure that had to be pre-reviewed and approved. Then Quality Assurance must be sitting next to you to document that you had performed each step with them. It was that way for mechanical assembly, electrical tests, everything had a procedure that was reviewed, approved, and then signed off, step by step, as it was executed." [I30]

In terms of reviews, the MECA team did internal PDR's and CDR's, but that was not a core NASA requirement. As one manager explained, "the rules were pretty loose on that because it was a PI-led mission" [I15]. However, the more formal (PDR, CDR, etc.) NASA reviews were done for the mission as a whole, so there was "very little emphasis on the instruments, including MECA—only small sections on them" [I15].

In its original pre-Phoenix proposal, the cost estimate was done using JPL cost estimation tools, including developing a detailed "work breakdown structure" and organization chart to cost the workforce and assemblies against that breakdown structure. The team also used rough order of magnitude quotations from suppliers for the assemblies and piece parts. However, MECA was "seriously underbid" in terms of the budget needed to accomplish it [I17], forcing the team to put "huge amounts of unpaid overtime" [I17]. To get MECA to an operational system for Phoenix, the team was still "very underfunded" with budgets cut too tight [I35]. Such budget issues caused a challenge to the MECA team during the development stage. Despite the team's basic philosophy for the instrument and hardware to be maintained as best as they could to keep costs low, operational testing and oversight posed a challenge to the team's funding [I35, I46].

During development, the team took the original MECA instrument directly to a test program for rechecking electronics and reliability engineering for parts that were still functional. The team put many efforts in trying to save money because, as one manager described, "if you have a small budget, you do what you have to do" [I15]. Since MECA was flown based on heritage, of having been built before [I14, I17], the team tried to "cut corners" on design costs. Despite being required to go through testing procedures (such as pressure and thermal testing) and similar processes, the team was allowed—within reason—to use inexpensive parts that were not necessarily the state of the art [I35]. Since expensive parts rapidly drive the costs up, the team was able to save money on that front, as a carryover from the FBC era.

Moreover, the MECA team tried to reduce costs on the number of people involved in processes such as radiation hardening [I14], drawing the line on what expenses make most sense [I15, I30]. The team built "cheap commercial boards" and developed an innovative part screening process to make sure of the team's crossing boundaries of domain expertise [I15, I30]. In that process, the team developed many of the "cheap regular boards" and tested them on the board, without "mounting and demounting them", hence saving money overall. As one manager described, "we acted like the customers, and we said here is how we want to do it, so we saved a lot of money that way" [I15]. The expertise of the team itself, as technologists and experimental scientists, allowed them to cut a lot of corners on risk reduction. As the same manager summarizes,

> "Mostly where the money gets spent on is people. If you have a team of six mechanical engineers that are working on a design and doing design modeling and structural analysis and thermal analysis and this and that, it is expensive. We relied a lot more on kind of pen and paper analysis and testing. We put less emphasis into expensive design and more emphasis into frequent testing. We tested more and cut a lot of corners on design costs." [I15]

- **Testing and Calibration:** MECA was done intentionally in a very innovative way, reflecting faster, better, cheaper. It was done by a team who were more experimental scientists than they were engineers, either by training or temperament or both, where the perspective on testing was very different. As one manager explained, "it was not done in a "by-the-book" way, it was done in a "does this make sense" way, and for several reasons, we had the freedom to do that" [I15].

One of the things that was done right was to field test bed units to put in the hands of the various science participants, at their respective universities [I30]. This process allowed them to begin to utilize that hardware and devise experiments. That was an important component to the Phoenix MECA development. As one system engineer describe, "It was basically functional equivalent experiments, but not form equivalent. It would basically do all the same functions as the hardware that we were building for flight" [I30].

A challenge faced, however, was the difference in levels of optimism among the team on how successfully things would work on Mars—especially when the tests showed a different story. One example was the probe on MECA's microscope that was done "fairly cheaply". The probe was shown to work under many conditions on Earth, but it caused a challenge to the team trying to get it to work on Mars and get the conductivity measurements, because "the soil did not act the way it was supposed to" [I35]. The soil conductivity experiment was "very difficult to run and was not well enough calibrated", although some attempts were made to calibrate after landing [I35].

The team also had challenge in the testing of getting the samples inside the instrument—a process that requires a coordination between the arm picking up a sample and then delivering it into a tiny opening inside of MECA instrument [I35]. It was difficult for the team to confirm the sample entering the instrument, even with the cameras available, causing "tricky handoffs between different groups" [I35]. The team had to develop special facilities to test the interoperability of the different instruments with each other, particularly with the arm and the camera. The tests were tricky and were not done under Mars operating conditions, to investigate how Mars pressure could affect the process [I35].

Hence, the main challenge the team faced there was not the lack of knowledge in building the instrument or the belief that the instrument would not work, but rather "it was that the testing would be inadequate for the complications that were going to be faced on Mars" [I35].

- **Flight Software Development:** One of the challenges with the Phoenix MECA development was that the flight software (which was run out of a flight software organization) was matured very early—significantly before any of the science participants had gotten their hands on test beds or "really had even done much thinking about how they would want to run the experiments" [I30]. This challenge was critical as it led teams to do a lot more work in operations trying to achieve the experiments that were desired, because the flight software has not been designed with those experiments in mind [I30].

  That gap between the flight software and the desires of the science team was left to the operational sequencing to fill. Using a virtual machine that had some flexibility for sequence architectures, the MECA team was able to do some complicated sequencing, "even generating binary instrument commands on-the-fly, based on input arguments", as one system engineer explained [I30].

- **Mission Duration and Surface Operations Flexibility:** Phoenix was a short three-month mission on the surface of Mars. Despite its short duration, Phoenix was run as "a very conventional mission" where instrument teams were not given flexibility on surface operations [I15]. The mission demands that were done on surface by headquarters would have made sense for a longer mission, but not for a short three-month mission. Such demands and lack of flexibility did not allow Phoenix to be run as a PI-led mission, and it moreover caused teams such as MECA's not to be able to fix some minor instrument issues that they faced after landing [I15]. One such issue for MECA was not being allowed to do a simple command change that fixed the noise in the received data until the end of the mission [I15]. Because Phoenix was only a three-month mission, by the time the team got permission to do the command change and demonstrate that they fixed removing the noise from the data, they were not able to collect science with it as the mission was ending [I14].

- **Post-Mission Support:** Once the three-month Phoenix mission was over, there was basically no funding to given to the MECA team to analyze and get the most out of the data [I15]. As one manager explained, "That was really painful because you do not have any time when you are running a short mission to analyze data. In the first few months, nobody had time, but that was the whole mission. And then funding was cut off." [I15]

In summary, despite its success, MECA faced several challenges in its development and operations, including budget and oversight, being bid under the FBC framework but required to adjust for the more modern era at NASA. MECA's other challenges included difficulties in adequate testing for possible complications faced on Mars, flight software development order, short mission duration, lack of surface operations flexibility, and the lack of resources for post-mission support and data analysis.

4.1.3 Flagships – Perseverance

Building upon the achievements of the Mars Science Laboratory and its Curiosity rover [I33], the Mars 2020 mission was designed with the primary objectives of searching for evidence of ancient life on Mars and collecting samples that can be returned to Earth in future missions, representing a critical milestone in a broader multi-mission initiative for Mars sample return (Farley, et al., 2020). Achieving these mission goals has been the Perseverance rover that launched on July 30, 2020 and landed on February 18, 2021 on the Jezero Crater at the surface of Mars (NASA Science). With its history of holding a lake, its prominent delta, and its surrounding diverse terrain, Jezero crater was a very strategic landing site, of high interest to the science and astrobiology community (Farley, et al., 2020).

Perseverance was equipped with series of advanced scientific instruments to explore and conduct the scientific investigations on the Martian environment and geology, in addition to the identification of habitable areas, and seeking potential biosignatures (Farley, et al., 2020). These instruments are the Mast-Mounted Camera System (Mastcam-Z), the Mars Environmental Dynamics Analyzer (MEDA), the Planetary Instrument for X-ray Lithochemistry (PIXL), the Radar Imager for Mars' Subsurface Experiment (RIMFAX), the Scanning Habitable Environments with Raman & Luminescence for Organics and Chemicals (SHERLOC), and SuperCam (NASA Science). In addition to these science instruments, Perseverance carries along two technology demonstrations, the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) and the Ingenuity helicopter.

During its first year on Mars, Perseverance had a series of achievements including: driving over 1.8 miles, setting the record for longest drives in a Martian day, collecting over six samples of Martian rock and atmosphere, demonstrating the first ever in-situ resource utilization on another planet by producing oxygen from the Martian atmosphere, returning over 50 gigabytes of science data and over 100,000 images, in addition to 18 flights by the Ingenuity Mars Helicopter (Samuels, 2021).

Despite the mission success and tremendous scientific and technological value return, Perseverance faced several challenges in its implementation and development, both on a mission and at an instrument level [I20, I22, I23, I25, I29, I32, I33, I52, I53, I20]. Some of its main challenges were the following:

- **Mars Program Budget and Directorate Collaborations:** The story of the Mars 2020 mission Perseverance rover starts, in some ways, after the Curiosity rover landing, with NASA's fiscal year FY2012 budget [I22, I25]. The Mars program line funding falls in the planetary science division's line within the Science Mission Directorate (SMD). In these budgets, a budget cost is published in the president's budget request, along with a prediction on the next five years, where the Office of Management and Budget (OMB) is important. At that time, however, the Mars program line was ramping down to just a maintenance mode by 2016. The Obama administration at the time, along with some NASA leadership, had agreed that the Curiosity rover will be the last major Mars program and all other Mars activity will occur in the competitive science line. There would not be a strategic Mars Program—partly in response to Curiosity's cost overruns [I22].

  It took a strong push from the Associate Administrator for SMD at the time for the Mars program's importance to be reconsidered, with intensive efforts and plans made with JPL and NASA headquarters to develop a strategy for "how to go forward and get support from the administration for a robust Mars plan" [I22]. Afterwards, the budget request recovered the Mars program by including the Mars 2020 Perseverance mission, the Ingenuity helicopter (done as a "Mars hack"), the International-Mars Ice Mapper (I-MIM) mission (not currently funded), and the Mars sample return architecture [I22].

Before the effort that would become the Mars 2020 mission was happening, the original plan was to target a 2018 launch for a joint mission with the European partners on Exo-Mars, to have an Exo-Mars rover and sample caching together [I25]. However, after that initial plan fell through, NASA pivoted towards the Mars 2020 mission plan [I25]. The main priority was "not to lose the momentum the team had from Curiosity" [I22]. There was a whole team at JPL that had just finished building, testing, launching, and landing the rover Curiosity rover, and if NASA did not get funding to continue these efforts, the team would all go to other projects or would leave JPL, leading to the lab's inability to build another rover [I22, I20].

The Mars 2020 mission was facing a big challenge with its budget [I25, I22], with the OMB being inherently frugal, as part of their responsibility in trying to minimize the expenditures in the federal government. An idea was suggested then of building a "fleet of Mars exploration rovers" that could be sent to multiple locations around Mars. However, after studying that idea, it turned out that "in FY2015 dollars, they would be a billion dollars apiece" and this was not worth the price given that they would not be able to have the same science return capability as a Curiosity class rover [I22].

To deal with the budget challenges, leadership had to work with JPL on estimating the cost of building "just another chassis with no instruments" [I22]. Based on that cost estimate and a push to use any spare or pre-built parts, leadership had a more confident proposal for a new Mars rover that could attract instruments onboard. However, to create a convincing case to OMB, the mission was presented an agency-level mission, led by the Science Mission Directorate (SMD), but also in collaboration with the Space Technology Mission Directorate (STMD) and the previous Human Exploration and Operations Mission Directorate (HEOMD). This collaboration was also pushed heavily from the NASA administrator [I22, I23, I25].

A Mars Program Planning Group (MPPG) was established to create the proposal for the combined idea of science and human exploration [I25]. During these collaboration discussions, multiple challenges were faced in terms of the varying priorities of the different directorates. That community effort, however, allowed the group to come up with a list of their strategic knowledge gaps of what does human exploration need in terms of precursor measurements that might be done with robotic missions [I25, I14]. In other words, as one program executive explained, "what can we do with robotic missions to enhance and or enable the things that you would need from a technology perspective for human exploration?" [I25]. That list was tailored, and the announcement of opportunity (AO) competition was focused on those top priorities. Based on this collaboration, STMD was paying for sensors that go on the heat shield called Mars Entry, Descent, and Landing Instrumentation 2 (MEDLI2) [I23]. Additionally, STMD and HEOMD were offered a "prime real estate" inside the rover for an in-situ resource utilization (ISRU) demonstration instrument [I22], where both directorates (especially HEOMD) can contribute a small amount of money and get a lot of benefit in return [I23].

Despite its eventual success, the budget constraints on the Mars program in addition to the challenges in getting the different NASA directorates to collaborate (especially HEOMD in this case [I25, I22]) were a big hurdle during the development of this mission. Additionally, despite the

Mars 2020 supposed to being a "rebuild" of Curiosity, making it less expensive, the cost of Mars 2020 did not achieve that. The main reason for this cost problem was that "although they were supposed to be rebuilt, none of the instruments were rebuilt, so all the instruments were new" [I33].

- **Instrument Accommodation:** Despite the general mission success, including several technologies and instruments on Perseverance faced challenges along the way in their development and operations. After the announcement of opportunity (AO) competition for the Mars 2020 instruments, an assessment of the received proposals was conducted by subject matter experts who used their extensive expertise to look at the technical aspects, in addition to the cost, management, and schedule of each of the proposals to assess them [I25]. In addition to rating each individual instrument, an accommodation study was conducted to figure out the best "mix and match" grouping of the instruments that could be accommodated within the rover. This process involved considering the spacecraft resource, such as volume, mass, power, thermal, etc. and seeing which grouping worked best for the science and within the resource constraints [I25]. The accommodation study forced some early changes to the selected proposals, such as the forced marriage of the SHERLOC instrument with a camera, that was not part of the original proposal [I25].

  Once selected, instruments, with oversight of the project overall, started developing their more detailed requirements, and the back-and-forth trades, conversations, and negotiations began between the instrument teams and the payload management group to figure out the boundaries on what could be accommodated inside the rover. A big challenge that the team faced here was explained by one program executive [I25],

  > "Oftentimes, you are building the spacecraft around the instruments. We have rarely had a strategic mission that starts out with the spacecraft and then says, "Alright, bring on instruments". Whereas since we were using the heritage Curiosity design, you must have this infrastructure to say, "Okay, here is what I could add in", as supposed to something like the Mars Reconnaissance Orbiter where the camera was the whole point, so you build the spacecraft around the camera."

  The constraint of the infrastructure and spacecraft heritage from Curiosity was a challenge to the Perseverance instrument teams. Due to the rover accommodation and budget or schedule constraints, multiple instruments, such as SHERLOC and MOXIE, also faced development problems, leading them to trigger termination reviews [I25]. Such reviews incorporated bringing in tiger teams or extra experts to dig in and resolve problems or assess based on "either downgrade or you do not fly" [I25].

  As many of the instruments were facing development issues, additional oversight and expertise from JPL was required due to the complex nature of the mission, to ensure their success [I29]. As one scientist described, "All of the instruments, except for one, ran into remarkable problems, that made us all wonder, are we going to make it" [I29].

- **Science vs Tech Demos and Instrument-Specific Challenges:** An additional challenge that faced the Mars 2020 team was the "huge amount of stress" that was put in while interacting with JPL, where science PIs were required to prove that their instruments work. As one scientist described, “It is a very weird thing for a scientist. Most of the scientists are not actually that technical, and when you tell them “Hey, you have a capacitor that has a crack in it”, a scientist is not good at answering that question” [I29]. Such necessary interactions, albeit getting the instruments to the finish line, were stressful among the science PIs. However, that oversight and risk reduction necessity was viewed as necessary for a Flagship mission, as the same scientist explains, “If you are not willing to say failure is an option, then you must sign up to having that level of scrutiny. Once you get married into the Flagship, I do not think there is any option, you must sign up to all of it” [I29].

On the other hand, aside from the science, Perseverance featured two technology demonstrations, MOXIE and Ingenuity, which caused internal debates about these decisions, about the amount of resources that these tech demos were “taking away from the science”, and how much oversight they were subjected to [I29]. Mars 2020 took some risks with the more complicated instruments overall (such as MOXIE, SHERLOC, and PIXL) [I32], but despite the challenging development, all of them proved successful.

The next two sections focus on the technology or instrument-specific challenges for Terrain Relative Navigation (TRN) and Fast Traverse, MOXIE, and Ingenuity.

4.1.3.1 Terrain Relative Navigation (TRN) and Fast Traverse

The Mars Rover program has seen great success throughout the years, with a progression of technologies going into each new rover, from Sojourner, Spirit and Opportunity, Curiosity, to Perseverance [I20]. A key factor to this technology progression, whether on the instrument or the rover infrastructure side, was having the team responsible for developing the flight versions of the rovers being from the technology community and having a deep understanding of how technology could be safely and robustly matured for operational use [I20]. As one Program Executive explained, “The folks who built Sojourner 25 years ago, as a technology experiment, went on to build the entire sequence of rovers since then, so they understand the technology community to begin with, and how technology can be safely and robustly matured so that it can be used operationally” [I20].

One example of such technology progression has been with the rover’s embedded autonomy. Albeit being a slow process, rover autonomy has drastically changed throughout the generations of Mars rovers. Initially, rovers were largely commanded from Earth—not in real-time, but “almost every turn of every wheel was calculated and pre-configured back on Earth” [I20], with a human operator in the loop to check the test results and make sure it was going to work the right way. There was only a small amount of autonomy and path planning tests on board, that was done only twice with Sojourner, out of the 90 days of traversing that it did [I20]. However, demonstrating the success of a small amount on onboard autonomy in the beginning gave the team more confidence in the navigation and autonomy technology, allowing them to further develop and incorporate it in the future rovers.

The continued technology development for future rovers such as Curiosity and Perseverance involved bringing the rover builders back into the lab, to showcase the advancements made since the last operational rover and the testing that was done to ensure the robustness of the technology for fieldwork. As the same Program Executive continued to explain [I20],

> "We were able to get the people that we knew would be responsible for designing and building the operational version very frequently before they actually had that job, constantly calling them back into the lab to say, "*Here is where the technology is advancing now, remember this when you build the next rover*". And as a result, we now have Perseverance doing what it is doing in terms of its own autonomous driving capabilities."

In terms of autonomy, two of the most important technology developments that Perseverance carried were Terrain Relative Navigation (TRN) and Fast Traverse. Despite being two distinct technologies, TRN and Fast Traverse are together discussed in this chapter due to the important overlap they both had in their development and use.

As shown in Figure *29*, TRN was the NASA navigation technology that helped the Mars 2020 successful entry, descent, and landing (EDL) on Jezero Crater—a challenging landing site due to its rocky hills and smaller craters. TRN used a camera to match visible terrain features to onboard maps and calculate positions and altitudes during descent, allowing for an autonomous spacecraft navigation, with increased landing accuracy and avoiding hazards (NASA, 2022). TRN has enabled NASA to explore areas that were previously too difficult to land, and with its precision landing capability, TRN has been already incorporated with other EDL and hazard detection technologies for future missions to the Moon and beyond (NASA, 2022).

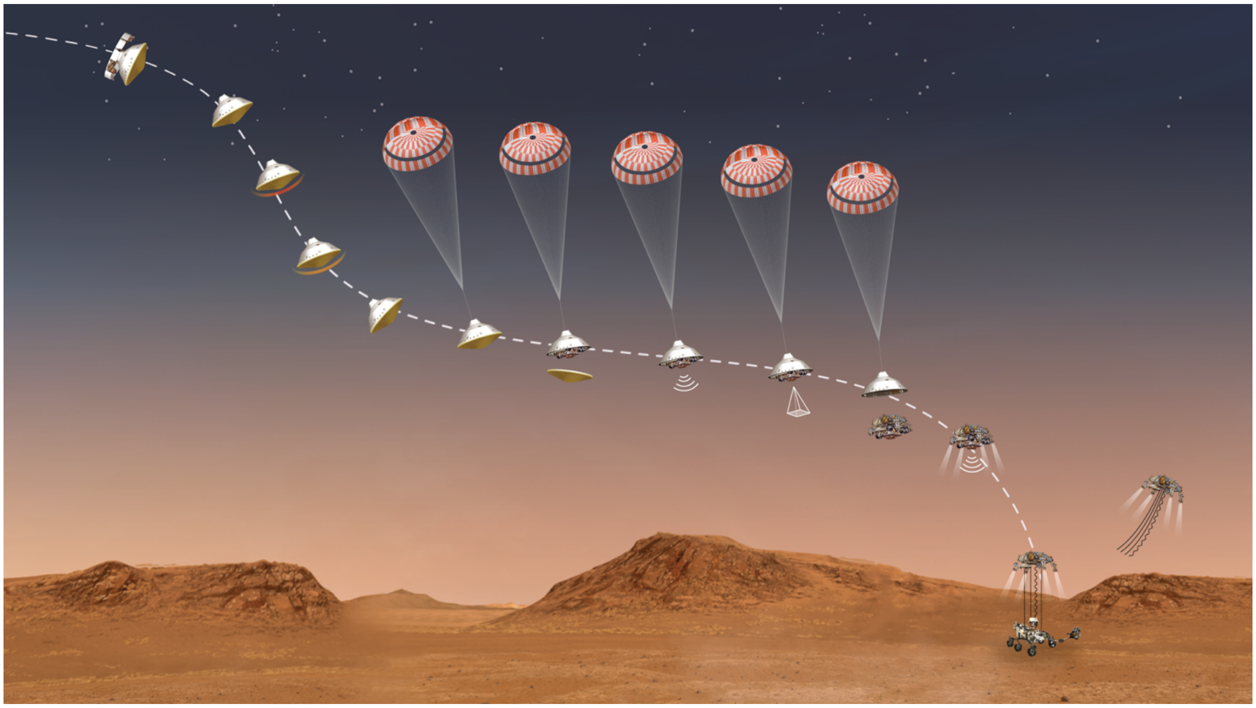


Figure 29. Illustration of the last minutes of Perseverance EDL on Mars. *(NASA, 2022)*

Before Mars 2020, TRN had had a long history of development, during which it was gradually climbing the TRL ladder [I55, I44]. The TRN story began with a group at JPL who worked on the Descent Image Motion Estimation System (DIMES) that was used during landing to estimate surface relative velocity for the Spirit and Opportunity twin rovers (Johnson, et al., 2007) [I55]. DIMES was the first use of computer vision for a Mars or any planetary landing, and it opened the door of possibilities for other applications [I55]. After the successful use of DIMES on the Mars Exploration Rovers (MER), the team started thinking about the next problem which was to do pinpoint landing on Mars or other moons and planets.

The team did an initial TRL 1 concept study, where they took some of the pieces of computer vision that were developed in DIMES and used them to match pieces of images between a "large orbital image and co-registered digital elevation map (DEM)" and a camera image taken while the spacecraft was descending [I55] (Johnson, et al., 2007). Once that was done, they were able to do the same process with multiple patches and get a position fix [I55].

At that point of the technology inception and early development, the team did not have a mission in mind, and the technology could have gone in multiple directions [I44, I55]. Lunar or Mars landing were the most probable use cases, but they had some potential to use it for landing or navigating around an asteroid or a comet nucleus [I55]. The team also did not pursue any external NASA funding for TRN and kept it within NASA, especially as the need for this technology was "fairly strong" where missions can clearly benefit from pinpoint landing [I55].

Back in around 2004, the team had to write proposals to fund the work to advance it, and the sources of funding ended up being a combination of Mars program funding, NASA level technology development funding, and JPL Internal funding [I55, I53]. The team wrote a proposal to the New Millennium program to do technology development. There were different phases of proposal writing, and they won both of those phases—winning the competition, Space Technology nine (ST9), the ninth mission that the program was going to fund. New Millennium, however, got cancelled, and while they had a good idea, the funding was not there anymore [I55, I53]. That proposal, coupled with some "small technology tasks" is where the team developed the initial technology, where instead of just using the imagery, they would also fuse the measurements with inertial measurement data. The two of those measurements together required a navigation filter, and it required some technology advances to be done. They integrated their software with an Extended Kalman Filter, and they were able to "demonstrate 10m landing precision during postprocessing of a sounding rocket data set" (Trawny, Mourikis, Roumeliotis, Johnson, & Montgomery, 2006; Mourikis, et al., 2009). At that point, TRL was about TRL 4 in its development [I55, I53]

Since then, until around 2011-2012, there was a "lull in funding" for TRN. However, the team had been told before by the Mars program that "at some point in the future, we are going to need you to work on this again" [I55]. Dedicated to make sure JPL gets to carry this technology forward, the team was finally contacted by the Mars Exploration Directorate at JPL, and they were given some focused technology funding to continue its development, moved it from low to mid-level TRL and get it ready to be handed to a mission [I55, I44]. At that point, the team started the development of the landing vision system. The TRN software was also tested in the Autonomous Landing and Hazard Avoidance Technology Project (Epp & Smith, 2008) using different terrains and illumination conditions (Cheng, Clouse, Johnson, Owen, & Vaughan, 2011), leading to TRN's modularization and its ability to deal with different terrains and illuminations (Alexander, Cheng, Zheng, Trawny, & Johnson, 2012).

In 2014, the team was able to develop and test a flight hardware and software prototype through two suborbital flights funded by STMD's Flight Opportunities program [I55, I38] (NASA, 2022). Entry, descent, and landing (EDL) is a critical area for STMD, so they were interested in supporting TRN [I38]. TRN was tested in a real-time helicopter field test (Johnson, et al., 2013; Johnson, et al., 2015) raising the technology to ~ TRL 6 [I55]. TRN was also successfully tested as part of the "Autonomous Descent and Ascent Powered-flight Testbed (ADAPT) aboard Masten Space Systems' Xombie vertical takeoff, vertical landing rocket in the Mojave Desert" (NASA, 2022; Trawny, et al., 2015). These successful TRN tests demonstrated the technology's ability to "recognize terrain features and providing relative position to the target landing site" (NASA, 2022). The successful demonstrations also increased the amount of internal funds that were put forward for the ADAPT task [I55]. The team wanted to use the Masten rocket for guidance to have a control test bed, and then gradually figure out how high and far it can fly, while working on how they can interface to it to control its trajectory. That process was conducted with a guidance algorithm called G-FOLD, followed by a combination of the guidance algorithm and Lander vision system [I55].

During the 2015-2017 technology maturation and growth period, TRN was funded by STMD's Game Changing Development (GCD) program, where the technology's capabilities were improved for potential Europa mission landings (as part of the Intelligent Landing System) (NASA, 2022). That period ended, as part of STMD's CoOperative Blending of Autonomous Landing Technologies (COBALT) project, with the successful demonstration of TRN once again on Masten Space Systems' Xodiac rocket (NASA, 2022). These developments the initial baselining of TRN for the Mars 2020 mission (Johnson, et al., 2016; Johnson, et al., 2017).

TRN was also commercialized in 2018 through Tipping Point technology development awards to Astrobotic Technology and Blue Origin for lunar landings (NASA, 2022). In the 2019-2021 period, TRN was further supported through STMD's Technology Demonstration Missions (TDM) with additional design reviews, helicopter demonstrations, and system integration to prepare the technology, as a bolt on sensor, for the Mars 2020 mission (NASA, 2022; Johnson, et al., 2020). The teams had to show that TRN would satisfy the Mars 2020 mission needs and constraints [I44] and that it would not affect the EDL architecture that Mars 2020 was using based on the previous Curiosity rover's landing [I55].

Once first proposed for Mars 2020, TRN had some opposers who thought "it was going to be a lot of money and distraction that we might not have needed" [I32]. With the overall lack of appetite for risk and the low availability of time and money to take risk on a flagship mission [I29], that reticence on the part of conservative project managers to infusing new technologies such as TRN required convincing project management and the program that TRN was robust and efficiently mature to infuse [I52]. However, soon after, everyone was very quickly convinced by the benefits of TRN and its success in taking the mission to places that were much closer to science objectives of interest, because of the strong correlation between interesting science and unsafe landing sites [I52]. TRN allowed Mars 2020 not to "land with its eyes closed, and then hope for a good day" [I52], and without it, Jezero crater would have been crossed off the list of landing sites.

It is noteworthy that TRN was also adapted for different projects and applications including GCD's Safe & Precise Landing – Integrated Capabilities Evolution (SPLICE) project, the STMD GCD-funded Lunar Digital Elevation Maps, Mapping, Modeling, and Validation effort, and the STMD Tipping Point award for Intuitive Machines (NASA, 2022).

In parallel to the TRN development was that of "fast and safe traverse". Before Perseverance, previous rovers such as Curiosity or the Spirit and Opportunity twin rovers had a very slow top speed, as one manager described, "watching them was like watching paint dry" [I52]. The Mars 2020 missions wanted the ability to cover more ground with Perseverance. Older missions relied on the rover's "ancient old" Rad 750 computer to do all the processing needed for driving. The old computer processor's ability to process the stereo images and figure out path planning was very slow [I52].

However, it turned out that one of the key advantages of TRN was its ability to perform rapid vision processing of images collected during descent. The Field-Programmable Gate Array (FPGA) used for TRN allowed for dual functionality during the descent phase and subsequently during the rover's surface operations [I52]. This FPGA repurposing allowed the speed of the vision processing for roving to be significantly increased, which enabled continuous driving and simultaneous thinking [I52]. As on scientist described [I29],

> "If you look at the computer processor that Perseverance is using, it is an archaic piece of technology, and the only reason we are even able to do this autonomous navigation is that we put on a second processor to do something else. And that's sort of incredible in the era when you can say your cell phone from five years ago, which cost you $150, is inferior to the giant computer that we are flying. That is an example of where the technology needs to get proven. It is one example of where technology, if it were available, would be totally enabling".

For Fast Traverse, the story started in the early 2000's [I53], and the role of pre-mission reimbursable work in advancing the technology was very important [I54]. The technology flipped back and forth between NASA research work and reimbursable Department of Defense (DoD) funding. However, at some important junctures, Fast Traverse needed "relatively deeper pockets" to really reach critical stages of maturity, and that came out of out of an army program [I54]. The very initial seeds of Fast Traverse go back to a "very small reimbursable project" with the Navy where they were "interested in making two small Digital Signal Processing (DSP) powered cameras smart cameras that could do stereo internally", as one technical supervisor explained [I54]. After that project where the technology was designed to have these two separate but symmetric smart cameras, the team started thinking about the next step of using only the DSPs with the FPGAs. That effort was the instantiation of implementing core image processing in the FPGA [I54].

The technology kept progressing along afterwards, until an important milestone in its development where Fast Traverse's lead committed the research project to demonstrating the FPGA processing on the Mars Science Laboratory (MSL) test bed vehicle [I54]. The demonstration involved the following steps: (1) integrating offboard a commercial FPGA coprocessor, (2) taking the images off the test bed vehicle, (3) transferring these images over the "pretty slow network" to another lab that had the FPGA Development Board in it, and then lastly (4) receiving the data back [I54].

Despite being initially "silly" from an engineering perspective, that demonstration was a critical step in raising the confidence in the technology for it to be later used in the Mars 2020 mission. As one technical supervisor explained [I54],

> "The mere fact that they saw the test bed vehicle that looked like a flight vehicle that they recognized and that they heard that it was being driven by an FPGA integrated with the flight software, lowered the fears about the risks of adoption and integration. That was enabling in selling the mission when it came along to baseline the technology."

Later, the Mars 2020 mission planning recognized that to cover the distance they wanted to achieve in the time available, they had to try faster. The way to do that was to overcome the computing bottleneck in the autonomous navigation. That mission pull thus developed and pulled the Fast Traverse technology work that was being done initially under JPL internal funding to NASA focused technology, and then into the Mars 2020 mission project funding [I53]. The leading technologist at JPL realized that there was a processor being used for TRN and landing that was very good at processing imagery fast and was not going to be used after landing [I44]. That realization prompted the use of the processor to process an imagery for surface operations [I44]. Eventually, Fast Traverse was very successful, getting the Mars 2020 mission a big increase in drive distance [I52], despite Perseverance being relatively the same chassis as Curiosity [I44].

However, despite achieving remarkable success and making significant contributions to enabling further science, TRN and Fast Traverse encountered many challenges during their growth and development. Some of their main challenges were the following [I19, I55, I44, I29, I52, I20, I53, I54]:

- **Stovepiped Technology Development:** One of the main challenges that the Mars 2020 team faced with TRN and Fast Traverse was the stovepiping that took place during their development. As one project manager and system engineer explained [I19],

  > "We wanted to drive faster and be able to find paths in more complex terrain. We were looking for a Research and Technology Development (R&TD) task that we can fit into what we were doing. There was an R&TD task that had been done called "Fast Traverse", and it was this idea of using a second processor to drive the image processing, to make it faster. The AutoNav algorithm was what these R&TD's have been doing for the last 20 years, but nobody had one [ready]. We actually had to spend millions of dollars to develop a new AutoNav algorithm since nobody had targeted it the R&TD world. And so that, I think, to some extent, is *this lack of connection between our projects and our technologies, similar to the lack of connection between the stovepipes and headquarters, including the technology*."

  Such a challenge was also similarly observed in the other aspects of rover autonomy such as the "simple planner". Due to the need for a conservative approach on the ground in Mars rover operations, significant efforts have been devoted to developing autonomy technologies such as the "simple planner" that enhances the rover's decision-making capabilities. This planning software enables the rover to make autonomous decisions based on priorities and energy allowances to improve the Mars rover operations' efficiency and effectiveness. However, what the team found was that all the R&TD work that had been conducted for algorithms for such a planner were great, but they required a processor that was "10 maybe 20 times faster than Mars 2020's" [I19]. The Mars 2020 team then had to "decapitate the whole thing and come up with a simpler method" [I19]. Therefore, once again, as one project manager and system engineer explained [I19],

  > "When the two came together, when the peanut butter and chocolate got together, and they said 'okay let's figure out how we are going to do this', neither side was ready for the other side. The technology teams weren't thinking about the platforms, so there is this middle part that gets lost. And then unfortunately, the projects have to pay for all of that."

  These technologies highlight the challenge of stovepiped technology development efforts at NASA, where the middle area of systems engineering is lost. The Mars Exploration Program has put efforts to look at future mission concepts, understand the capability gaps to execute those missions, and figure out the investments needed to close those gaps [I52]. Over the last decade, roughly, the Mars Exploration Program's specific Mars technology investments have mostly been in the focused area [I52]. There were a lot of focused investments targeting the Mars Science Laboratory Mission and the Curiosity Rover, with the new EDL technique that was applied there with a more capable rover. More recently, there were a lot of developments aimed at the

Perseverance Rover and the Mars 2020 Mission [I52]. However, the challenging gap persists on asking the following series of questions, "What are we trying to? What are the technology pieces that must be done to achieve that? What are the technologies that must be done to get those pieces done? And who is going to do that across NASA?" [I19].

- **Back-and-forth Technology Pull and Technology Push:** TRN and Fast Traverse went through a series of different funding sources and mission pulls. TRN's funding sources included the following: SMD (MER, New Millennium Program, Mars Tech Program, Mars 2020), JPL Internal (JPL R&TD, PEMC (Project and Engineering Management Council)), STMD (Flight Opportunities), HEO (ALHAT (Autonomous Landing Hazard Avoidance Technology)), and the Mars 2020 TRN was funded by SMD (Mars 2020, Ocean Worlds Tech, Europa Lander Tech) and STMD (Tech Demo Missions) [I55]. In a similar fashion, with many sponsors over time, Fast Traverse was funded by the Navy, NASA research work, reimbursable Department of Defense (DoD) funding, and then later by JPL internal funding, NASA focused technology, and Mars 2020 mission project funding [I53, I54].

  Coming hand in hand with the challenge of the varying funding sponsors over the years was the challenge of "waiting for the right mission". For example, TRN could have been demonstrated and done earlier than Mars 2020 [I55]. The timing of the science motivation, however, was what really pushed it forward at a good pace [I52]. In other words, at that the same time that the TRN technology development was ready to push to TRL 6, the science team really needed the rover to go to the places that were most scientifically exciting. There became a strong pull for TRN [I52]. When the TRN team received funding from the Mars technology program in the 2012 to 2014 period, it was focused technology funding, where they had to test the technology specifically as it pertains to the Mars 2020 mission (including the altitude of position estimation and other parameterized aspects that were tuned to Mars 2020). That focused technology development was what saved TRN from the "valley of death" between TRL 4 to TRL 6, since they had a specific customer that pushed the development [I55].

  Then, in some ways, as one manager explained, "Fast traverse was able to kind of ride on the coattails of TRN by taking advantage of a lot of the same vision processing capabilities, but to a surface navigation application" [I52]. It is noteworthy that the project management baselined the compute element designed for the TRN lander vision system for the use on Fast Traverse. Hence, there was a simultaneous aspect in their development [I55, I54].

  One advantage for these technologies was their applicability to multiple planetary bodies and multiple missions, which provided a higher chance of getting funded at the early stages [I55]. However, these technologies faced a lot of challenges in finally being able to be integrated into a mission. The first challenge was convincing the scientists to agree and get behind these technologies, since "any technology is going to have a much better chance of infusion if the science community is behind it" [I55]. To do that, the teams worked hard, since the beginning, on framing the benefits of what they were offering in a quantitative way that is necessary to sell a project [I54]. The TRN team had to also ensure a "bolt-on" nature for their technology to comfort the Mars 2020 team that what they were adding "was not going to ruin or perturb the already proven Mars Science lab EDL system" [I55].

The second challenge was the funding needed. In the case of TRN, for example, the technology funds were not in the baseline that was proposed by JPL. To do it and take on that extra development risk, the project wanted to be paid for it, and they were not willing to put it into their reserves or take it from reserves [I55]. This funding challenge forced the team to go through a lot of effort to line up co-funding, such as that from the Europa Lander technology program, with the argument that "the lander vision system could be used on the Europa Lander, and if Mars 2020 develops it, it will reduce the risk for Europa Lander" [I55]. Then the STMD funding came along and "pushed it over the edge", after a series of closed-door meetings between the Mars 2020 representatives at NASA headquarters and STMD [I55].

In parallel, fast traverse had its own challenges. This technology had its own mission pull in that the nature of the sample collection mission demanded more driving in shorter period of time than any of the previous missions had done. That was a "fairly compelling pull" from the mission [I54]. Despite the commitment to the vision compute element preceding the commitment to the TRN system, all the "deep money that had been going to develop the hardware" was being funneled through the TRN project, as that was where the hardware building investment was happening [I54]. The project then, very early on before project adoption, committed resources to make sure that that Fast Traverse's internal architecture for the surface use was consistent with what they were building on the TRN side [I54].

However, one challenge for Fast Traverse's development, in hindsight, was that its milestone of getting demonstrated on the MSL Hardware was only possible because the Fast Traverse's lead and a part of their team were also working on MSL. If it were not for that personal connection and shared personnel with MSL, it would have been impossible for other technology demonstrations [I54]. As one technical supervisor explained [I54],

> "They would not have access. They would not have had familiarity. It would have been very difficult, and frankly, they might not have been readily given the access to the test bed resource to do it, even if they knew enough to do it efficiently."

This challenge is key as it iterates back on the lack of overall strategy at high leadership level at NASA to follow such technologies through in their development, leaving it for personal champions of each technology to push it forward.

Thus, despite NASA's interest in technologies such as TRN or fast traverse going back at least to the 1980's, the development journey of these technologies had a series of challenges where the "wheel turns and goes full circle" on funding and NASA programs [I53]. As one technology coordinator explained [I53],

> "There is this back-and-forth between tech push and tech pull, where the tech push people see possibilities and are trying to advance the technology into the mid-TRL range. However, to really get it all the way, tech push people see the possibilities and get it to a certain level. Then you have to have the real mission pull that gets it to a level where you can really use it."

There are some technology coordinating offices at NASA responsible for looking at what the science aspirations are for the next decade or two (based on the Decadal Surveys), trying to understand what the capability gaps are for achieving those science goals, considering the programmatic context of what is possible from a funding and programmatic perspective, and then trying to find a happy medium in between to develop technology that has the best chance of having the most impact on future science [I53]. NASA's focus technology efforts are derived in a top-down sense from a strategic mission that the agency wants to do, to address these specific planned directed missions and addresses capability gaps for them. Base technologies, on the other hand, are defined more broadly to enable more than one kind of mission, and they are more or less bound with the programmatic context.

Hence, the programmatic context in addition to the science context helps NASA set priorities, before they look at "what capabilities do you need in that context that you are going to currently have? What can you afford? How can you try to maximize the impact of your investments" [I53]. However, by observing the technology development journeys of many technologies such as TRN and Fast Traverse, it becomes clear that such efforts at NASA do not tell the full story and its challenges. Such efforts have been rather leaving some technologies at the constant risk of "wheels turning and going full circle" and lack of "cradle to grave" development process. As a caveat to this challenge identifies, there is always a danger of "locking in" the dynamic research flexibility too early if such a change were to be made. However, in the case of Fast Traverse, for example, as one technical supervisor explained, "If things had played out differently, and we had a clear mission perspective earlier, then things would have been architected different and better, and the Rover would be more capable" [I54]. For Fast Traverse, such compromised capabilities include the internal FPGA architecture implemented within the flight architecture, in addition to the we have lots of inefficiencies that come from having to send the imagery from the rover's compute elements, as well as the architecting of what was easy to pull out of the heritage mobility software versus what would have been hard just from a software architecture perspective [I54]. The lack of such inefficiencies would have allowed a much higher rate access to imagery, easing the use of the FPGA, "not just for the image processing as it is now, but for some of the navigation processing, which exist only in the rover compute element" [I54].

Thus, there is a case where, if technology teams had more foresight and have been able to get serious about integration earlier, they would have had a better, more capable architecture. Hence, addressing this identified challenge would only be efficient "if the place that you expect to end up at the beginning of the technology development is really where it ends up at" [I54].

In summary, despite their enabling success, TRN and Fast Traverse faced several challenges in their development journey, including the stovepiping of the technology development and the back-and-forth technology pull and technology push, without a strategic leadership plan, leaving it for personal champions of each technology to push it forward.

4.1.3.2 Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE)

In-Situ Resource Utilization (ISRU) in space missions is the process of using technologies to convert space-based resources at the mission's destination into needed material and resources, particularly ascent propellants, to significantly reduce the cost and risk of carrying large masses of those resources from Earth. ISRU is often referred to as "living off the land", and it is crucial for enabling future space exploration missions. Minimizing the mass needed to be launched from Earth—which is mostly comprised of the propellant mass—is key, since the initial mass to low Earth orbit (IMLEO) is a rough proxy of the mission's cost (Drake, 2009).

Ever since the presence of carbon dioxide (CO_2) was confirmed in the Martian atmosphere in the 1970's, ISRU technologies for Mars have a been a topic of research (Nier & McElroy, 1997). Making up ~95% of the Martian atmosphere, CO_2 is an abundant resource that serves as an excellent candidate for Martian ISRU processes (Muscatello, et al., 2016). The first concepts of Martian ISRU were developed by Ash et al. in 1978 in their "Feasibility of rocket propellant production on Mars" study. They proposed a methanation reaction using a combination of atmospheric carbon dioxide CO_2 and water to produce methane and oxygen that can in turn be used as a fuel and oxidizer combination for a Mars Ascent Vehicle (Ash, Dowler, & Varsi, 1978). Following that, several approaches for ISRU on Mars have been explored over the years, and the importance of these technologies was further highlighted in many reports and mission architecture studies including NASA's Design Reference Mission 5.0 (Drake, 2009).

Some of the ISRU technologies explored and proposed involved CO_2 electrolysis, water electrolysis, the reverse water gas shift (RWGS), Sabatier reaction, Bosch reaction, steam reforming, and methane reformation (Sanders, et al., 2015). Despite the numerous ISRU-based methane-oxygen propellant ideas, a manned mission architecture in 1989 initially produced only oxygen on Mars, while carrying methane from Earth, to eliminate the complexity of methane production upon landing (Romohalli, Lawton, & Ash, 1989), which would require establishing ice-mining and water purification systems.

Prior to 2021, the main ISRU experiment that has been heavily tested on Earth in the past was the Mars ISPP Precursor (MIP) (Sanders & Larson, 2011; Kaplan, et al., 2000). Despite the previous MIP development, there was "almost nothing" from the MIP technology that carried over to future instruments [I15]. MIP did not serve as a "prototype", but it was an important proof of concept, showing that the idea "was not crazy" [I15].

At NASA and at JPL, there were multiple advocates and champions of ISRU who tried to keep the efforts ongoing this technology to be further developed and demonstrated. However, it was not until years later, during the planning for the Mars 2020 missions, that ISRU more officially came back to the table, unexpectedly. As previously discussed, to save the Mars program, the mission was presented to OMB as an agency-level mission, led by the Science Mission Directorate (SMD), but also in collaboration with the Space Technology Mission Directorate (STMD) and the previous Human Exploration and Operations Mission Directorate (HEOMD). This collaboration was also pushed heavily from the NASA Administrator and Associate Administrator for Science at the time [I22, I23, I25]. Based on these efforts, STMD and HEOMD were offered a "prime real estate" inside the rover for an in-situ resource utilization (ISRU) demonstration instrument [I22], where both directorates (especially HEOMD) can put a small amount of money and get a lot of benefit in return [I23].

After releasing the announcement of opportunities (AO) request for proposals for this ISRU experiment and finishing the proposal selection process, there were two finalist oxygen generators, both of which were based on a sorbent bed CO_2 reduction [I22]. After an extensive review of both proposals, both were deemed "unrealistic, for the cost, for the schedule, and for what they were proposing"; however one of them stood out with the highest probability of success, after a "big descope" from what was proposed [I22]. This selected instrument was the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE).

MOXIE was the first demonstration of ISRU in a space mission. It built upon the notion of using the abundant CO_2 in the Martian atmosphere to produce oxygen via solid-oxide electrolysis, according to the process presented in *Eq. 1*.

$$2CO_2 \xrightarrow{electrolysis} 2CO + O_2 \qquad Eq.\ 1$$

This idea was also put forward by Robert Zubrin in his book, "The Case for Mars", where he said that all we need to land humans on Mars is, "present-day technology mixed with some nineteenth-century chemical engineering, a dose of common sense, and a little bit of moxie" (Zubrin, 1996).

MOXIE was developed by MIT and NASA's Jet Propulsion Laboratory (JPL) to demonstrate, for the first time, ISRU technologies on another planet (Rapp, Hoffman, Meyen, & Hecht, 2015; Hecht, et al., 2020). MOXIE extracts O_2 from CO_2 in the Martian atmosphere using solid oxide electrolysis (SOE) (Meyen, Hecht, Hoffman, & Team, 2016). When scaled up in the future, this ISRU-produced oxygen can be used as an oxidizer for the rocket propellants for Mars Ascent Vehicles (MAVs) in human Mars missions, in addition to being used as life support for future Martian astronauts (Nasr, Meyen, & Hoffman, 2018; Hecht, et al., 2020). A MOXIE-derived ISRU system can result in large cost and mass reductions for Mars exploration missions, thus making them more feasible and sustainable (Nasr, Meyen, & Hoffman, 2018; Hecht, et al., 2020).

MOXIE has produced more than 10 g/hr of O_2 (McClean, et al., 2021; Rapp, Private Communication, 2023). It collects Martian CO_2 at a low ambient pressure of ~6 mbar and uses a mechanical compressor to compress it to roughly 0.7 bar. This compression helps in creating Earth-like operational conditions as the gas flows into the solid oxide electrolysis (SOE) cells shown in *Figure 30*. (Rapp, Hoffman, Meyen, & Hecht, 2015). These Earth-like operational conditions are important only because that is the condition where there exists most experience with the technology. *Figure 31* shows the three main sub-systems that make up the MOXIE system: Carbon dioxide Acquisition and Compression (CAC), Solid Oxide Electrolysis (SOE), and Monitor and Control System (MCS). *Figure 32* is a broken-out view of the MOXIE assembly, showing the compressor at the far left, the SOXE assembly and sensor panel in the center, and the closed-up MOXIE on the right.

On this sensor panel, MOXIE has a set of temperature, pressure, and gas composition sensors. There are four commercial off-the-shelf (COTS) composition sensors, three of which are Non-Dispersive Infrared Radiation (NDIR) sensors measuring carbon dioxide on the cathode and anode sides and carbon monoxide at the cathode. The fourth sensor is a luminescence oxygen sensor at the anode side. These four composition sensors were designed for Earth-ambient conditions and thus must be calibrated to understand their behavior under Mars-like conditions.

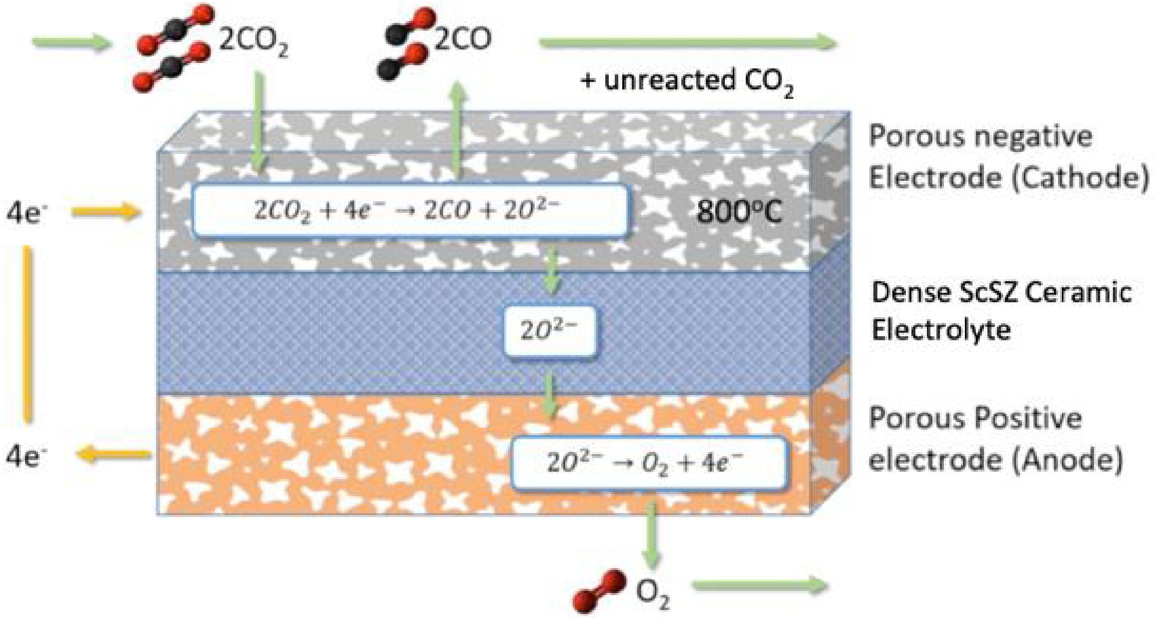


Figure 30. Reactions across a SOE cell that extract O2 out of CO2 *(Meyen, Hecht, Hoffman, & Team, 2016)*

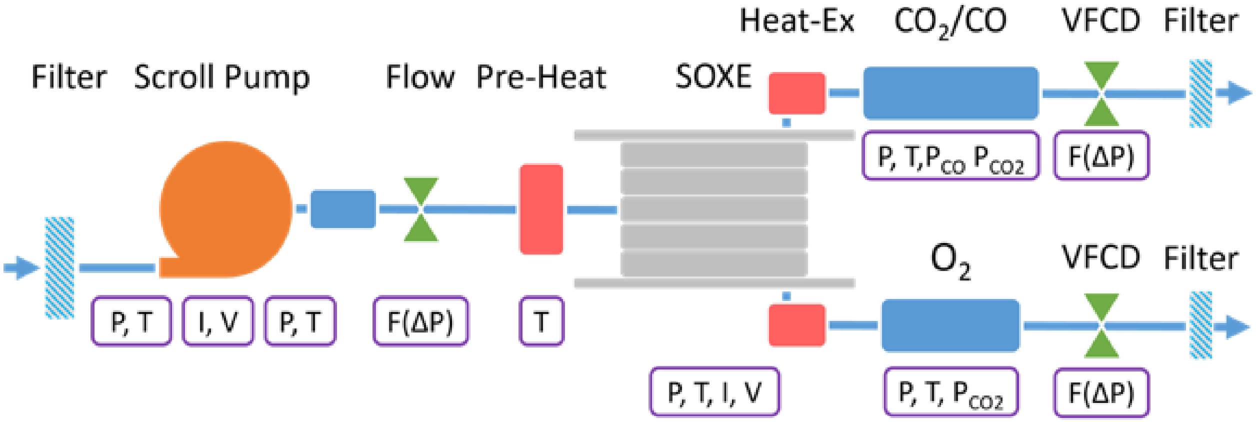


Figure 31. Outline of MOXIE subsystems *(Meyen, Hecht, Hoffman, & Team, 2016)*

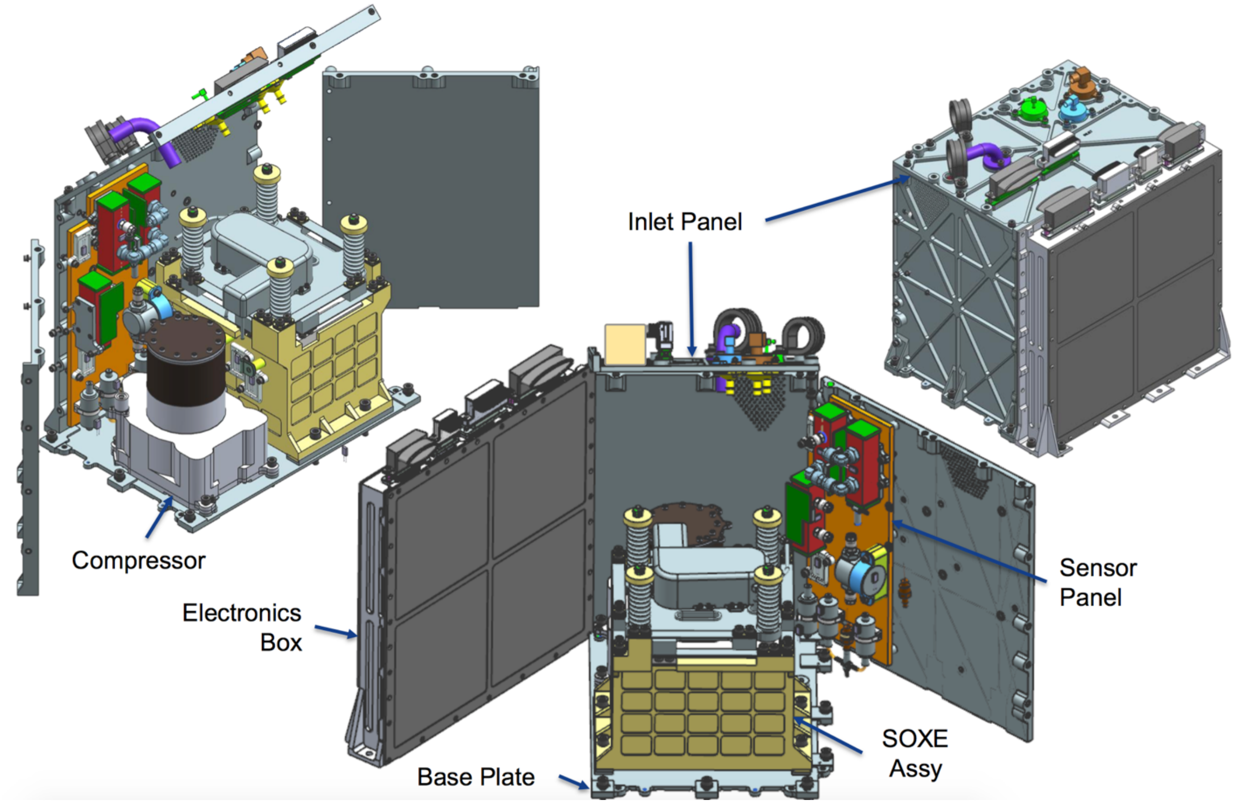


Figure 32. Broken-out view of the MOXIE assembly. Credit: JPL

However, despite achieving its success criteria and successfully demonstrating ISRU for the first time on another planetary body, MOXIE encountered many challenges during its development. Some of the main challenges were the following [I36, I14, I22, I25, I42, I24, I38, I19, I29, I23, I14, I15]:

- **Technology Champions and Directorate Collaborations:** As previously discussed, having an ISRU experiment on Mars 2020 was unexpected. It mainly took place due to champions in NASA leadership who pushed that forward and presented it as a collaboration case between the three different NASA directories: SMD, STMD, and HEOMD, to prepare for activities relating to future human exploration of Mars [I22, I23, I25].

  Based on these efforts, STMD and HEOMD were offered a "prime real estate" inside the rover for an in-situ resource utilization (ISRU) demonstration instrument [I22, I23], where both directorates (especially HEOMD) could put a small amount of money and get a lot of benefit in return [I23]. NASA headquarters, then, ran their "highly refined" selection process. As someone from NASA senior leadership explained [I22],

  > "I am a champion of human spaceflight, and I am a champion for science. At the time, I said it really does not matter what it is, as long as it is a true In-Situ Resource Utilization Experiment, and to me the highest priority. We ought to tip the scale to oxygen production, because if you want to scoop up regolith and use it, that is going to take a little arm or scoop on material handling, it will be way too expensive."

It was hence clear that that push and support by a champion for the technology in NASA leadership was one of the key aspects that made its infusion possible [I23]. The situation would have been very different otherwise. The mission was then presented to OMB, convincing them that that this is the first step in a "grand plan to cooperate more with human spaceflight" and that the rover having this in-situ resource utilization experiment is the next logical step for NASA in preparing to send people to Mars someday [I23, I22].

Thus, the rover package presented to OMB highlighted generating oxygen from Martian atmosphere, in addition to the other planned scientific investigations, with a stress on using the spare parts from Curiosity and keeping the previous team that knows how to EDL. Otherwise, it would be incredibly expensive to recreate that package in a decade, because the people who know how to do the sky crane and the rover might not be there anymore. That showcased Mars 2020 as the "wisest investment that could be made to maintain NASA's capability to explore Mars versus trying to do it with random competed missions" [I22, I23].

However, the other challenge was the three-way partnership and collaboration itself between the different directorates, especially with HEOMD [I38, I23]. In the beginning, the agreement was that HEOMD would take responsibility for any water-ISRU technologies, while STMD would focus on any atmospheric-ISRU ones [I38]. For this partnership to happen, a Memorandum of Agreement was established and signed off by the highest level of each organization, agreeing on the budget, schedule, and allocation of costs, including accommodation expenses (integration, power levels, and volume, etc.) to authorize the project to proceed. That agreement served as a high-level document that authorized the project to proceed.

A challenge was that while the human spaceflight management scheme allowed them to do "capsules, rockets, and Hubble missions", and they had an advanced exploration systems program for their technology development relating to human exploration needs [I38, I25, I14], HEOMD were not experienced at managing programs like a rover [I22].

- **Science vs. Tech Demos:** One of the first challenges for MOXIE was convincing the science community to stand behind and support this technology demonstration, when they could have had another scientific analytical instrument on the rover instead. As someone from NASA senior leadership explained, "Giving up that space was extraordinarily painful because that is where you would put a gas chromatograph mass spectrometer or some amazing microfluidics instrument that could detect life on Mars, but we would have never gotten the rover that way" [I22]. NASA leadership champions, however, "appealed to the scientists' humanity", especially those doing Mars-related work, that ISRU was something that would benefit future human explorers [I22].

  With the convincing effort from NASA leadership, scientists eventually recognized importance of using that instrument as a lever to try and get the Mars 2020 mission to happen. The science community saw that this was a unique opportunity to advance that technology—that that small trade of not having an analytical instrument in the rover that still allowed Perseverance and the start of sample return to happen was well worth the trade. That argument decreased the pushback from the scientific community, from the Mars Exploration Program Analysis Group (MEPAG) and from the academics. That decrease in pushback helped in turn not only at NASA headquarters, but also at OMB in developing that budget line that would allow Mars 2020 to fly and keep a robust Mars program.

However, since MOXIE was not originally being considered as a science instrument, but rather a technology demonstration, the Mars 2020 team, which at that point was relatively small, had to spend a long time trying to figure out how to accommodate MOXIE in terms of strategically fitting in its needs with the rest of the mission [I29]. The challenge was that this technology demonstration demanded resources, as one scientist explained [I29],

> "MOXIE uses an enormous amount of energy, and it was effectively simply inserted into the science mission without enhancing the goals of the science mission. I would say this is *not* something that should be done again. Both, MOXIE and Ingenuity, were inserted without recognizing that the time to meeting the mission science goals, from my perspective, was already oversubscribed. We were being asked to do something incredibly ambitious and then told 'Oh, and by the way, please spend a lot of time doing these other things too, which do not further the things which you have been tasked with furthering'."

After MOXIE's selection, as a tech demo, it was not clear that MOXIE team members were going to be part of the Mars 2020 science team, or that the MOXIE leadership would be part of the project science group [I29]. After the other science leadership, excluding MOXIE, got together and had a conversation, they agreed that "the best way to make sure that MOXIE gets used in a way that does not have an overly negative impact on science mission is to ingest it and work together to schedule when it works" [I29].

However, that stage of deciding the future of MOXIE was "a bit awkward", as one scientist described, because they had a very "egalitarian approach" to the science team, where "anyone who is a member of the science team is a member of the science team, disregarding where they came from, or why" [I29]. That agreement eventually ended up working well for the science instruments on the mission, and it allowed a "peaceful coexistence" to occur.

- **Decision-Making for Tech Demos:** As a technology demonstration, owned by STMD, MOXIE's funding and decision-making were treated separately, disconnected from the rest of the mission. MOXIE's development was done in the most "traditional JPL way", where MOXIE leadership had "really no influence on how it was done" [I15]. However, because technology payloads are treated separately, they are "generally either forgotten, not done well, or left too late" in the organization, as one project manager and system engineer explained [I19].

  These technology projects were not well integrated at the project level, especially when multiple mission directorates were involved. This challenge showcased the gap in doing STMD collaborations without figuring out "how to make the costing work well" [I19]. As the same project manager and system engineer continued, "The mission is the mission, and the fact that two different pieces at headquarters manage the money for parts of it, should not make it so complicated for the mission" [I19].

  The other gap that this challenge showcased was the lack of representation of the technologies, such as MOXIE, at the project decision-making level. The Mars 2020 leadership includes the Project Manager, Deputy Project Manager, Deputy for Operations and Anomalies, Project Scientist, and Deputy Project Scientist. Hence by looking at the project organization chart to see where MOXIE sits, "you see it is four levels down, but who is representing at the top?" [I19]. This lack of technology representation on the decision-making level is a big challenge for technologies like MOXIE.

- **Tech Demo Risk on a Flagship:** When the MOXIE proposal was being reviewed for selection, the proposed instrument was broken down by its components, such as scroll pumps and others, to get an understanding of how hard it would be for the team to develop a spaceflight-ready instrument that has a reasonable chance of working. As someone from NASA senior leadership explained, "We did not want to send something up with a 50-50 chance of working because too much is riding on it. If it fails, then no future NASA leaders are going to want to risk putting a technology demo on a multibillion-dollar spacecraft" [I22]. Upon selection, MOXIE was descoped to focus on the parts that NASA leadership though the team could make work in the time available [I22]. After selection, the team was not left alone, but they had to do lots of reviews, for the leadership to watch its progress and "make sure that its slope was appropriate to the development time", with the possibility of being cancelled if large overruns were observed [I22].

  One challenge that MOXIE faced on the mission was that it was more coupled with the Perseverance rover, in comparison to other cases of technology demonstrations such as Ingenuity, for example, that are more isolated and only requiring mass, volume, and communications [I19]. The Mars 2020 system already had vulnerabilities that MOXIE could exacerbate, which made it more complicated and required the Mars 2020 team to a lot more testing on issues that might affect the rover [I19]. Even in the series of reviews that MOXIE had to do, from PDRs to CDRs, the focus was mostly on the spacecraft systems and how the team "was going to avoid breaking the rover" [I15].

  Starting with a low TRL and with an "obsessive focus" on risk reduction, MOXIE had too much attention paid to meeting requirements and not enough paid attention in the development to operations and what could be learnt from the instrument [I14, I15]. As a successful "by the book" instrument, MOXIE was, hence, "overbuilt" for risk reduction, but at the same time, it was underbuilt in other areas [I14]. One example of such are MOXIE's gas composition sensors, which were a victim of "cutting corners" in the instruments and proved to create additional calibration and characterization problems during operations [I14].

  By even looking the original AO for MOXIE, the instrument was not labeled as a "technology demonstration" but rather as an "exploration technology investigation" [I25]. This distinction is key because, in terms of project management and risk approach, MOXIE was not perceived as a tech demo during development. Despite the label and despite its "demonstration" of a technology, MOXIE was rather perceived as an instrument development, where stakeholders would say "this has to work" [I25]. The risk aversion of piggybacking on a flagship strategic mission led to "tailoring process upwards" [I25] to include more aggressive risk reduction processes that would normally not be included in the tech demo development cycle.

  Thus, despite being a Class D development (meaning cheaper and with more allowed risk taking), MOXIE was in many ways treated as a "D—thou shall do no harm", with added reliability and care in order to protect the rover form any issue that might arise on the instrument [I42]. As one manager described, "No instrument, regardless of whether it is a technology demonstration or a science instrument is allowed to create risk for the Mars rover, and we do a lot of work to make sure that that happens. It is not a choice. Some things you have choices on, some things you do not. That is an area that you do not have a choice. Everything else, especially when it comes to a technology demonstration, is a choice, and you weigh a value proposition" [I36].

From a management perspective, the risk reduction processes at JPL are there to force projects to keep thinking about how things can fail and how to mitigate anticipated failure, as part of the general culture. "I think that you need to consider how your design could fail because that will be the first line of questioning at a Congressional hearing", as one manager explained [I36]. The critical challenge, however, is that such processes, albeit important, tax technology demonstrations with additional cost and needed resources that can limit their infusion as they are inherently riskier. As the same manager continued [I36],

> "We have a lot of processes to help us do that. Are they useful? I'd say that well JPL has been successful. Can you be successful without them? Perhaps. I think we are most effective when engineers think about their design, think about the processes and the objectives of those processes and continuously try and do what they think is right versus just checking a box. *I always prefer thinking over box checking, and sometimes the processes can simply result in box checking.*"

Despite that perspective on risk management, this is an area of "endless aggravation to managers", as it normally requires so many planning documents, which typically "get written and then put on a shelf, and then everybody works the way we always work" [I36]. Similarly for Problem/Failure Reporting Procedures (PFR), despite the requirement to communicate residual risks through PFRs, it can be "incredibly onerous" and can become "very labor intensive and very expensive" [I36]. The reason is, especially for a flagship missions, there are many stakeholders that have to get involved, and "the higher the visibility, the more stakeholders you are going to have" [I36].

- **Proposal Underestimates and Termination Review:** As previously mentioned, when the two finalist oxygen generation proposals were picked, both were "unrealistic, for the cost, for the schedule, for what they were proposing"; however one of them stood out with the highest probability of success, after a "big descope down to the very minimum" from what was proposed [I22]. This selected instrument was MOXIE. However, after getting MOXIE onboard, the instrument had a challenging implementation [I36], and shepherding the development process was tough [I22].

  Since selection, MOXIE had a "very dynamic" development process [I42], mainly because when MOXIE was proposed, "the technology maturation, what it meant, and what it was going to take" were all underestimated [I36], and the initial TRL was misconceived [I42]. Additionally, the process of fitting the instrument into the rover was complicated by a lack of full understanding about its volume and the engineering resource constraints. This challenge extended to the practical engineering activities, where "the scope and challenges of designing the instrument were not fully understood" [I36], eventually causing MOXIE's large cost overruns [I42].

  Moreover, following on the previously identified challenge of the technology demonstration risk on a flagship, risk reduction further exacerbated these cost and schedule overruns. As one system engineer described [I24],

  > "From the beginning, MOXIE was an essentially an instrument which everybody thought would be great to have it work, provided it did not cost more than a certain amount. Thus,

> the task of doing the job was 'how do you knock down the risks as cost effectively as possible'. On a flagship mission, however, we do not do that as cost effectively as possible. If a risk emerges that has a 1 or 2% chance of causing the mission to fail, we do whatever is necessary to fix it. […] To take something from 80% to 90% to 95% [chance of success] triples or quadruples the cost."

MOXIE's development showcased drastic changes from the initial proposal, and it presented a long path from TRL 4 to flight readiness. MOXIE's precursor technology was a CO_2/H_2O co-electrolysis technology, which required "almost everything to change, except the ceramic electrolyte" to mature the technology for MOXIE purposes. Hence by the originally proposed time to complete environmental testing and achieve TRL 6, the instrument had not even achieved a functioning electrolysis cell [I36]. TRL 6 was achieved a year and half later than what was proposed, and it was not until over two years later than a SOXE assembly got built, but not yet tested [I36]. As one manager explained, "I think that at the time of the proposal, the idea was that all you had to do is build it and test it. Well, we had almost three years of work to get this to the point of an Engineering Model (EM)—far more work than they ever planned" [I36].

The development required a whole range of changes in response to the different environment and performance requirements than the technology precursor, including seals for oxygen purity, interconnect material, adding CO recirculation from the unused cathode gases, vibration and shock testing, and operational cycling that precursor technologies did not do [I36]. These process and design changes each required iterations and extensive testing on more than 40 SOXE technology development units, in additional to a smaller number of full electrolysis stacks and flight quality units [I36]. In comparison, the proposal only planned two design-build cycles before flight, which was orders of magnitude of difference compared to the issues realistically observed in the development process [I36]. As on manager described, "In a NASA competed instrument development, you compete and you propose a mass, volume, technical capability, and a cost. If you start violating any of those, it is going to cause heartache for somebody. And MOXIE started breaking out through all of those things" [I36].

In addition to these challenges, MOXIE's development faced a lot of work with system technical resource constraints, such as mass, where the instrument's final mass was over two times what originally was proposed, gradually accounting for heaters and other underestimated or missing estimates of hardware [I36]. The project had to also decrease its originally proposed oxygen production rate to avoid another steep increase in mass, given that the instrument mass was already growing quickly as the prototype SOXE design matured [I36].

Along with the mass constraints came volume allocation—which was "even more challenging on a rover than mass", with MOXIE ending up as the tallest instrument in the rover [I36]. Power was another big challenge, where it also "almost doubled" from what was proposed [I36]. Accordingly, as one manager explained, "By any of those metrics from mass, volume, power, iterations to build, and the conversion efficiency (the fraction of CO_2 converted), and the oxygen production per cell, all of these had to change dramatically as reality had to be dealt with in that first year, year and a half of the development" [I36].

With the overruns discussed came the cost overruns as well. MOXIE's final cost of over $60 million was more than double what was proposed [I36]. Despite the safety and mission assurance, risk management, and oversight on Perseverance contributing to that price increase, process requirements in this case were not the major significant drive for the cost [I36]. MOXIE's longer-than-proposed development period, in addition to SOXE development challenges and JPL staffing and organizational issues for electronics [I38, I36] were the main reasons for the cost increase [I36]. The schedule slips were also mainly prompted by discovering issues later at the integrated MOXIE level that had to be redesigned and qualified, including the SOXE assembly design and fabrication problems and the thermal challenges with the scroll compressor [I36, I42]. Those issues were the "type of things that you can never know what dragon was going to be out there in unexplored parts of the map, but you know there is going to be dragons there", as one manager described [I36].

In terms of cost, MOXIE's original proposal did not account for management or business support, and it only had a fractional allocation for costs of systems engineering, which incorporates not only oversight, but also the "active engagement in the design of the system" [I36]. Lastly, but importantly, MOXIE's proposal also did not include costs relating to an engineering model, other technology testbeds, and other mechanical aspects of the system that were later added and developed [I36].

The combination of these cost and schedule overruns during MOXIE's development triggered a termination review [I38, I36, I24, I25], where the project was investigated to decide whether it met the Mars 2020 program objectives, the credibility of its costs and schedule to complete, and its overall risk and benefits to the mission. This review was important to identify many of the issues mentioned above and to "get MOXIE back on track" [I25], especially in terms of cost and schedule. Cost was critical, especially for STMD which paid for the "lion's share" of the technology development, as one director explained, "We have a whole portfolio to manage. MOXIE is one of many projects, but we have a dozen things that we have to keep running, and we have a zero-sum gain in this program. That means we're not getting more dollars in when we have cost overruns. So, we have to figure out fiscal year to fiscal year how that goes" [I38].

Thus, since its proposal, MOXIE's technology maturity was overestimated and its implementation scope was understated and not well understood, resulting in cost and schedule overrun challenges in its development along the way [I36, I42]. The instrument required the termination review intervention, to address any shortcomings in the initial phases and make the adjustments needed for its success [I36, I24].

In summary, despite their enabling success, MOXIE faced several challenges in its development journey, including the role of having a champion in NASA leadership for its infusion, the partnership and collaboration between the three NASA mission directorates, the initial pushback from the science community, the lack of representation at a project decision-making level, the rigorous risk management and reduction on a supposedly Class D development, and the underestimates in MOXIE's proposal that exacerbated its cost and scheduled overruns, triggering a termination review.

4.1.3.3 Ingenuity

Ingenuity, a technology demonstration "bolted to" the Perseverance rover's undercarriage, was the first powered aircraft to fly on another planet (Potter, 2020). A small, autonomous helicopter, Ingenuity demonstrated its flight ability despite the very thin Martian atmosphere and the low temperatures drops at the landing site (Potter, 2020). The helicopter weighs only 1.8 kg and is equipped with two carbon-fiber rotors that are positioned one above the other and rotate in opposite directions at approximately 2,400 rpm (Potter, 2020).

On April 19, 2021, Ingenuity made history in its first flight on Mars (Tzanetos, et al., 2022) that was described as the "Wright brothers moment on Mars" by MiMi Aung at JPL after the flight (Crane & Sparkes, 2021). The first flight was a short test where the helicopter flew to around 3 meters, turning afterwards towards the rover and landing after about 30 seconds (Crane & Sparkes, 2021). Since then, Ingenuity transitioned from its demonstration to its operations phase (Tzanetos, et al., 2022), and it has done many flights of varying altitudes, distances, and speeds (NASA, 2023). As of February 25, 2023, Ingenuity's records have been 46 flights, 10,104 meters flown highest altitude of 14 meters, fastest ground speed of 6 m/s, and ~79.4 minutes of flight time (NASA, 2023).

The background of this technology goes back to the late 1990's, where people at NASA and some universities were interested in the possibility of rotorcraft flight on Mars. The American Helicopter Society then sponsored its International's 17th Annual Student Design Competition in 1999 for proof-of-concept demonstration for rotary-wing flight on Mars, with the winners being the Georgia Institute of Technology and the University of Maryland as announced in 2000 (Vertical Flight Society, 2018). University of Maryland's winning proposal for their Martian Autonomous Rotary-Wing Vehicle (MARV) used two-bladed coaxial rotors on a square fuselage, but it was large in size, at "50 kilograms gross take off mass and 10.8 kg of payload capability, over a range and endurance of 25 km and 39 minutes" (Vertical Flight Society, 2018; The Martian Autonomous Rotary-wing Vehicle (MARV), 2000).

In the years following, NASA Ames Research Center and other partners in Japan were also working on this Mars Helicopter technology area [I53] (Koning, Johnson, & Allan, 2018; Escobar, Chopra, & Datta, 2018). As the development on such technology was continuing with multiple papers and publications produced (Young L. A., 2000; Young, Chen, Aiken, & Briggs, 2000; Young L. A., Aiken, Derby, Demblewski, & Navarrete, 2002; Young L. A., et al.), money was "hard to come by" [I53]. It was necessary to have a strategic vision and leverage multiple sources of funding for this technology development, which raised the idea of its "dual use" and needs not only for NASA, but also for other government agencies and military autonomous drones [I53].

The idea was that working on autonomous drones for the army might someday provide capabilities to fly in close proximity to small bodies in the solar system, like comets and asteroids. Serendipitously, there were some ongoing revolutions in commercial electronics at the time that were vey enabling for army drones' autonomy, such as very small cameras, very small processors, small radios, and other small sensors [I53]. There was a substantial progress achieved with the army technology, until one day where JPL leadership saw that technology advancement and proposed doing that for Mars [I53]. JPL discretionary dollars were then funneled into enabling the technology development internally at JPL [I53].

For Mars 2020, Ingenuity was a big question mark and was not selected originally, but it was rather quite "late in the game", after project PDR [I42]. This instrument was treated differently from the other selected instruments, mainly based on the difference in its schedule of selection. Ingenuity was also a priority all the way up to headquarters, but it was more internal, and hence more easily controlled [I42]. The helicopter was not something that was specifically requested in the announcement of opportunity (AO) for proposals, but JPL proposed it as an interesting idea [I25]. After being proposed, however, Ingenuity was not selected "right off the bat" because there was a push to get it more matured first in laboratory chambers before selection [I23]. Selected based on merit for continued studies, Ingenuity received money from the planetary science division Mars program's technology funding line, in addition to JPL internal funding [I23, I25, I51]. There was an additional unsuccessful attempt to create a partnership between the Aeronautics Mission Directorate and SMD, but the former was "not particularly interested", as they believed it was an "interesting" technology, but not enough to invest in their very highly constrained budgets [I22].

Throughout the received funding, the Mars helicopter team was able to advance this technology and develop it as a potential new exploration mode for Mars [I51, I25]. This process involved a series of test bed work and experiments, demonstrating flight in JPL's low-pressure environmental chamber that could "recreate relevant Martian conditions" [I25] (Veismann, Dougherty, Rabinovitch, Quon, & Gharib, 2021). The helicopter was eventually accepted as a demonstration, but still in a in a "do no harm" fashion since Mars 2020 has a very important primary mission [I25, I23]. A critical aspect of Ingenuity was that in addition to the helicopter itself, the team had to develop the deployment system, which was integrated with the rover, and added risk management on that part of the process [I25]. In planning operations, the helicopter team was originally given a limit of five flights during a 30-day period due to concerns that it would drain the operations team's time and hold up the progress of the Rover—effectively becoming an anchor [I25]. However, after a while, the science team was still able to do what they wanted to do, and the helicopter team progressively got better at integrating, especially with the color cameras turning out to be useful for science [I25]. That organization helped the Ingenuity helicopter to keep accompanying the mission till the time of this research (Alibay, et al., 2022).

Ingenuity ended up costing more money than initially proposed, putting pressure on the rest of the project's resources [I25]. However, it was a technology that NASA leadership was prioritizing and willing to take a risk on because it opened up the ability to incorporate such technologies on future missions, such as Mars Sample Return [I25].

Despite achieving remarkable success and making significant contributions to enabling a revolutionary technology that can further future science, Ingenuity encountered many challenges during its development. Some of the main challenges were the following [I42, I23, I29, I19, I20, I32, I25, I53, I52, I14, I51, I22]:

- **Technology Champions:** Holding some similarity to MOXIE on that front, Ingenuity was a major technology investment on the Mars 2020 mission, whose infusion was backed by key advocacy from NASA leadership [I22, I25, I53, I51, I14, I42]. Added after the mission's PDR, Ingenuity was not a "completely unique case", but it was a highly unusual one [I53], whose priority was all the way up to headquarters [I42]. A key event in this technology's initial adoption and internal funding at JPL was someone at JPL's leadership seeing the technology progress at the army and deciding to fund it for Martian applications. As one technology coordinator described, "That was a case where the small-scale technical division jumped to somebody in a leadership position who had the authority and the resources to promote it based on revolutionary possibilities." [I53]

  Another director also added, "We do not believe that necessarily every technology that is invested in at an early stage needs to go through the tech maturation portfolio and the tech demonstration portfolio before it is made available to users. We see things going early stage and skipping to use quite a bit if a customer identifies it as addressing a critical need and they want to take it over the last mile." [I51]

The decision for infusion on the Mars 2020 rover was also backed by NASA leadership, appealing once again to the team's "humanity", and advocating for how compelling such technology could be for advancing the potential of scientific investigations, despite the resistance received [I22].

Ingenuity's path was highly similar to the journey of development and infusion of the Sojourner rover on Pathfinder, as the first ever rover mission on Mars. As one manager explained, "The lesson for that one was the force of will, having a visionary that had a flock of adherents who would support it down to the end" [I14]. On Pathfinder, Donna Shirley (the manager of the Mars Exploration Program at the time) was the main champion, who sold her idea for the rover "over everyone's skepticism" [I14]. On Perseverance, NASA and JPL leadership played a key role. JPL is unique among the NASA centers in having more internal resources for R&D and proposals. They are very aware that there is an imbalance with the other NASA centers [I14]. Such leverage pulled to infuse Ingenuity into the Mars 2020 mission caused sensitivities within the team and provided an "unfair playground" for other technologies that have been striving for years to be flown but did not have a champion at the NASA leadership level. As one manager summed up this challenge [I14],

> "JPL had unsuccessfully tried to propose multiple times, with various PI's, flying on Mars, as full missions. Then they just said, 'well, if this is ever going to happen, we just have to make it happen without going through the proposal route, because we have not been lucky that way'. They exerted a lot of leverage with NASA, uncomfortable leverage, to get it to fly. They took resources away from the mission; it was incredibly expensive. This is really got to be an exception. You are asking a lot of people to commit to a process that cannot support more than a very occasional winner, and that is not fair."

- **Science vs. Tech Demos:** One of the main challenges that faced Ingenuity was the very strong backlash from the science community on Mars 2020. The resistance received was mainly because the helicopter was not enabling to the prime mission—with certain people even considering "a threat" to the prime mission [I52]. As one system engineer said, "No matter how decoupled it could have been, it was a burden because people did not like it" [I19].

  Ingenuity was almost a perfect analog for the Sojourner rover on Pathfinder, in its infusion, received resistance from the science community, and later revolutionizing ability in upcoming Mars missions [I20]. As one program executive explained, "It [Ingenuity] was similar [to Sojourner], in terms of how it was developed by a very small insular, almost skunk work type team, to the fact that it was not wanted by the mission. The science team actively fought against it. They considered it a barnacle that they want to scrape off as soon as they possibly could" [I20].

  Since the helicopter was added late into the mission, a large portion of the Mars 2020 team were worried since they believed that the last thing the mission needed at that point was that "distraction". As one manager described, "I had nothing against the helicopter. I had *everything* against the helicopter disrupting Mars 2020's development" [I32].

Many people were worried about schedule and about conflicts of budget, especially that it did cost a lot more than what was originally stated [I22]. The team had fought against Ingenuity for years, especially that they could not "afford the time that it was going to take" [I29]. The Mars 2020 team was also worried that if Ingenuity were to be successful, there was no end of mission plan for it, neither was it capable of keeping up with Perseverance in the rover's drive mode [I29].

To the science community, Ingenuity was not and neither meant to "in any way further science" [I29], and most of them thought that scaling Ingenuity to be large enough to "actually do anything useful" was going to be a big ask. It was not obvious that you could fly bigger helicopter [I29]. At the end of its technology demonstration phase on the mission, the Mars 2020 team had a conversation and agreed that because of where the rover was at and how they were doing science at the time, that it was okay to keep Ingenuity in the mission. That was the transitional point to what was called the "operational demonstration phase" where the team was able to gain more knowledge about the helicopter (Tzanetos, et al., 2022). However, the major fact learnt was that, as one scientist described [I29],

> "Ingenuity was having a very hard time keeping up with us, and we kept talking about how it was going to scout for us, it was going to find science targets for us, it was going to find routes for us. But the fact was it could not get out in front of Perseverance, even with Perseverance driving slowly. There are a lot of reasons for that, some of them are simply structural, for example, risk aversion and not wanting to do things that are not certainly going to work, even though it was all bonuses. Anything you got after the Tech Demo phase is your gravy."

The Ingenuity team, however, helped the Mars 2020 team in "letting it go" and saying "If Ingenuity dies, Ingenuity dies"—which was not as easy for the Perseverance team that interfaces with Ingenuity [I29]. In the end, as the Mars 2020 team was getting to the point where they decided to start their fast drive of the rover, the situation became "very stressful" as they were not allowed to let the helicopter go out of communications range, for fear that they would not get it back. Most of the science community's reaction was not as sympathetic, as the priority was for science. Such issues did not get easily resolved [I29].

Despite being met with a lot of resistance and hostility [I53], Ingenuity was eventually very successful and compelling, as it unlocked the potential for future more advanced abilities such as path scouting that would help advance science [I22]. Several scientists changed their minds about the technology and started advocating for the revolutionary potential and added value that it could provide [I20, I53]. However, as one scientist sums up the science's challenge with Ingenuity [I29],

> "That is an example of where the needs of the science mission were not factored in by the high-level decision makers that said "thou shalt fly this thing", and this was unnecessary. There should have been a better understanding among all the stakeholders that, if you ask us to do this, then we can do less of the thing that you asked us to do originally, collect samples or do science."

In summary, despite being successful and in some ways "outclassing Perseverance in the public interest" [I22], Ingenuity faced several challenges in its development journey, including the need of a champion at NASA leadership to get this technology infused on the mission and the huge backlash and resistance from the science community whose needs were not "factored in by the leadership decision makers".

4.1.4 Discovery – Pscyhe

Psyche: Journey to a Metal World, illustrated in *Figure 33*, is NASA's PI-led, ~ $1 billion Discovery class mission, targeting the metal asteroid Psyche, located between Mars and Jupiter (Oh, et al., 2019) [I43]. This mission is based at Arizona State University and entered its final design and fabrication phase in 2019 (Oh, et al., 2019). As presented by (Oh, et al., 2019), Psyche's three main science goals are:

1. "Understand a previously unexplored building block of planet formation: iron cores.
2. Look inside the terrestrial planets, including Earth, by directly examining the interior of a differentiated body, which otherwise could not be seen.
3. Explore a new type of world. For the first time, examine a world made not of rock or ice, but of metal."

These goals led to the mission's science objectives below (Oh, et al., 2019):

A. "Determine whether Psyche is a core, or if it is primordial unmelted material.
B. Determine the relative ages of regions of Psyche's surface.
C. Determine whether small metal bodies incorporate the same light elements into the metal phase as are expected in the Earth's high-pressure core.
D. Determine whether Psyche was formed under conditions more oxidizing or more reducing than Earth's core.
E. Characterize Psyche's topography."

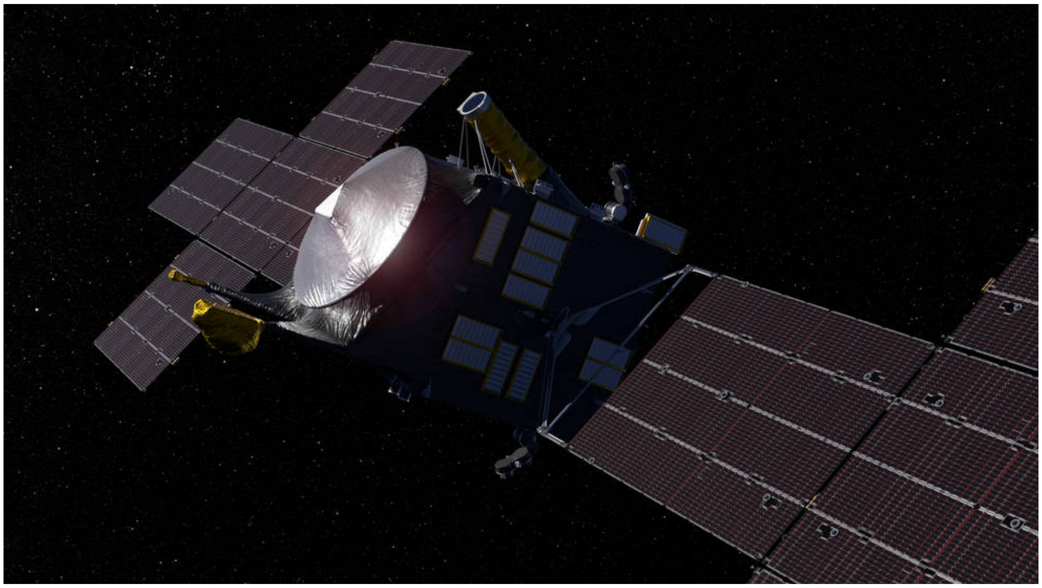


Figure 33. Illustration depicting NASA's Psyche spacecraft. *(NASA/JPL-Caltech/ASU, 2022)*

Psyche carries a set of instruments including two magnetometers (led by MIT and delivered by the University of California, Los Angeles (UCLA)), two multispectral imagers (led by Arizona State University and delivered by Malin Space Science Systems), a gamma ray and neutron spectrometer (GRNS) (led and delivered by Applied Physics Laboratory), and a gravity investigation (led by MIT) using X-band radio transmissions (Oh, et al., 2019).

In addition to the set of instruments, two of the main technologies onboard this mission are (1) the solar electric propulsion and Stationary Plasma Thruster SPT-140 Hall thrusters and (2) the Deep Space Optical Communications (DSOC). While the propulsion system used for rendezvous and orbit is one Psyche's most important technologies, being the first mission to use Hall thrusters beyond cis-lunar space (Oh, et al., 2019), this research briefly tackled the propulsion system, but mainly focused on DSOC and the challenges of its infusion within Psyche.

The Psyche mission was originally slated to launch in 2022, but it got delayed by a year to October 2023, triggering an Independent Review Board (IRB) investigation (Foust, 2022; Psyche IRB, 2022). The IRB review was chaired by the aerospace executive Tom Young, and it identified a series of challenges that contributed to the mission's delay. These challenges, taken verbatim from the published report, were (Foust, 2022; Psyche IRB, 2022):

- **General:**
    - "Late Guidance, Navigation, and Control software delivery and lack of testbed maturity
    - Open flight software issues
    - Incomplete verification and validation (V&V), including fault protection
    - Operational readiness"

- **Management and Communications:**
    - "Major communication failures on Psyche resulted in project management not recognizing the seriousness of issues until too late to resolve them in time for a 2022 launch.
    - Psyche team members raised alarms but felt their concerns were not being heard and/or acted upon at multiple levels of management.
    - No formal Independent Technical Authority (ITA) dissents were raised on Psyche.
    - A culture of "prove there is a problem" led to important issues raised by team members being disregarded.
    - Senior management changes in JPL's Planetary Science Directorate, including three leadership changes and a reorganization within the last two years, had an adverse effect on Psyche.
    - Senior and Line management did not recognize Psyche development problems in time to take corrective action to prevent the launch delay.
    - Senior management did not penetrate project execution sufficiently to recognize seriousness of the development issues.
    - High demands on management's time to continually balance staffing requirements contributed to the launch delay."

- **Staffing:**
    - "Multiple staffing issues resulted from JPL having more project work than can be supported by the available workforce:
        - Inexperienced managers and technical personnel in multiple project positions
        - Worker burnout
        - Inadequate staffing
        - Excessive number in stretch assignments
        - Lack of mentoring
        - High turnover

    - Key project positions were not staffed:
        - Lack of a Project Chief Engineer
        - Lack of a GNC Cognizant Engineer (CogE) contributed to late GNC subsystem technical definition, development, and testing"

- **COVID-19 Related:**
    - "COVID-19 is a contributing factor to the issues that led to a launch delay and the lack of visibility of these issues within JPL.
    - Resulting remote work substantially reduced informal communications:
        - "Walking the floor" and "drop-in discussions" did not happen.
        - Various teams within Psyche became more isolated.
    - Remote and hybrid work arrangements persist and pose a high risk to remaining Psyche Project development."

- **Project Metrics:**
    - "Lack of meaningful progress metrics and risk assessment hindered visibility into, and the ability to highlight and elevate, issues.
        - Inadequate and unrealistic Integrated Master Schedule minimized the value of traditional "actuals vs. plan" metrics to assess progress.
        - Risk assessments did not accurately communicate project health (i.e., many yellow risks, no red risks). Based on interviews, there was an aversion to "going red" by project management.
        - Project schedule and progress-tracking metrics masked true development status.
    - Project focused on hardware development and problem resolution, and neglected software and other non-hardware areas of activity."

- **SRB Review Process:**
    - "Psyche Standing Review Board (SRB) reports for the Preliminary Design Review (PDR), Critical Design Review (CDR), and System Integration Review (SIR) identified schedule performance as a risk to the LRD.
    - Psyche agreed that schedule was an issue, noting that they had appropriately mitigated the identified concerns. The project's position was accepted by all authorities, including the Psyche SRB, JPL, Program Office, and NASA HQ management.
    - This SRB activity was consistent with the overall NASA/JPL review process for Psyche. The net result was that this concern by the SRB was not adequately mitigated in the go-forward plans for Psyche—an issue that was exacerbated by the excessive duration between SRB reviews post-SIR."

- **JPL/Maxar Relationship**
    - "Maxar supplied the spacecraft chassis for Psyche, including the structure, power, and electric propulsion subsystems, under a fixed-price contract; Maxar also provided simulation software, testbed equipment, and personnel for a joint ATLO campaign.
    - Maxar has built and developed multiple spacecraft using electric propulsion for Earth orbital applications but no deep space applications prior to Psyche.
    - JPL teamed with Maxar early during proposal development and continued a strong working relationship throughout the design phase, aided by frequent and extended face-to-face interactions between the two teams.

- The COVID-19 pandemic prevented the planned team-to-team immersion of ATLO personnel, scheduled to happen before the joint ATLO, and as a result, the early stages were inefficient and hindered the melding of culture, procedures, and expectations.
- Misunderstandings between the two partners about the details of the joint testbed simulations significantly delayed the V&V activities and contributed to the launch delay."

Thus, in summary, the IRB report identified a number of challenges that caused the mission delay that were not only related to testing, verification and validation, but to additional JPL institutional issues, management and communication mishaps, and Covid-19 effects.

However, in addition to the IBR identified challenges for the mission that contributed to its delay, Psyche encountered many challenges during its development that were unique to its infusion of DSOC and its solar electric propulsion, as discussed in the next two sections.

4.1.4.1 Solar Electric Propulsion

Psyche will use solar electric propulsion (SEP) and Stationary Plasma Thruster SPT-140 Hall thrusters for rendezvous and orbit. Electric propulsion is one Psyche's most important technologies, this being the first mission to use Hall thrusters beyond cis-lunar space (Oh, et al., 2019). This technology stems all the way back in the DS1 mission discussed in Chapter 4.1.1 New Millennium – Deep Space 1. The incorporation of the Maxar solar electric propulsion (SEP) chassis involved some deviations from JPL's design principles because it was built as a commercial product. The team "took a lot of time to work through those", but that conversation was important to happen [I49]. Despite not being the main focus of this research, this technology was a good example of some challenges at NASA such as the following [I49]:

- **Gaps between Technologies and SMD Needs:** The development of this technology showed the gaps the technologies that are being developed by NASA and what is needed in the Science Mission Directorate. These thrusters, such as NASA Evolutionary Xenon Thruster (NEXT), were developed to Design Reference Missions (DRM's) that were originally outer planet's exploration. After the idea of outer planetary exploration fell out, an effort was made to fit the DRM's to Discovery-like missions [I49]. As one system engineer explained, "First of all, that switch from Flagship to Discovery meant that the thruster which was being developed, which was originally designed for these flagship missions is being shoehorned into Discovery missions. So it is not the ideal technology." [I49]

  Additionally, the technology development timeline for these technologies within NASA was much longer than the technology development timelines that the science missions normally need. The NEXT thruster, for example, has been under development since 2003, and it was not until 2021 that it launched on NASA's Double Asteroid Redirection Test (DART)—which was "so many Discovery cycles away to keep track" [I49]. Hence, by the time NEXT was mature, there were alternatives developed faster by commercial industry, which were more mature and therefore more suitable for use on science missions. As one system engineer sums up this challenge [I49],

  > "So that gap is real. It exists. It is driven by the speed at which NASA can develop technologies, and it is driven by the separation between the technologists and the mission

needs, because at the end of the day the mission folks are focused on mission and what that technology can do for them."

- **Industry's Pace vs. NASA's Strengths:** Building upon the previous challenge, another challenged was that the NASA's technology developments strength lies in area of technologies that have never been flown before, such as DSOC, MOXIE, or the first DS1 Ion thrusters. However, when carrying on technologies such as electric propulsion afterwards, the commercial industry caught up to the point where they were doing their own development. That was the point in which NASA "should have dropped out of developing the same thrusters that industry was developing and should have moved on to the bigger ones" [I49], as opposed to trying to invest in such technologies for Discovery missions while there was a "perfectly good analog out in commercial industry" [I49].

  The long development time that NASA suffers through in technology developments, exacerbate the challenge in climbing the TRL ladder. As one system engineer explained, "It takes us a long time to develop these technologies, and that timeline was compatible at a time where you had twenty years to develop a mission. However, that is not the way most missions are developed anymore." [I49] Compressing the technology development needed time allows a quicker and more compatible response to its initial set of requirements. Otherwise, as technologies mature and meet the original requirements, "the rest of the world has moved on, and the technology is no longer directly relevant" [I49].

  In addition to some technologies' inherent development complexity, a prominent cause of this challenge in technology development timelines that applies to SEP was that NASA sometimes "peanut butters" its technology development money instead of concentrating in a few areas. That concentration could instead allow the agency to work hard to get those specific technology areas done fast, so that they can be integrated as quickly as possible [I49].

In summary, the SEP technology on Psyche provided a good example for common NASA challenges such as the gap between the technology development and the science mission needs, in addition to the industry's pace picking up the technology that NASA kept investing in developing.

4.1.4.1 Deep Space Optical Communications (DSOC)

DSOC is a flight laser transceiver technology demonstration payload that would be the first demonstration of optical communication beyond Earth-Moon distance. This demonstration will be critical, as it will complement the increase of expected data return from deep space missions in the future, by providing 1.2 Mbps at 2.62 AU, which is the farthest Mars-Earth distance (Deutsch, 2020). The DSOC flight terminal (FT) figures are competitive with deep space radio systems, weighing approximately 29 kg, consuming about 100 W of spacecraft power, and equipped with a 22 cm telescope mounted on a "floating" platform on Psyche (Deutsch, 2020). The FT utilizes an uplink beacon, vibration isolators, and a focal plane array to "maintain the pointing and stability necessary to achieve the accuracy needed for Earth pointing" (Deutsch, 2020). According to (Deutsch, 2020), during nighttime, DSOC will be able to transmit data at around ten times the rate of a similar radio system into a 12-meter Earth receiving telescope (Deutsch, 2020).

The background for this technology goes back to the FY2010 NASA Space Operations Mission Directorate (SOMD)/Space Communications and Navigation (ScaN) funded Deep space Optical Terminals (DOT) pre-phase-A project. That project identified four key technologies to be advanced up the TRL ladder from TRL 3 to TRL 6 to "to meet this 10X performance goal while minimizing mass and power burdens on the host spacecraft" (Podolski & Biswas, 2020). These technologies were "a low mass spacecraft disturbance isolation assembly, a flight qualified photon counting detector array, a high efficiency flight laser amplifier and a high efficiency photon counting detector array for the ground-based receiver" (Podolski & Biswas, 2020).

Since then, multiple key tests for laser communications occurred, most notably NASA's Lunar Laser Communications Demonstration in 2013 that tested "record-breaking uplink and downlink data rates between Earth and the Moon", and NASA's Laser Communications Relay Demonstration launched in 2021 to test "high-bandwidth optical communications from geostationary orbit and to demonstrate relay capabilities so that spacecraft don't need to maintain a direct line of sight with Earth to communicate" (Frazier & O'Neill, 2022).

On Psyche, DSOC would be proven for the first time in deep space, setting the foundation for higher data-rate returns in future deep space missions (Frazier & O'Neill, 2022). DSOC was offered as part of the original instrument AO as an "incentive" for the competing proposals [I43, I52, I49]. Teams were given a choice of several different tech demos to consider, with an amount of money to cover the accommodation cost [I52, I43, I49]. The winning Psyche proposal picked the one that they thought the mission "was going to be able to help the development of the most", since they were doing a Mars flyby and hence have the Mars distance for the technology demonstration [I43]. However, DSOC had no relationship to the mission's science goals [I43]. This technology demonstration will also be turned off after passing Mars and will not "ever be on again", hence only affecting the mission's science in its effect in building and redesigning the spacecraft. DSOC could not be allowed to "compromise the science in any way", as the science was the prime purpose of the mission [I43, I49].

Psyche encountered many challenges during its development that were unique to its infusion of DSOC. While DSOC did not cause the mission to have the delay, it taxed the team with a lot of extra work at a critical time in the activity [I50]. Some of these main challenges were the following [I43, I52, I49, I50]:

- **Technology Demonstration on a Discovery Mission:** A big challenge for Psyche's infusion of the DSOC technology was that Psyche was a cost-capped, competed mission, with a very modestly funded mandate added to it [I50]. When the DSOC technology incentive was added in the original Discovery AO, there were different views on what the funding was intended to do [I49]. While within SMD the incentive money was viewed to be used for accommodation of DSOC or to be used for science, others viewed that as a way to "improve the mission as a whole" [I49].

  DSOC was pitched as "plug and play", "no-impact" piggybacking technology, but on the contrary, it affected "probably every subsystem of the of the spacecraft" [I43, I49]. DSOC was an incomplete and not fully designed instrument, whose resources were very large relative to the mission [I43, I50]. It was a "gigantic add-on" that impacted the whole system engineering problem for the mission and forced the team to do "a lot of rework and redesign" [I50].

One example of what required additional work was the issue of the magnets associated with DSOC that cannot be turned on while the Psyche magnetometer is on. Even when turned off, there were concerns that the strength of the magnets on DSOC would create any residual magnetic field that could affect Psyche's magnetometer [I43]. The main groups who were concerned with DSOC were the many subcontractors who were all working on creating the spacecraft. The primary subcontractor who faced challenges was Maxar, as they were developing the spacecraft panel on a confirmed fixed price contract, and they had to redesign the whole panel, which created a problem for them. As one PI described [I43],

> "DSOC is larger in mass than all of our science instruments combined. It takes more power than all of our science instruments combined, and it is more expensive than all of our science instruments combined. It is bigger than our entire payload, and so it did require redesign of almost every subsystem of the spacecraft to accommodate it, and that design was not done by the time we were selected because the design process had not been completed."

Since DSOC was not part of Psyche's Level 1 requirements, as a technology demonstration, the team had to ensure that the science instruments were not compromised by the technology integration within the spacecraft [I43]. The Psyche team tried "really hard" to integrate science and engineering as one team—not a science team and a project team as a lot of missions are run—to ensure that the science objectives were not compromised or affected. For example, at their biannual team meetings, all the scientists and all the engineers were invited, and they had science and engineering presentations for everybody to know what was going on [I43].

This challenge, therefore, raises the main question of how much can and should be added to a cost-capped medium class mission before creating an extreme burden on the mission, such as the case of Psyche [I43]. Having a more developed instrument that was ready to be installed and that the Psyche team could plan around would have been very helpful for the mission [I43]. However, the limited available resources on a Discovery or a New Frontiers mission to mitigate the risk of a technology development stresses the challenge of technology infusion into these missions to begin with. This question is a topic of debate, especially since Psyche's cost ended up being ~$1 billion. As one system engineer asked, "Is it really that different than a three-billion-dollar mission in terms of the risk you are willing to take with this with a technology development? That is the question. Why would you really take more risk on that billion-dollar mission based on the technology? Particularly if it is not part of the Level 1 requirement." [I49]

Discovery missions such as Psyche generally have no incentive to take more risk on behalf of the technology development. Moreover, because the Discovery and the New Frontiers competed mission processes for spacecraft, one of the biggest drivers on whether a proposal would be selected or not is risk. Hence, as the same system engineer continued, "We have a strong incentive within those processes to minimize risk, stronger incentive than on the flagships actually." [I49, I34]

This challenge leads some people to believe that flagships are inherently a better place to infuse technology, since they have a lot more resources to be able to deal with the inherent uncertainty in the technology infusion [I49, I30]. If it were not for the added incentive that NASA offered for Psyche, there would have been "zero percent chance that a Discovery mission would incorporate such new technology" [I49]. As the system engineer explained [I49],

> "There is just absolutely no reason. It is so penalizing within the selection process that you would never choose to take the higher risk technology, even if you had a theoretical cost savings from it. Then in practice you would not have a cost savings because of the cost of the incentive."

To some extent, NASA tried to "do their best" for the original AO, omitting technology from the risk evaluation process, or at least "giving a pass on that technology itself", to help proposals get through. They provided some monetary incentive to infuse DSOC by "making it an assigned thing" [I49]. However, having a Discovery AO that incentivized certain technologies, before or after selection, proves its challenges and limits the diversity in the approved Discovery missions [I49]. Demonstrating DSOC on Psyche, once done, will be a high-value outcome for NASA and one of the main reasons for flying the mission overall [I50]. Nonetheless, the process that this technology infusion carried was very challenge for a cost-capped mission such as Psyche.

- **Incomplete Early Requirements Conversation:** The nature of the Discovery competition process created a big challenge for Psyche to infuse DSOC. In Discovery missions, an AO is normally issued for the mission, not for the individual instruments. The instruments and the spacecraft partnership are all negotiated as part of the competition. After the AO issues for the whole mission and the teams that are competing put together their own partnerships, those partnerships are what go in and are selected as part of the AO.

  For Psyche, the DSOC accommodation was something which was meant to be incorporated into that partnership. However, unlike with the instrument providers that the Psyche team was selecting for the science, where they had a free flow of information, a free choice of vendor, a free choice of instrument, with DSOC, they could only decide to fly it or not. They only had one vendor [I49]. The government provided the equipment, and then the only requirements the team had were the guidelines that went with the original AO for Discovery, in addition to what was then provided as part of the "question and answer" for the technology [I49]. That process was very challenging for Psyche, as one systems engineer described, "That had certainly heavily restricted the flow of information—a very different situation than when picking instrument partners." [I49]

  Part of the challenge was that the requirements which were levied in the proposal process were incomplete compared to what the team ended up with after selection [I49]. During the proposal process, the Psyche team was firewalled from DSOC. They were not allowed to talk to the DSOC team inside of JPL because "it was part of a competition that was being done with other NASA centers which could also in principle have used DSOC" [I49]. This firewall, as part of the competitive process, deliberately restricted the Psyche team's ability to talk to the DSOC team, only allowing a "very limited number of interactions", including a technology day and written questions which were passed back and forth across the interface [I49]. Missing from those interactions were a series of critical requirements for DSOC which ended up being difficult and expensive for Psyche to accommodate afterwards [I49]. As one systems engineer described, "That meant that the DSOC accommodation onto the Psyche mission put a pretty big and unexpected burden on the mission, which was not expected after selection." [I49]

  This challenge of restricted information flow is "somewhat akin" to an instrument AO, after proposals get received in response to an official AO release. However, Psyche's experience with

DSOC was "even more restrictive" because they did not have a controlled AO that they were issuing for a technology demonstration [I49]. The Psyche team was mostly provided the information which the Discovery program office thought was appropriate, and they were able to ask some questions and get some answers back. However, the critical challenge there was that "without open flow of conversation, there were questions they did not ask, because they did not know they needed to ask them." [I49]

Another fundamental Psyche challenge that relates to the restricted information flow was that DSOC was conceived and pitched as a replacement for the Radio Frequency (RF) communication system. The DSOC optical communications terminal was pitched as a replacement for the antenna on the spacecraft, and therefore when the team went to place it on the spacecraft, they placed it as though it were an antenna [I49]. That decision turned out to work for antenna-like instruments that are "largely passive structures". However, in terms of accommodation, DSOC was closer to a telescope instrument than an antenna—hence requiring more stability in its accommodation that could have been better provided inside the spacecraft not externally [I49]. As one system engineer explained [I49],

> "If the design had been understood to be that, then it would have been placed differently on the spacecraft, and it would have been dealt with differently on the spacecraft. The Psyche team did not understand that distinction. With DSOC, you could make an argument that there is a different set of requirements which could have been written at the very beginning if all parties had understood what was being done, which would have made the initial accommodation harder, but it would have made the final design easier. Getting information like that as early as possible in a design flow is what would have made that easier from Psyche's point of view."

This challenge goes hand in hand with the previous one concerning the infusion of technology demonstrations within Discovery missions, especially technologies that are provided as less than fully developed subsystems. Such technologies tend to lack the commitment to fully develop the subsystem and all the pieces around it, so that they can be integrated into the spacecraft as a whole. The spacecraft needs the commitment by the technology provider to put all those elements to a subsystem, and the resources that go with that, as opposed to "a bunch of pieces of a technology which are not fully integrated." [I49]

- **Lack of Margins and Contract Specificity:** A key challenge, and lesson learned, for the Psyche mission and its DSOC technology demonstration was the lack of specificity in the contract written between STMD, SMD, and the Project on "exactly what the guardrails and decision points are" [I43]. Had the team continued their work as they were during Phase B and Phase C of development, DSOC could have "killed the entire project", just by the weight of its requirements [I43].

  The contract had no clear way to appeal to STMD or SMD for extra help, or "how to decide whether things are okay or not" [I43]. Despite the ability to "renegotiate when things get tough no matter what your contract says", having more of an understanding in the beginning of what was expected would have been helpful to the team and to the technology itself. The contract did not clearly specify who was the "ultimate decider", and it caused friction between SMD and STMD [I43]. One example on such friction points was regarding cost, where SMD would say that "the mission was incurring tremendous additional costs", and STMD would reply "that's tough" [I43]. As one PI explained [I43],

> "The culture in STMD is not to have margins the way SMD has, from years of painful experience that you need your 30% margin on everything. No or very, very little margin exists in STMD. That was that was a challenge […] In general, my observation is that STMD is run from top-down like military, and SMD is from bottom-up, like a science organization, and so it makes it difficult."

Hence, despite the Psyche team's understanding of DSOC's importance and support for it, the lack of contract specificity and margins created a challenge to the team in infusing DSOC [I43].

- **Lack of Interface:** Another challenge that the Psyche mission faced with DSOC was the lack of provided personnel from NASA headquarters and JPL who interface with the project and ensure that the work was flowing in the right direction. That lack of interface further exacerbated DSOC as a "burden" on the Psyche mission, forcing the team to "spend an awful lot of time on the project thinking about DSOC, where the brains of everyone on the project should be thinking about Psyche" [I43]. Hence, having a full-time person since the beginning, not provided from Psyche's already cost-capped budget, to be responsible for that interface would have helped the project overall. Eventually, and through negotiation, the team was able to receive that interface personnel, but they "could have used it a lot earlier" [I43].

In summary, Psyche and DSOC faced several challenges in the development journey, including the constraints of infusing a technology demonstration to a cost-capped Discovery class mission, the incomplete early requirements conversation, the lack of margins and contract specificity, and the lack of interface personnel between NASA headquarters and JPL and the project early on.

4.1.5 Other "Low-Cost"

Prior to analyzing and understanding the challenges in NASA's current low-cost efforts, SIMPLEx and CLPS, it is critical to look back at the challenges that NASA historically had in the aftermath of its low-cost attempts, such as the previously discussed Faster, Better, Cheaper (FBC) era. Incorporating an FBC-like model in NASA's more recent low-cost efforts could allow technologies to be matured faster and could keep the agency nimbler and more balanced in how it does business, especially with different classes of missions, where it is difficult to have a "one size fits all" business plan [I19].

In the FBC era, employees were given permission to "push the envelope" as hard as they could push it, to do as much as they could for as little money as possible, in any way they thought makes sense [I45]. However, the caveat was that these were fixed-price jobs. Teams at NASA at the time were given permission to push their technologies, they were given permission. As one engineer described, "The key was not to say 'yes'. The key was that no one said, 'no'. An absence of 'no' and a sense of trust were central to the faster, better, cheaper era" [I45]. However, as time went on, "greed took hold", and suddenly margins disappeared while resource and time constraints grew larger [I45]. This growth of constraints threatened the flexibility and innovation, because the resources shrank, the expectations for "doing a lot for little money" were growing, and the scope and complexity of what was being planned increased [I45]. After the 1998 Mars mission failures and the demise of the FBC practices, JPL came up with its flight project practices and design principles, which have been growing over time, since as one manager described, "inherently, bureaucracies just grow" [I33]. The JPL design principles have strengths in incorporating JPL's core knowledge, but weaknesses in carrying forward practices that may be outdated and some codified practices that are different than what the industry has moved on to [I49].

Therefore, the transition from the FBC era headed towards a constantly increasing bureaucratic procedures, with an inherent tension lying in updating them to match current practices or sticking to codifying the best practices, regardless of the rest of the industry [I49]. The tension on the flight project practices and design principles also incorporates the debates on whether such rationales should be encoded and understood mainly at the subsystem level only, rather than at the institutional level [I49]. Hence despite their seeming necessity within an organization with JPL's low flight rates, the flight project practices and design principles face a constant tension on how they are used, whether they are treated as set in stone checkboxes or rather with clear understanding of the rationale behind them [I49].

However, in addition to increasing bureaucratic procedures, the end of the FBC era created a drastic cultural shift at NASA, centered around the agency's public image, use of taxpayer money, and the notion of "failure is not an option". Consequently, this culture instilled an employee environment of fear and risk aversion accompanied with a lack of appetite for institutional change.

Over time, many veterans from failed FBC missions, who experienced first-hand what was supposed to be the "low impact risk of failure", were more acceptant of NASA's growing required procedures, communication, documentation, verification, and validation [I31]. As one system engineer described, "You are supposed to be able to fail, and it is supposed to be okay. And of course, it never is okay. So they were having sort of an organizational reckoning" [I31].

Many people concur with and confirm this cultural shift in the aftermath of FBC's demise, saying, "It certainly became clear that engineers who were in the faster, better, cheaper era, who were associated with missions that did not succeed, paid the price. Faster, better, cheaper should have also said, faster, better, cheaper, riskier." [I29] One scientist explained that there is an expression at JPL "*take the head*" that employees use to refer to this mantra, emphasizing that "you cannot tell people to be riskier and then, when they fail, take them from this high-level job and go stick them in some backwater." [I29]

Hence, the words "faster, better, cheaper" make people at NASA who experienced that era "shudder" [I38] because, as one PI and manager described, the lesson the NASA took away was that, "when you fail, you put the whole program at such a risk with respect to Congress, you get hearings, you get investigations, they want to know why you failed, and they do not know why they can trust you with more money." [I14]

In exploring NASA's ongoing "low-cost" efforts and programs, such as SIMPLEx and CLPS, understanding the FBC contextual culture and the challenges birthed in its aftermath is critical. Despite the exciting opportunities that these programs allow and the wealth of first order science that can be done with simple instruments [I29], NASA's cultural challenges post-FBC shaped its core policies. The notion of risk-taking is complex, and as someone from NASA leadership said, "For example, maybe if two out of 10 missions fail, that is okay, but there is a corollary to that, that says it cannot be one of the first three missions that fails. If the first mission on the string of 10 missions fails, for example, the program is likely to be cancelled, so this notion of taking more risk again is fairly complex" [I37]

4.1.5.1 SIMPLEx

In the 2013-14 timeframe, an attempt was made at NASA to reserve some mass margin in every planetary mission sent out for planetary CubeSats [I22]. These efforts were intended as an approach to "push the envelope" for planetary technologies [I22]. In contrast to the Earth science and heliophysics realm, that offers a good technology pipeline such as Earth systems observatory, high Class B spacecraft, suborbital programs, flying airplanes, high-altitude balloons, rockets, CubeSats, etc., the planetary world is more difficult [I22]. Despite the number of planetary programs, getting technologies to another planet is very expensive, unless paired with other bigger missions [I22]. Launched in 2018 to the Red planet, the twin communications-relay CubeSats Mars Cube One (MarCO) were the first interplanetary CubeSats [I22]. Due to the importance of planetary CubeSats, the SIMPLEx program was born. The details of this program were discussed in Chapter 1.1.1.5.4.1 SIMPLEx.

As previously discussed, SIMPLEx-1, the first planetary science CubeSat PSD solicitation in 2014, capped mission proposals to $5.6M for the full mission lifecycle of the mission and limited the size to 1U, 2U, 3U, or 6U for launch (Mercer, 2019). The two selected proposals in 2015 were the CubeSat Particle Aggregation and Collision Experiment (Q-PACE) and the Lunar Polar Hydrogen Mapper (LunaH-Map) (NSPIRES NASA PRS, 2015; Hardgrove, 2016; Genova & Dunham, 2017; Colwell, Brisset, Dove, Jarmak, & Q-PACE team, 2019).

However, SIMPLEx has faced a series of challenges since its initial solicitations. Some of the main challenges were the following [I21, I22, I34]:

- **Drastic Cost Increase over Time:** The cost cap for SIMPLEx drastically increased from $5.6M in 2014 to $55M along with the mass limit increase to 180 kg in the 2017 PSD SIMPLEx solicitation— "an order of magnitude higher than those given under SIMPLEx-1, but […] an order of magnitude less than PSD's Discovery program" (Mercer, 2019). The three selected proposals in 2019 out of this solicitation were Lunar Trailblazer, Janus asteroid mission, and Escape and Plasma Acceleration and Dynamics Explorers (EscaPADE) (Foust, NASA to continue Lunar Trailblazer despite cost overrun, 2022). Lunar Trailblazer has already exceeded its cost cap by 30%, reaching $72M in its development, and the latter two missions have both encountered problems delaying their launch that was originally slated, then removed, as part of NASA's Psyche mission (Foust, 2022). With these cost increases, the 2022 planetary science decadal survey recommended increasing the SIMPLEx cost cap from $55M to $80M (Canup & Christensen, 2022).

- **Increased Bureaucracy over Time:** With the increase of the SIMPLEx mission cost cap came another challenge relating to risk posture and oversight. As one technologist explained, "SIMPLEx is probably the only one you can get away with a little bit more [risk]. However, as that program ages, in the same way Discovery aged, it gets more conservative because that is the bureaucracy within NASA. You do not want things to fail. If missions only happen once or twice, you do not want them to fail, so the risk posture within NASA is very low." [I21]

That decreasing risk posture for programs initially intended to "push the envelope" defies their initial purpose of existence. As a program executive emphasized, "SIMPLEx is a little different once we raised the cost cap. It is now kind of a lot of money, and so even though we streamlined the Class D management of that, we are still giving them a little bit more oversight than necessary. We are actually doing it." [I34] Such challenges of increasing bureaucracy over time and changing efforts reflect NASA's attempts to figure out how to best manage Class D missions.

In summary, despite its initial goal of pushing the envelope and taking for risk for developing and maturing planetary technologies at a low cost, SIMPLEx's cost profile has drastically increased since its beginning, and its bureaucracy and risk aversion have in parallel rapidly increased.

4.1.5.2 Commercial Lunar Payload Services (CLPS)

As previously discussed in Chapter 1.1.1.5.6 CLPS, the Commercial Lunar Payload Services (CLPS) initiative is one of NASA's commercial programs that aim to leverage the capabilities and expertise of the private sector specifically for the delivery of scientific and other payloads to the surface of the Moon (Dunbar, 2023). Starting with nine companies in 2018, the program increased its number of contracts to 14 a year later. In its selection process, NASA reviews and evaluates the technical feasibility, schedule, and price in each of the vendor bids, providing "indefinite delivery, indefinite quantity (IDIQ) contracts with a combined maximum contract value of $2.6 billion through November 2028" (Dunbar, 2023). Some examples of CLPS contractor companies are Astrobotic Technology, Draper, Firefly Aerospace, and Intuitive Machines. Among the initially selected vendors, OrbitBeyond backed out of its offer and Masten Space Systems had critical financial struggles including filing for bankruptcy in 2022 (Foust, 2022).

CLPS is a higher risk initiative, and NASA is aware that not all the missions will be successful. Each CLPS mission will be carrying several different payloads, however, one mission of particular interest is Astrobotic's launch in late 2024 that will carry NASA's Volatiles Investigating Polar Exploration Rover (VIPER) (Chen, 2022). VIPER has cost NASA nearly half a billion dollars and has thus been requiring additional testing and additional cost for Astrobotic's CLPS mission to ensure risk reduction (Foust, 2022).

Since the beginning of this program, CLPS has faced a series of challenges that include the following [I34, I24, I38, I47, I48, I41, I22, I46, I44, I34, I57, I58]:

- **Initial Selection of Commercial Contracts:** One of the challenges that CLPS faced was in its initial process of contracts selection. Despite the companies demonstrating good technical capabilities to build Moon landers, involving many employees who had technical depth and experience, the unknown question that CLPS had to deal with was, "Do they have enough structure and management presence, expertise or experience, to make sure they do not make a mistake, because the space business is highly unforgiving of mistakes." [I58]

  CLPS had a two-phase selection process. During the first phase, they were just putting companies in the pool—what they call the "master contract". They did two rounds of putting vendors in the pool, ending up with 9 companies in the first pool, before they added five additional ones a year later. That process was not hard, nor was it intended to be. The running joke around that process was "If you could spell Moon, they would let you in the pool." Hence it was not a very demanding process, nor was it very high bar to jump over [I58].

During the first phase, companies had to demonstrate they understood what it meant to build a lunar mission, but they did not have to show hardware, they did not have to show their money and business plans, and they did not have to show "really much of anything about their true capabilities", other than demonstrating they understood what building a Lunar mission looked like [I58].

It would have been hard to put vendors onto the first selection process with much more rigor without having promised more to the companies. Companies would not spend a lot of money writing proposals unless there was some promise of a contract. As one manager described, "If we were making them compete aggressively to make any money after the award, we cannot ask them to spend a lot of money in the first phase of the process." [I58] If more rigor were expected, then the only companies who would have been able to do that would have been the traditional bigger aerospace vendors that have more money. Small companies cannot afford to compete in that kind of a process, and the CLPS program really wanted to make sure they were "leaving room for the small companies." [I58]

After the first phase, the companies had to compete again, on purpose, as part of the "experiment" that the CLPS program was conducting. As one manager explained, "The more competition you have the better prices get, and at least we hope you get more innovation because they have to compete hard. If you give companies guaranteed contracts, there is not a lot of reason they are going to take risk and innovate." [I58]

The CLPS program had a belief that the work that the Google Lunar XPRIZE had sponsored had "laid the groundwork" for commercial companies to be able to build landers to the Moon, without "a ton of NASA investment" [I58]. However, the challenge that CLPS faced was that the Google Lunar XPRIZE did not mature a lot of the companies as much as they would have hoped [I58]. Despite the investment from the XPRIZE, both in the United States and internationally, the extent to which the companies were ready to actually build the lander and fly to the Moon varied "more than they would have hoped" [I58]. Moreover, as one manager explained, "Nobody had a lot of insight into what the companies were spending during the Google XPRIZE process. We could see what they were saying publicly, but I think we have learned, now that some of them had to actually back that with real work, was that they probably were not as far as we would have hoped." [I58]

These uncertainties in the selection of vendors to work with led to problematic cases, like the example of Masten Space Systems that eventually filed for bankruptcy in 2022, taking down the investment that NASA has put into it [I46]. However, despite this bankruptcy example, the remaining companies were still progressing at "a fraction of the cost of the NASA missions", leading to an optimistic view that some people involved with CLPS have that "if these companies succeed, it will be at significantly lower costs. I am optimistic if we let them—this is the hard part we have to let them—they can go at a faster pace than we ever do." [I58]

- **VIPER and Increasing Bureaucracy:** As previously mentioned, CLPS is a more innovative, higher risk initiative, and NASA is aware that not all the missions would be successful [I57]. This acceptance of possible failures is mainly because these are uncrewed missions that do not carry NASA's multi-billion-dollar assets, but rather are less expensive landers [I57]. However, this campaign premise has proven challenging for CLPS over time. As with other NASA programs and initiatives, bureaucratic processes have been slowly increasing over time. One example of that is the selection process itself. As one manager pointed out, "We have been continually evolving the selection process and the task order awards based on the things we learned, *so the rigor has gone up*. […] As compared to the first time, now there is a whole series of new steps in that process based on what we learned about Masten going bankrupt." [I58]

CLPS has been fighting "every day, all day long" in a constant battle to keep the program from losing its low-cost, innovative persona. Such an approach succeeds when the payloads are small and relatively cheap, where the program is willing to take "a fair amount of risk and to give a lot of leeway" [I58]. However, the main challenging example for CLPS on that front has been NASA's Volatiles Investigating Polar Exploration Rover (VIPER) that is planned to launch with Astrobotic in late 2024. VIPER has cost NASA nearly half a billion dollars, and so the agency went "wait, that is an important asset, and so we do not want to accept as much risk" [I57]. This change for the risk profile when dealing with VIPER caused a delay in the mission, requiring additional testing and additional cost for Astrobotic CLPS task to ensure risk reduction [I57]. Hence, as one system integrator at NASA described [I57],

> "It has swung, probably not completely, but a bit more back towards the traditional but the more recent commercial model, where we do have pretty heavy insight with the vendors, and a lot a lot more involvement."

Being "not a cheap mission", where many people at the agency do not want to take risks, VIPER is a good example the type of missions where CLPS's contract structure and procurement strategy were not the best fit [I58]. NASA was willing to pay under 100 million dollars to regularly deliver payloads to the Moon with little or no oversight, and CLPS has been relatively successful with the support "all the way up to the Administrator level" for the low-cost missions with payloads that NASA is willing to risk on [I58]. However, VIPER was a different story, causing the CLPS program an everyday struggle in its accommodation. They have added more oversight on VIPER, partly because the agency was not comfortable in taking that amount of risk for the expensive payload.

This challenge created a "lot of back and forth" in the program between what VIPER wanted to do and what the CLPS contracts would allow. The contracts were not written to run a traditional mission, and thus CLPS cannot do some of the processes common for a traditional NASA mission, that VIPER would like [I58]. This discrepancy led to a discussion on whether to remove VIPER from CLPS, but the decision from NASA leadership was not to. This decision forced an unexpected change in the spirit of what CLPS was originally intended to do. As one manager emphasized [I58],

> "It has been extraordinarily expensive to fly, to change to a more traditional class mission. And we do not have that budget. We are going to try and thread the needle to make sure VIPER is delivered successfully within budgets we can afford with an amount of level of risk we can accept."

- **The Question of Standards and Protocols:** Another challenge for CLPS was the question of setting standards and protocols for the ongoing lunar activities. The overall NASA lunar activities create a struggle because the whole architecture is not fully defined, but rather open ended at this point [I57]. As one system integrator at NASA described [I57],

  > "NASA had this vision that 'Hey, we are going to do all this commercial services model, and give the vendors as much flexibility as possible to allow innovation'. But what is becoming reality is that if you let everybody do whatever they want, there is no guarantee everything is going to work together. We are finding that leaving everything open for the providers to figure out amongst themselves was too open-ended."

  Some offices at NASA have been "playing catch up" by pushing trade studies in surface-to-surface communications, navigation, logistics transfer, interoperability, etc. to reverse course and address this challenge of not having any protocols. The same issue applies for other areas as well, such as surface power and the lack of developed power transfer standards with industry that could allow such enhanced capabilities [I57]. These offices' desire is to also involve the industry in this process and receive their input before they develop requirements and detailed specifications that might hinder the commercial vendors' innovation or preclude them from being able to use things for their own business purposes [I57]. Hence, in setting up a framework that attracts industry and allows them to meet "whatever they think their business case is", many people at NASA believe that they "probably swung a little too far and now need to course correct back" [I57].

  The argument about standards and protocols was something that the CLPS program had discussions about, but the belief was that standards generally do not emerge first but rather after a program has matured to a certain point [I58]. It is difficult to create new industries based on a set of standards because that is essentially building the industry on what is already known how to be done. This notion stifles innovation and limits competition, because everybody has to "seal the same box" to meet the standards [I58].

  Thus, despite the possible challenges facing the lunar activities due to the lack of standards and protocols, CLPS purposely did not try to impose a lot of standards for multiple reasons. First, it was partly because Google Lunar XPRIZE had already started this process, and there were already companies out there who had their own designs for landers based on their own concepts. If CLPS were to impose standards too aggressively, it would have limited competition, because all these companies believe "their idea was better than anybody else's" [I58]. As one manager explained, "Your basic [necessity for standards] is somebody else's commercial opportunity." [I58]

  The view that CLPS has been holding is that "standards will emerge in the places where the marketplace is ready to support them, and the government can and should take advantage of that as soon as possible" [I58]. However, there has been a worry about the government driving the standards before the marketplace is ready, consequently limiting the opportunity for commercial companies to succeed and inhibiting best capabilities by "dictating solutions before the marketplace understood what would work" [I58].

  The other piece of the standardization challenge has been the extent of competition and lack of consolidation happening between the vendors themselves. When task orders began to be awarded in 2019, the majority of the CLPS team thought that within 2 to 3 years, they would see "enormous consolidation within the vendors," as it was difficult to believe that NASA or the commercial marketplace could support 14 companies building landers to go to the Moon [I58]. However, the opposite of that prediction of vendor consolidation and industry shrinking proved to be the case. There has been very little consolidation, and most of the vendors, even if not necessarily bidding, are still in the pool. After NASA's initial "pretty big thumb on the scale" on investments in these vendors and with this lack of market consolidation, the CLPS program has been wary of standardizations and protocols. The vendors themselves, who could in some cases benefit from standardizing their lander designs more rapidly to control their costs, are not pushing for the benefits from standardizing [I58].

This challenge of standards and protocols reemphasizes the vision of near-term needs for the lunar surface that NASA went into this program. As one system integrator explained, "We will put down a few pieces of hardware, rovers, maybe a habitat, and then we are really looking to leave the door open for industry to build upon that, to partner with us, to enable their business case" [I57]. The problem, however, has been that "that is not happening at the grassroots as NASA thinks it could or should" [I57]. As the same system integrator summed up this challenge [I57],

> "I think we are struggling with 'Are we doing the right things to really enable those industries?', and it is like a chicken and egg, in that industry is looking for more from us, but they do not say it explicitly enough for us to act on it. […] I think the intent is good on both sides, but I am not sure it is going to play out the way we envisioned or hoped.
>
> The long-term vision for the lunar architecture work, in terms of needs, goals, objectives, and capabilities, is run out of NASA headquarters, but we struggle with the lack of a real defined plan as it is so open-ended. This is a challenge when we are developing hardware that has to operate on the surface for over 10 years and interface with things that are completely undefined at this point."

Thus, despite the hope of having successful missions, there is a concern that the "thriving lunar economy" campaign as a whole is very open ended, creating a risk of having a shorter life than what NASA wants it to be.

- **Drastically Varying Views within NASA:** The interviews conducted for this research showed a drastically varying spectrum of opinions within NASA on the CLPS program, from those who thought it was the "best model in the agency" [I34] to others who believe it will "historically end up being a colossal failure" [I24].

  CLPS is not a technical program in the normal sense. CLPS is very much a procurement strategy, focusing on changing the way NASA procures services for space [I58]. When the government buys anything, the Federal Acquisition Regulations (FAR) document defines how these things can be bought. However, it is a rather complicated process, especially for an entity like NASA that has developed a set of practices and processes for doing business in the space for over 60 years. The challenge for NASA has been marrying how they do their own practices and processes with the way that the FAR allows them to do business [I58].

  Such activities revolve around the tight relationships between the government and the primary contract. For example, NASA has a long history of paying companies to build rockets while still being heavily involved in every aspect of the development process, such as defining requirements and testing. However, there has been an ongoing effort from the commercial community for NASA to shift more responsibilities towards commercial companies. Such responsibilities include the recent development of commercial crew and cargo programs for delivering services to International Space Station, allowing the vendor to substitute their processes for traditional government processes, make decisions, and reduced costs considerably. Despite this shift, however, NASA maintains a heavy oversight role in both programs due to the risk involved in flying humans to space [I58].

CLPS, on the other hand, has been an uncrewed, "acknowledged experiment" all the way to the agency's Administrator level to see "how far NASA can go in letting the vendors run things their way" [I58], with NASA taking a lighter oversight role than usual. With that philosophy in mind, CLPS cut out as much regulation and overhead out as they possibly could to see if that allowed a faster work pace [I58]. Such a program presented itself to a lot of people at NASA as a "resurrection and another manifestation of the faster, better, cheaper (FBC) era" [I24], ringing alarm bells on risk management and expected failures and bringing back the divide in opinions at NASA between those who support such efforts and those who do not.

Supporters of CLPS believe that these missions are inherently high risk, but by building multiple copies of instruments and flying them on multiple landers, "hopefully, at least one or two of those will work" [I47]. Such supporters of the program accepted from the beginning that they would be "completely happy with a 50% success rate", accepting that some of the companies were not going to make it. The belief there was that this program was not only driven by saving money, but rather by growing the capabilities in the commercial sector and having multiple providers that can do science or provide services for NASA to do science at the Moon [I47]. For the commercial lunar community, CLPS mainly addressed the fact that there was a lot of desire and a lot of capability out there, but without "the jumpstart with NASA funding, that was never going to get off the ground." [I47] Commercial investors were not going to invest until they demonstrate that they can actually do it, so NASA made that initial investment [I47].

Hence the supporters of the CLPS model as the so-called "best model in the agency" for light touch and oversight [I34] were generally excited by CLPS's purpose of fostering the commercial industry. Additionally, as one program executive explained, they believe that despite the risk, "NASA is not trying to throw money away. By dialing way back on the oversight, NASA can reduce some of those costs and can therefore afford more payloads. The more NASA tries, the better they get" [I34]. Another person from NASA leadership concurred with that view saying, "With this advent of the smaller, lower cost missions, we are able to take more risk, but I think when you actually integrate under that curve, we are accomplishing more" [I44]. Moreover, other supporters also believed that "if launch costs were cheap or you had a recurring system delivery, you could get beyond the thought process of failures" [I46].

To its supporters, then, CLPS was in fact designed to build faster, better, and cheaper missions [I22, I38]. The main difference was, as one program executive explained, "faster better, cheaper was still NASA led program period, end of story. Even if many CLPS failures were to occur, the price of those failures would be borne by entities others than NASA. That is a huge difference, and that is why I think it is going to succeed this time" [I34]. This discussion of risk and who is taking it is critical and challenging, as the space business tends to be "very unforgiving of mistakes, even if there are no humans involved" [I58]. As part of the political infrastructure of the US, NASA's failures tend to get "outsized attention", which adds additional pressure on the CLPS program.

Not everyone agrees, however, with the notion that CLPS failure would not be tied back to NASA. Some supporters have a more nuanced view, agreeing that CLPS might be trying to accomplish a reset of the risk equation—who takes risk, and how much risk is accepted. However, the main nuance there, is that with an acceptable enough success rate, even if one mission fails, NASA will still spend less money than it would have on a traditional custom mission. As one manager explained [I58],

> "It is certainly described as pushing more risk. Any time you go to commercial service contracts with firm fixed price, by the very nature of it, the government in theory is taking less risk. It is a little less clear we are actually doing that yet. Masten Space Systems has gone bankrupt. They had a task order from CLPS. They got 60 million dollars, did not complete it, but NASA is not getting any of that 60 million back. So most of that risk *still* looks like it was on the government side.
>
> However, you cannot let the story be about 60 million dollars. The right story is that for seven task orders, we will spend less than what it would have cost if NASA had done a traditional NASA custom mission."

Despite these different levels of supporting views for CLPS, the program still faces a lot of backlash from other camps at NASA [I24, I44, I48, I38]. Opponents of the program fall on different levels on the spectrum. Some are mostly wary of scaling up issues, since flying on CLPS missions requires scaling down to a smaller size and weight. The main question that opponents raise there is "When things are scaled down, are you going to experience problems when you scale up into the relevant size?" [I38]. The answer to some things in the technology portfolio is yes. One example is cryogenic fluid management, where NASA wants the relevant tank size that they are going to be using because that is going to be the relevant storage transfer and mass gauging of liquid hydrogen needed on orbit. Hence, people in these NASA camps would rather see a full size rather than "a third or a fourth size and then worry about scale up problems". The main pain point that such opposers view then is that CLPS would create another iterative step for technologies, instead of a step forward.

The other camp of opposers view CLPS as "an experiment in progress" [I44] that they have yet to see how successful it is [I48]. The main concern there has been that "the pendulum on oversight and rigor in CLPS has really swung far back, and it is like two guys in a garage", as someone from NASA senior leadership described [I44]. The last view falls on the extreme of the opposition spectrum, believing that CLPS will "historically end up being a colossal failure" [I24]. The core issue in this opposition to "FBC resurrection" is not opposing innovation or new people, but rather focused on the lack of experience of the people who have not flown missions in the past, where some of the proposals "were blatantly absurd", as one systems engineer described [I24]. The lack of expertise has led to vendors that were unable to quantitively understand their own risk profile [I24].

With these drastically differing views NASA on the program, CLPS faces a challenge of triggering the same response from NASA to FBC if failures were to happen. As one program executive described, **"**We expect failures, and one of my biggest fears is that when those failures necessarily occur, that NASA will get cold feet and abandon this whole concept. I think those failures are part of the process, and we should embrace them" [I34].

- **Difficulty of Expansion to Non-Lunar Applications:** Lastly, a big challenge for CLPS is the difficulty in expanding the concept for non-lunar applications. While in theory, it would be great to be able to have a CLPS-like model for low-cost Mars missions, there is no major market for companies to make profits from repeated deliveries for places like Mars, due to the timescale difficulty [I41]. It is harder to plan a "longer-term vision for Mars with a defined role of the commercial sector" [I57]. The Moon, consequently, is a "great proving ground in several respects", such as testing the success of the interaction between the commercial sector and NASA [I41].

  The challenge in expanding CLPS is that there is more than one dimension to what that would entail, where cost is only one of these components [I58]. First, the Moon is "unique right now in the planetary discussion", because of the potential for economic activity there. While there are a lot of people that believe they can make money doing something at the Moon, there is a much smaller pool of people who think they might be able to make money at Mars [I58]. Then, going past Mars to outer planets or to Venus, there does not seem to be any "credible case for making money", as one manager explained [I58].

  Hence, the motivations that allow investment in CLPS companies that the program takes advantage of are different for other parts of the solar system. CLPS is paying under $100 million on such smaller missions. The vendors then make up for the rest of needed funding through venture capital and commercial payloads. That component of the mission cost would not be credible, "even for Mars, and certainly not for outer planets" [I58]. For such an expansion to happen, NASA would have to bear a higher percentage of the cost for planetary missions other than the Moon.

  With the growing conversations at NASA for low-cost Mars technologies, instruments, and missions to leverage those capabilities, for more frequent planetary missions, with more risk but lower cost [I41], CLPS might offer some insight on commercial practices in NASA. CLPS could provide the learning needed at NASA on how to shift the risk profile, shift the responsibilities, and rely more on commercial service missions. However, the program cannot be easily expanded for places like Mars because the incentives for the commercial marketplace are very different for Mars than they are at the Moon, and even more different for the rest of the solar system [I58].

  In the case of Martian missions, the processes in place for big missions have been deemed useful, but there is a recognition that NASA needs to find the sweet spot for smaller missions where they can achieve similar science but with fewer requirements [I47]. NASA has been transitioning in how people think about their technology portfolio selection as they move from having focused technology programs for flagship missions to also focusing on low-cost missions that could run in parallel, which would be selected through an AO process, most likely at a smaller cost range [I52]. However, most of the low-cost Mars efforts have been focused either on orbiters or minimum complexity, low-cost entry, descent, and landing (EDL) attempts [I35, I35, I52]. EDL on Mars is notoriously difficult and drives mission costs up [I35, I52]]. These efforts discussed in low-cost workshops are thus being conducted separately and differently from the CLPS model. NASA is basically looking for opportunities to conduct low-cost missions on Mars while the majority of the planetary resources are tied up in the sample return strategic effort [I25]. The goal is to conduct small missions that are lower cost, higher risk, but still able to do interesting science [I25].

In summary, despite CLPS's potential innovative promise for low-cost commercial lunar activities, this program has faced a series of challenges since its start, including its process for selecting commercial vendors, VIPER's infusion, the increased bureaucracy and rigor with time, the lack of standards, the drastically varying views on the program at NASA, and the difficulty in expanding the concept for other non-lunar planetary applications.

4.1.6 Overall Challenges Identified

> "*NASA has to discover. NASA has to make things happen. We are caught in this desire to use some new technologies and then make sure the mission works. These are actually two opposite forces.*" [I23]

> "*The science enterprise at NASA is relatively streamlined because it is driven by decadal surveys and such. The technology enterprise is completely broken.*" [I28]

After the deep-dive analysis of the six case studies and identifying each of their specific challenges, this section of the thesis seeks to integrate the findings and extend them to the identification of innovation challenges in NASA's planetary program. The overall identified challenges could be placed within two main categories: (1) Policy and Structural Challenges that include issues of oversight, pipeline between technology development and mission needs, the technology development process, relationship to industry, instrument selection, mission process, technology demonstration infusion and scaling, technology representation, etc., and (2) Cultural Challenges that fall under the theme of "failure is not an option", taxpayer money, public image, employee environment of fear, and lack of appetite for institutional change. These overall identified challenges are summarized below, under different subcategories.

4.1.6.1 General NASA Structure

- **General Disconnect at the Highest-Level between Directorates and Centers:** Many NASA missions and technology efforts should be orchestrated together to accomplish an objective, almost as a *system of system of systems*. However, technology development efforts at NASA are currently stovepiped, with a lack of strong system of systems engineering at the at the highest level to pull them together. This architectural decomposition is a challenge for innovation at NASA.

- **Lack of Pipeline between Technology Development and Mission Needs:** There is a lack of connection at NASA between projects and technologies, similar to the lack of connection between the stovepipes and headquarters, including the technology. For many R&TD efforts, at infusion time in missions, either side is ready for the other side. Technologies were not thinking about the platforms, and vice versa, so the middle part gets lost and projects have to pay for that. Hence, technology activities are *very ad hoc* and *very non-strategic*, and the reason for that is NASA has "a lot of masters". Consequently, many decisions are not made in a systematic way or through studies to examine technology trade spaces. Rather, many NASA decisions are made by Congress and motivated by political or parochial concerns. Hence the technologies that get infused tend to either be the "low hanging fruit", that have a lot of benefit and are doable, or otherwise require a technology champion for it that is willing to work on it, using different funding sources over many years to keep it moving forward.

- **Political Baggage with Technology Offices:** NASA struggles with "political baggage" associated with its technology offices, in addition to a lack of unification of technology and policy strategy and efforts.

4.1.6.2 Technology Development Processes

- **"Technology vs Engineering" and "Enabling vs Enhancing" Debate:** The is a constant debate facing technologies in their distinction from engineering and in their classification as enabling or enhancing. Such distinctions are critical as they shift the expected risk profile and raise different eyebrows accordingly, in terms of their "mission creep".

- **TRL and Valleys of Death:** Given the well-known break points at TRL 3 and 6 and valleys of death, and with NASA's spread-out technology development efforts at SMD (PICASSO, MatISSE) and STMD programs (Game changing, SBIR, STTR, NIAC, etc.), there is a challenge that these programs that basically go to those points and then stop might be making those valleys into almost a certainty.

- **Difficulty in Assessing Technology Needs:** NASA faces a challenge is assessing its technology needs as compared to its science needs. Science is driven by the decadal surveys, where there is a clear traceability between missions that are decided and those priorities. Technology is not amenable to the decadal process because "too much changes too fast". There has been an internal attempt, similar to the decadal process, of having a survey of what is needed and what is coming up next. However, by the time such a survey was done across the entire agency, a large portion became already obsolete. Moreover, there is a lack of clear high-level "somewhat persistent" goals.

- **Funding Uncertainty with Multiple Different Tech Push and Mission Pulls:** NASA features a lack of a more consolidated technology development funding source that is more "cradle to grave" to eliminate the hand-offs and streamline the path from low TRL to TRL six. This challenge incorporates the debate of whether NASA should (1) continue "peanut butter spreading" its resources but being open to the full breadth of good ideas that are out there and giving them all a chance, versus (2) provide a "cradle to grave" approach that reflects a more integrated consolidated technology program where one process is looking at the full technology development lifecycle, accelerating the pace of moving up the TRL scale.

4.1.6.3 Instrument Selection & Mission Process

- **Decadal Priorities:** In deciding how much technology or instrumentation is going to be put on a mission and why, one main challenge for NASA technologies is the power of the science community relative to technologists. Since most mission and instrument AO's focus on the science, a fundamental shift in philosophy is needed for proposal about what is asked for and how much (1) risk, (2) new technology, and (3) incentives for inserting new capabilities are written into the call for proposals in the first place.

- **Paradoxical Order Driven by the Ecosystem around Instruments:** Mission objectives are put out there before the instruments are selected. Then instruments get selected, followed by the landing site. However, a more efficient approach could involve taking a step back to ask, "if we go to site X, we can learn about Y, so we need a vehicle that does Z with these instruments."

- **Selection Process and Review Teams:** Another challenge is the need for the right review teams. Current review teams hold many NASA retirees, because one needs to take ~3 months off to do the selection process, so there is a lack of current experience in the selection team. Infusing more current flight experience would be helpful for technology infusion at NASA.

- **Lack of Harmonized Incentives for Tech Infusion Very Early in the Process:** Because science takes priority in selection, there is limited ability to do directive work, and thus many technologies get infused by being "shoved in" sometime later into the mission. NASA should adopt a more intentional strategy to encourage the early and effective integration of technology by providing harmonized incentives

- **Project Decision-Makers:** Technology currently lacks representation at the project level as a stakeholder, as many project management teams consist of the project manager and any deputies, the project scientist and any deputies, and the chief engineers, but no technologists.

- **Requirements Challenges:** In addition to misconceived requirements in science in some cases, one challenge that faces some technologies is PI's, project scientists, and even engineers attempting to dictate Level 4 detailed implementation requirements in the Level 3, handcuffing implementation teams.

- **Operational Issues:** Another challenge that faces many technologies is that NASA focuses resources and efforts into landing safely, for example, but provides less resources post-landing and operations. The challenge facing NASA there is how to take available resources and spread that among the program in a way that addresses total mission success, not just landing safely.

4.1.6.4 NASA versus Industry

- **Risk Posture of Iterations vs. One-off's:** When comparing NASA to industry, such as SpaceX, one notable difference is in industry's approach to technology development. SpaceX is focused on producing large numbers of vehicles through constant iteration and learning from failure, while NASA tends to focus on one-of-a-kind missions that aim to answer specific questions. This constant iteration with the expectation that the final test of each stepwise iteration may result in the destruction of the vehicle may be acceptable for industry, but is something that NASA finds challenging due to its fundamental philosophy driven by the way the decadal survey is put together and what it is asking for. Hence, if a mission fails, it was a one-shot deal trying to achieve success to answer one fundamental question from the decadal survey. Mission cases such as Spirit and Opportunity" and "Curiosity and Perseverance" that are almost twins are a rarity and an exception—not the norm.

- **Clear Taxpayer Traceability:** A big challenge that NASA faces in its technologies as compared to industry is the clear traceability of taxpayer money in its activities. Despite the amount of NASA and governmental funds that is received by industry, the traceability of the funding source in case of failures does not receive the same attention as NASA.

- **Technology Demonstrations vs. Advancement:** While NASA proves effective in demonstrating new technologies, a challenge faced there is that the industry has a better pace in carrying out this technology's advanced development compared to NASA. By the time NASA advances and infuses some technologies, the industry would have already moved on to something different.

4.1.6.5 Rideshare Tech Demos

- **Best Place to Infuse is Flagships, but:** Despite the larger amount of resources available for a flagship mission, these strategic missions create a mismatch for technology demonstrations due to the *enormous risk aversion* in that "everything must work, every time". Additionally, when the instructions that come into a project that has to marry together a science mission with technology demonstration, there is a lack of consensus and understanding at the very highest level at NASA that "nothing is free". The challenge then is that the tradeoff between mission objectives and technology infusion ends up always being done at a much lower level instead, where project teams "would hustle over it". Therefore, there has been a *lack of early partnerships and early incentives* in technology infusion on flagships, leaving it to certain champions pushing certain technologies as a "free rider", while in reality, it is not free—somebody is paying for it from pre-existing mission resources. There is a constant gap there in the understanding of the cost risk, schedule risk, off ramps, and clear guardrails for the process of infusion.

- **Cost-capped Missions Issues:** With the higher constraints in resources for cost-capped missions, the main challenges for infusing technology demonstrations on these missions are (1) the need to provide a more developed instrument, (2) the need for representation for the technology from NASA HQ/JPL to create an interface and ensure smoother flow of work, (3) the need for detailed level of specificity in contracts written between directorates such as STMD and SMD and the Project on exactly what the guardrails and decision points are, and how to appeal for extra help, and (4) the need for better early communications of requirements despite the structure of the competed proposal process.

- **Scaling-up:** Aside from the infusion of platform of flagships vs. cost-capped missions, one of the significant challenges that technology demonstrations face is the possibility that the demonstrated technology may not be advanced enough to make the leap to a scaled-up version. This concern can result in the need for additional iterations in the future, creating an additional hurdle in the development process.

- **Strategic Planning and Timelines:** Due to lack of strategic planning, many technology demonstration efforts have been 'building bridges to nowhere", especially in their extended timelines. The limited and stretched-out budgets allocated over a decade are often insufficient to showcase a technology effectively. As a result, by the time the technology is finally demonstrated, it has already undergone significant changes, rendering the previous demonstration obsolete. This situation can feel like a futile effort, akin to "spinning your wheels".

4.1.6.6 Low-cost Efforts

- **Growing Expenses and Increasing Bureaucracy:** A main challenge that can be observed in many low-cost technology programs is their increasing costs, increasing bureaucracy, and increasing risk aversion over time, defying their initial purpose.

- **Lack of Strategic Planning & Standards:** The focus on short-term plans creates a challenge for sustaining many low-cost programs due to longer-term vision that lacks strategic thought-through plans and standards.

4.1.6.7 Cultural Gaps and Oversight

- **"Failure is not an option", Taxpayer Money, and Public Image:** Going hand in hand, these three concerns create a critical challenge for technology development. NASA holds fears of its credibility decreasing in the eyes of the public, thus forcing the culture of "*Everybody is class A at the pad*". Hence NASA is often caught between two opposing forces of having to innovate and explore and having to ensure that all of its missions work.

- **Employee Environment of Fear and Lack of an Appetite for Institutional Change:** A core challenge, especially for veterans of failed missions, is the fear of repeating failures because the teams associated with failures tend to pay a heavy price. Hence this notion of "taking the head" creates a culture where people talk about accepting risk until "their neck is on the line". The lack of rewards and incentives for investigators and project managers to include newer capabilities and upgraded capabilities as a standard part of what is done is a clear challenge for innovative technologies. Such a challenge would not be overcome until these experiences are replaced with a different reality that says, "risk really is acceptable, and innovation, which comes with a higher level of risk, is okay, and if you get bit by the probabilities of failure of one in three, one in 10, you will not be punished, but instead you will be given another shot to balance it out again."

- **Constant Balance between Executing with Rigor and Ensuring Quality:** Over the years, NASA's evolving versions of 7120.5 have led to cultural changes that pose a challenge for technology development. Balancing the need for rigor and quality assurance can be difficult in the face of increasing bureaucratic processes. Although such processes can be helpful in some cases, they can also be perceived as a way to make project management "idiot proof", as some at NASA have described. These exhaustive procedures can be a hindrance to technology development, encouraging a "check box" mentality instead of a true understanding of the underlying rationale for the procedures, which can be risky.

In summary, NASA's planetary technology development programs are currently facing critical challenges. Identifying these challenges not only facilitates the implementation of solutions for new and innovative technologies but also helps maintain capabilities and workforce for technologies that may not be currently in demand. By acknowledging these challenges, NASA can nurture the technology ecosystem and support a broader range of capabilities beyond technical factors.

4.2 Research Question #2

4.2.1 Identified Pain Points

Different interviewees identified different pain points within the enterprise, as anticipated. Over the course of the interviews conducted, a few themes became clear. These themes developed into a final list of three pain points, outlined below, that the research attempts to address with proposed architectures.

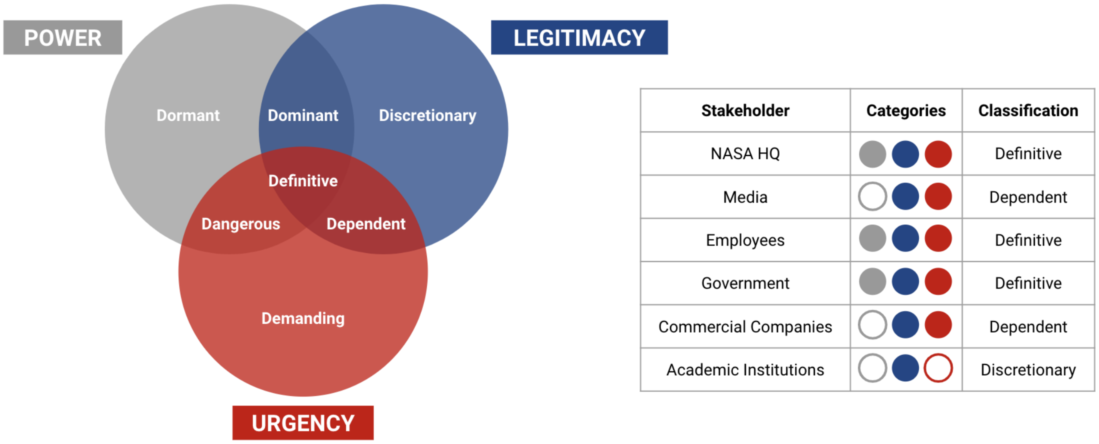
- Financial architecture
- Communication: internal, external, and IT-related
- Cybersecurity

As mentioned before, the power of the project managers to control project budgets creates a source of tension within the matrix organization, both between the lines and projects and between the projects and senior leadership. When project managers control their entire budget, they don't have to follow JPL's strategic goals or prioritize money for multiple interests, but generally prioritize their project alone. Since their primary goal is successful operation of their hardware into space, this results in project managers spending a lot of time and effort on building redundancy. This money could be spent elsewhere in a way that better benefits all of JPL rather than just one project. These issues all stem from the project manager's power over money, which developed into the first pain point listed, "financial architecture."

A few people we interviewed mentioned that communication with other NASA centers was a concern, and a few others mentioned that communications with external collaborators (academic institutions and commercial companies) were a concern. In addition, communication for information technology was also identified as a major issue, since information within JPL is difficult to find and share. Part of this stems from the previously mentioned fact that access to information is usually restricted to specific groups of people, such as the people working on a specific project. This results in a situation where a new project is not able to access information that could be useful for them from previous projects that could be useful to them. For example, when the Mars 2020 project began, they would not have access to information about previous similar projects like the Curiosity rover, which resulted in duplicated work. The root cause of these problems boiled down to communication, which led to the second pain point, "communication: internal, external, and IT-related."

Finally, a few JPL employees mentioned that cybersecurity is a major concern for the organization. JPL works on many sensitive projects that could easily be threatened by minor design changes. JPL is already working to hire more cybersecurity specialists; this concern represented such a serious risk that it developed into the final pain point: "cybersecurity."

4.2.2 Stakeholder Analysis



Stakeholder	Categories	Classification
NASA HQ	● ● ●	Definitive
Media	○ ● ●	Dependent
Employees	● ● ●	Definitive
Government	● ● ●	Definitive
Commercial Companies	○ ● ●	Dependent
Academic Institutions	○ ● ○	Discretionary

Figure 34. JPL Stakeholder Analysis.

Many stakeholders interact with JPL. *Figure 34* presents the main identified stakeholders as NASA Headquarters, the media, JPL employees, the government, commercial companies, and academic institutions. While analyzing each of these stakeholders and their relationship with JPL, NASA Headquarters, JPL employees, and the government stood out as “definitive” stakeholders. These stakeholders have a relationship that combines the power, the legitimacy and the urgency in defining JPL's decisions and course of actions. The media and commercial companies were both identified as "dependent" stakeholders, which means they have a relationship that combines legitimacy and urgency, but not the power to define what JPL does or affect it in comparison to the other stakeholders. Finally, academic institutions fell under the “discretionary” stakeholder group, which means they have a relationship that includes legitimacy but does not include the power or urgency that other stakeholders have.

4.2.3 Internal Landscape

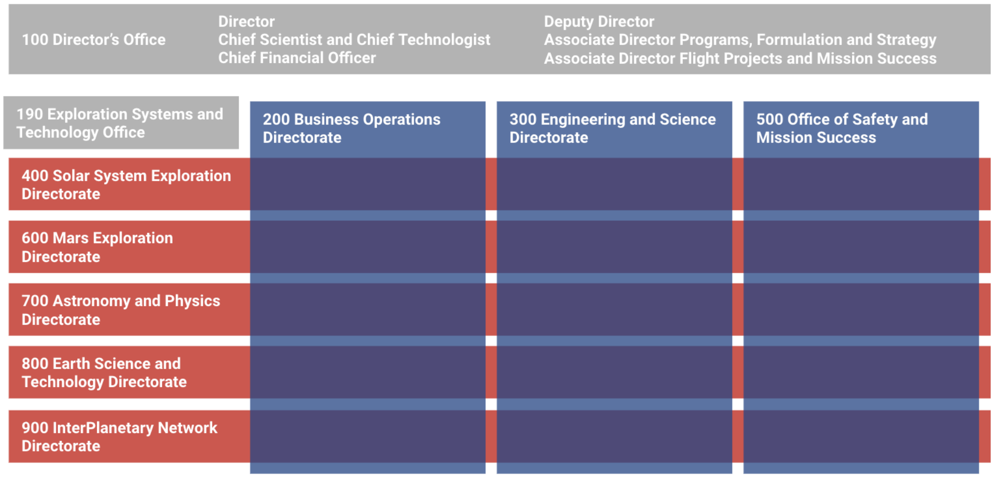


Figure 35. The JPL Matrix. Adapted from (Baroff, 2006)

JPL, like many large technical enterprises, uses a matrix structure to organize employees. *Figure 35* shows the internal layout of JPL's matrix, in which project management groups (called "projects" for short) are shown in red and functional/service management groups (called "lines" for short) are shown in blue. The groups shown in the figure are divided into many subgroups: for example, within 300 Engineering and Science Directorate there exists subgroup 347C Robotics Mechanical Engineering. The project groups also consist of subgroups: for example, the Mars 2020 Rover project sits within group 600 Mars Exploration Directorate. Outside of the project-line matrix, there is one group: 190 Exploration Systems and Technology Office. The Director's Office sits above the matrix and provides high-level management as well as a single vision for the organization.

This structure assigns each employee to at least two managers: one project manager and one line manager. It is possible for employees to have more than two managers, since employees usually work on multiple projects at a time, meaning they would have a project manager for each project they work on. While this type of internal structure is common and can be useful, "the disadvantage of matrix organizations is the possibility of conflict between project management and functional group management" (Baroff, 2006). Interviews with current JPL employees confirmed that there is conflict between lines and projects, including how time and money are allocated and managed. A particular point of tension stems from the management of money: projects managers (PMs) are responsible for their own budgets, but line managers do not have a say in project budgets. Interviews revealed that JPL used to have a "PM of the PMs" who was responsible for overseeing all the project managers, aligning their decisions with the strategic vision of the enterprise. This position no longer exists but is being discussed by internal stakeholders with the possibility of bringing it back.

4.2.4 Proposed Architectures and SWOT Analysis

Using the pain points identified through interviews with JPL insiders, four potential architectures were conceptualized, each designed to target specific points.

The first architecture created was nicknamed Partnership Manager and was designed to focus on improving JPL communications with external collaborators, such as commercial and academic entities. In this architecture, a new position or responsibility would be created within JPL, and those assigned would oversee all external communication for the lab. This architecture also involves the support structure necessary to make this new role more effective. Relevant individuals who are currently doing contract or external work must be identified and brought in to contribute. We thought that having a single, consolidated port for communications would reduce confusion and make it easier for information from collaborators to be quickly and widely disseminated to stakeholders. The eventual goal of the architecture would be to have all contracts go through the partnership office to ensure that they all achieve overall JPL strategies and innovation objectives. The Foundry (the innovation center of JPL) must be incorporated into this new architecture to ensure that the partnership office is aware of all projects that are occurring throughout the organization.

The second architecture created was nicknamed Chaotic 2.0. In 2005, JPL's Chief Information Officer (CIO) Jim Rinaldi introduced the first chaotic architecture to consolidate data and allow users to create and use their own tools to interpret data. Chaotic is a "data-first" architecture that ensures data is protected and reusable while allowing enough freedom and flexibility for technical experts to use the data in manners that they see fit. The focus of our proposed Chaotic 2.0 architecture is to expand upon the basic framework of the original chaotic architecture and incorporate more digital engineering and model-based systems engineering (MBSE) to improve data sharing. Currently, there are communications gaps between divisions, and employees do not know what their colleagues in different projects and lines are currently working on. Data is often replicated and stored in locations that are hard to access by everyone. The new IT communications and data infrastructure required by the architecture would synchronize all divisions and allow for better coordination across all projects. Changes made in higher tiers of the organization would be quickly and widely replicated within the lower tiers for easier change management. However, the freedom and flexibility of the chaotic architecture would still be available as individuals would still be able to leverage the tools they are most comfortable with.

The third architecture created was nicknamed the PM of PMs. In this context, PM is an acronym for project manager. This architecture was designed to focus on improving strategy implementation and organizational communication for the lab. It would require a new financial and managerial position that is primarily focused on innovation. The new PM of PMs role would be in control of all finances to increase accountability and alignment of resources to the overall lab's strategic goals. By reducing individual PM autonomy, more managerial power would be given to line managers than to project managers. Certain financial incentives would be put in to place to encourage innovation, strategy implementation, and communication. These financial incentives could be used to influence employee behaviors and incentivize them to adopt digital engineering. The overarching goal of this architecture is to facilitate an internal culture change to encourage better communication among divisions within JPL and discourage the prevailing mindset of only managing individual projects.

The fourth architecture created was nicknamed the Perfect Architecture and is essentially one that incorporates all the main components of the three previously proposed architectures. A PM of PMs would oversee finances and resource management. That role would also incorporate the partnership manager responsibilities of standardizing and streamlining communications with external collaborators. Additionally, a Chaotic 2.0 communication and data infrastructure would facilitate the synchronization of divisions and further encourage increased organizational coordination.

To evaluate the four architectures, each was analyzed based on their strengths, weaknesses, opportunities, and threats (SWOT). Strengths refer to the characteristics of the architecture that give it an advantage over others. Weaknesses refer to the characteristics of the architecture that place it at a disadvantage relative to others. Opportunities refer to the elements in the environment that the architecture could exploit to its advantage. Finally, threats refer to the elements in the architecture that could cause trouble for it in the future. *Table 6* presents the SWOT analyses for all four architectures:

Table 6. SWOT Analysis of Proposed Architectures

Architecture 1: Partnership Manager	**Strengths**	• Functional integration • Aligns individual project with overall JPL goals/strategies • Archive information (keep track of technology developments) • Forces status updates and schedule/cost management • Dual responsibility of quality control and responsibility management

	Weaknesses	• New roles and responsibilities for workers that may already be overloaded with work • More work for project teams - need to submit reports, more oversight • Initial confusion and resistance • Remove flexibility that PMs currently have
	Opportunities	• Can streamline technology transfer and licensing • Keep everyone updated on what's going on • Could accelerate work, identify problems early on and create initial strategy
	Threats	• May delay work • External organizations may go to other research organizations because the process is too much work for them to adapt to
Architecture 2: Chaotic 2.0	**Strengths**	• Increase communication between divisions • Help in effective data management • Ease burden on future projects - past work is more accessible and usable • Better documentation, better change management
	Weaknesses	• Data privacy (non-standard solution) and Data Security - Single point of failure • Reliance on One tool - Only one way to conduct operations, no other choice or redundancy • Integration/interface with other data source • Resistance to change - high learning curve, split adoption (younger generation will use, older gen won't)
	Opportunities	• Further conversation and collaboration among divisions • Efficiency in data management
	Threats	• Hardware culture that is resistant to software mindset • Increased risk of unwanted interference - security must be increased • Increased cybersecurity risk

Architecture 3: PM of PMs	**Strengths**	• All projects are aligned with JPL's overall success • Resource synchronization across all lower-level PMs • Incentivize innovation through financial leverage • Reduce duplicates, better data management • Streamline processes, optimization of single structure once established
	Weaknesses	• More managerial bureaucracy - more upper-level management • Training and communication cost after implementation • More overhead cost upfront - establishing new entity, hiring more people • Changes to daily operation - finance route completely changed; data management methods revised • Resistance to change - Legacy • Potential power dynamics • Could discourage grassroots innovation (people are incentivized to pursue their own funding for new ideas)
	Opportunities	• Exploit centralized power to pursue goals of organization • New sponsors/projects who prefer new architecture
	Threats	• Sponsors/Projects go to other organizations due to process changes
Architecture 4: Perfect Architecture Note: The SWOT Analysis for this is simply a combination of all the points from the three previous architectures.	**Strengths**	• Functional integration • Aligns individual project with overall JPL goals/strategies • Archive information (Keep track of technology) • Forces status updates and schedule/cost management • Dual responsibility of quality control and responsibility management • All projects are aligned with JPL's overall success • Resource synchronization across all lower-level PMs • Incentivize innovation through financial leverage • Reduce duplicates, better data management • Streamline processes, optimization of single structure once established • Increase communication between divisions

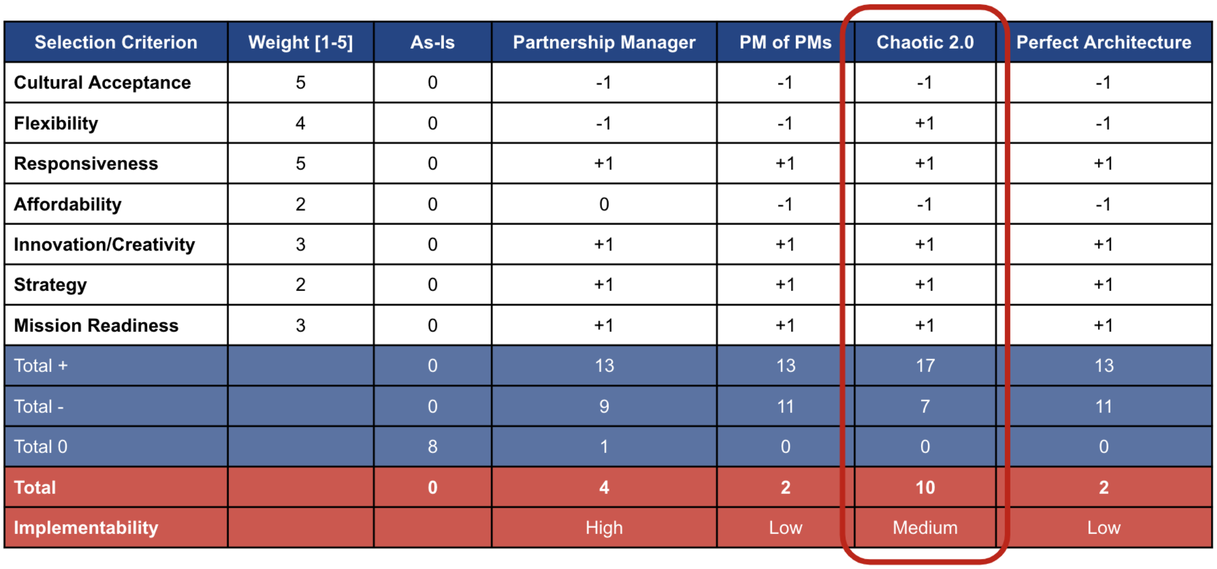
		• Help in effective data management • Ease burden on future projects - past work is more accessible and usable • Better documentation, better change management
	Weaknesses	• New roles and responsibilities for workers that may already be overloaded with work • More work for project teams - need to submit reports, more oversight • Initial confusion and resistance • Remove flexibility that PMs currently have • More managerial bureaucracy - more upper-level management • Training and communication cost after implementation • More overhead cost upfront - establishing new entity, hiring more people • Changes to daily operation - finance route completely changed, data management methods revised • Resistance to change - Legacy • Potential power dynamics • Could discourage grassroots innovation (people are incentivized to pursue their own funding for new ideas) • Data privacy and security issue (non-standard solution) • Solution reliability • Integration/interface with other data source • Resistance to change - high learning curve, split adoption (younger generation will use, older gen won't)
	Opportunities	• Can streamline technology transfer and licensing • Keep everyone updated on what's going on • Could accelerate work, identify problems early on and create strategy • Exploit centralized power to pursue goals of organization • New sponsors/projects who prefer new architecture • Further conversation and collaboration among divisions • Efficiency in data management
	Threats	• May delay work • External organizations may go to other research organizations because the process is too much work for them • Sponsors/Projects go to other organizations due to process changes

		• Hardware culture that is resistant to software mindset • Increased risk of unwanted interference - security must be increased • Increased cybersecurity risk

4.2.5 Downselecting

To downselect to an overall ‘winner’ from the four proposed architectures, the following scoring metrics were used:

- **Implementability** - How easily can this architecture be implemented into the existing institution?
- **Cultural Acceptance** - How easily will the architecture be adopted by the people and culture of the existing institution?
- **Responsiveness** - How quickly will communication flow in this architecture?
- **Flexibility** - How easily could the power/dynamics of the architecture respond to change?
- **Affordability** - How affordable will it be to implement and operate this architecture?
- **Innovation/Creativity** - How much innovation/creativity and knowledge creation will this architecture promote within the organization?
- **Strategy** - How much alignment does this architecture have with the long-term strategy of the institution?
- **Mission Readiness** - How easy will it be for this architecture to produce quality deliverables on time?



Selection Criterion	Weight [1-5]	As-Is	Partnership Manager	PM of PMs	Chaotic 2.0	Perfect Architecture
Cultural Acceptance	5	0	-1	-1	-1	-1
Flexibility	4	0	-1	-1	+1	-1
Responsiveness	5	0	+1	+1	+1	+1
Affordability	2	0	0	-1	-1	-1
Innovation/Creativity	3	0	+1	+1	+1	+1
Strategy	2	0	+1	+1	+1	+1
Mission Readiness	3	0	+1	+1	+1	+1
Total +		0	13	13	17	13
Total -		0	9	11	7	11
Total 0		8	1	0	0	0
Total		**0**	**4**	**2**	**10**	**2**
Implementability			High	Low	Medium	Low

Figure 36. Pugh Matrix Comparing Proposed Architectures.

In the downselection process, a Pugh matrix was used, as shown in *Figure 36*, to score each architecture based on the chosen metrics. Cultural acceptance, responsiveness, and flexibility were weighted as the top three evaluation metrics, because weighting these evaluation metrics higher captured the importance of having a new architecture that targets the pain points identified through interviews with JPL insiders, while also considering the probability of success for the architectural change.

As seen in *Figure 36*, the PM of PMs architecture and Perfect Architecture came out with the lowest score, mostly due to low scores on cultural acceptance, flexibility, and affordability. We foresaw significant employee backlash because the status quo would be shaken up with organizational and process changes necessary for those architectures. Additionally, putting more controls with a higher-level project manager leads to more structure and therefore less flexibility, which may contradict JPL's tendency toward a flat hierarchy. To top it all, making these institution-wide changes would require a significant financial commitment, because new people would need to be hired and new equipment would need to be purchased.

Compared to other architectures, the Chaotic 2.0 architecture was evaluated to provide more flexibility than the current and the other proposed architectures because streamlining the digital process and increasing communication would allow individual entities to do as they see fit with the data and tools at their disposal. Due to increased coordination, different entities could make changes without worrying about the time and communication frictions from the current architecture. Additionally, changes would be quickly and clearly propagated throughout the system. Especially since flexibility was weighted so highly in the Pugh matrix, Chaotic 2.0 resulted in a point advantage over the alternate architectures.

4.2.6 Pain Point Analysis

A pain point analysis was conducted using a X-matrix to identify potential issues between the metrics, key processes, stakeholder values, and strategic objectives used by JPL within the proposed Chaotic 2.0 architecture.

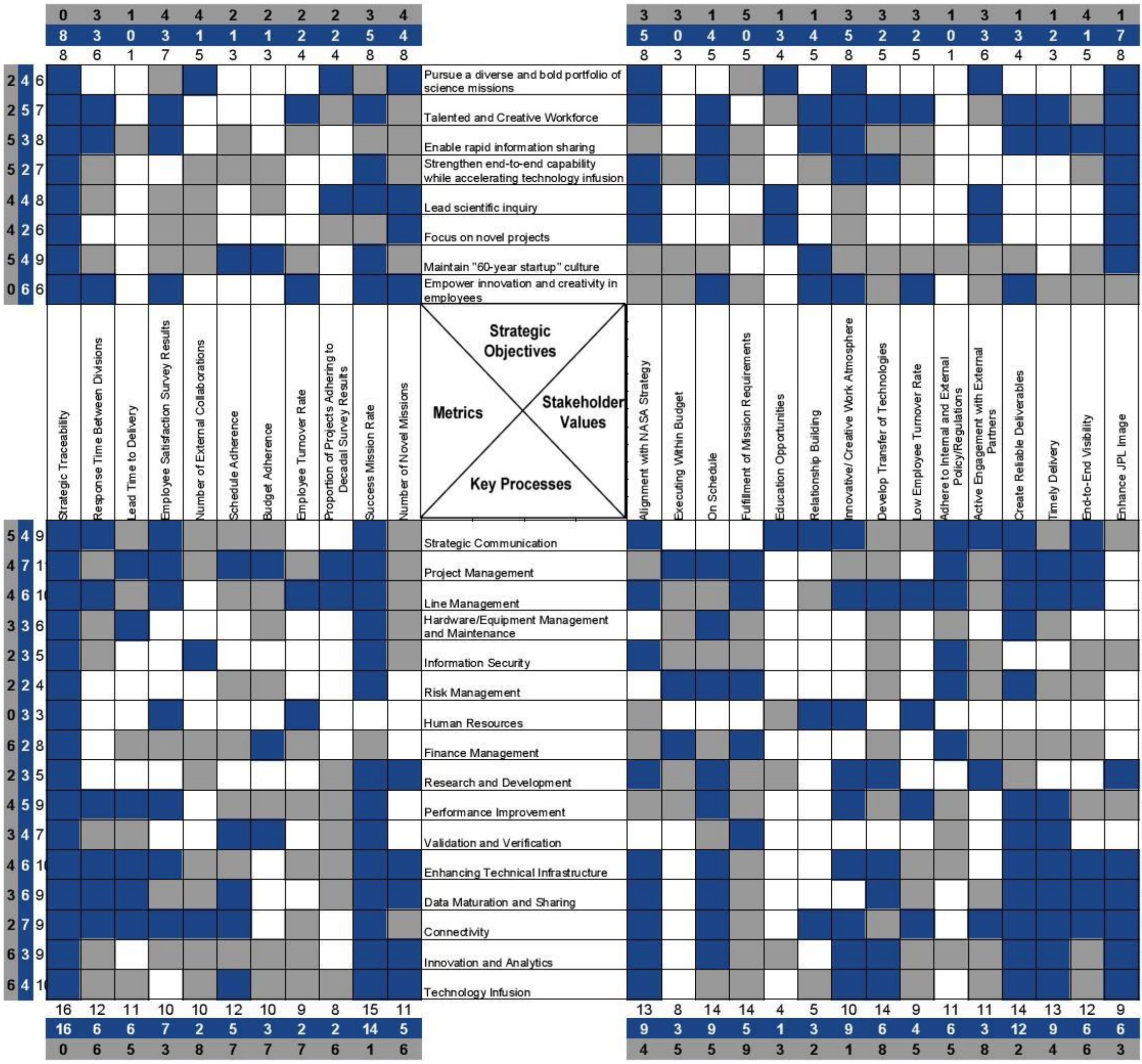


Figure 37. X-Matrix for Chaotic 2.0 Architecture.

As seen in *Figure 37*, JPL overall has strong links between strategic objectives and stakeholder values along with strong links between key processes and stakeholder values. Those two quadrants have a wide spread of both weak connections (indicated by gray boxes) and strong connections (indicated by blue boxes), with relatively few non-existent connections (indicated by white boxes).

With the Chaotic 2.0 architecture, there are strong connections dispersed throughout the matrix, which indicates that the proposed architecture could target pain points relatively effectively. Strong connection with strategic traceability and communication and integration shows that ensuring everyone is on the same page is crucial to achieving strategic objectives. This is exactly what the Chaotic 2.0 architecture was designed to achieve. Additionally, processes that lead to project success (project management, line management, connectivity), along with processes that enhance technology, performance, and innovation are all strongly linked with timely delivery of reliable deliverables. This shows that good management, communication, and connectivity, along with enhanced technology and innovation are good contributors to successful and on-schedule projects.

Figure 37 also shows that there are some improvements that could be made when integrating Chaotic 2.0 into JPL's structure. Information security and risk management processes do not have many connections with stakeholder values, which could be an issue in the future when IT infrastructure and data become more critical to everyday operations and organizational security. Stakeholders should prioritize these values in the future of the organization.

4.2.7 Implementation Plan

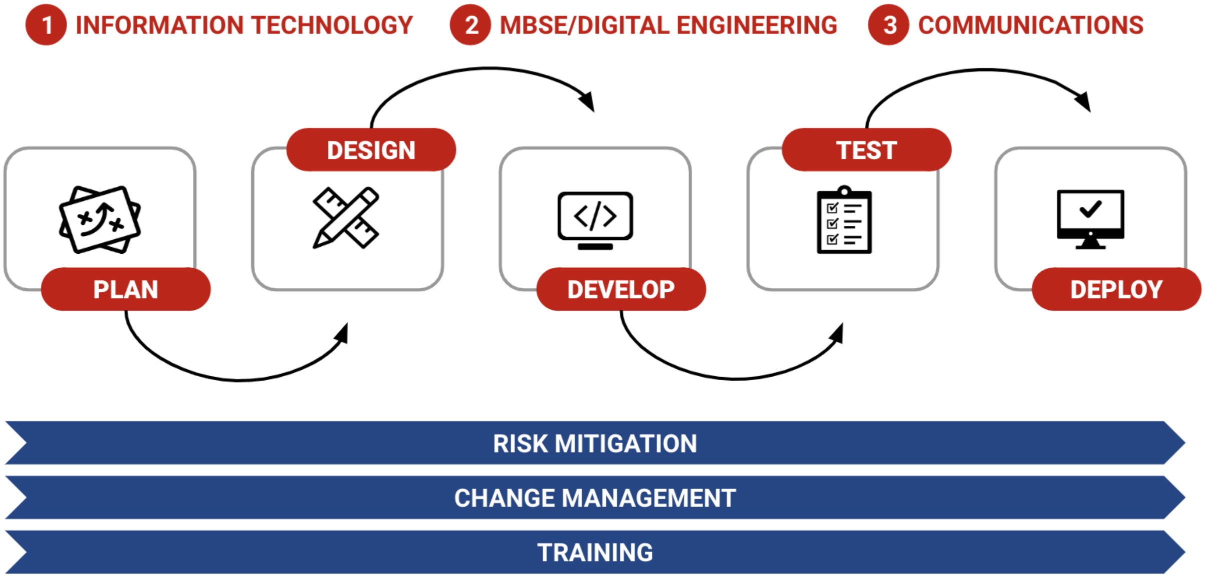


Figure 38. Strategic Implementation Plan for Chaotic 2.0 Enterprise Architecture.

A clear implementation strategy is critical to the success of the new proposed enterprise architecture. If the implementation goes poorly, the likelihood of employees accepting the change decreases significantly.

The strategy for implementation is shown in *Figure 38*. Since the Chaotic 2.0 architecture focuses mostly on software implementation, we will use the software development lifecycle (SDLC) as the basis for our implementation plan. This cycle includes five phases: plan, design, develop, test, and deploy. These phases will be applied to the three areas that were identified as areas of improvement: information technology (IT), model-based systems engineering (MBSE) + digital engineering, and communications. Information technology would require one type of software to be implemented, and SDLC will be suitable for this. MBSE and digital engineering will require a separate software, which JPL is currently developing in-house, and which can also be implemented following SLC. For communications, software is not a necessity, but following the phases in SDLC will help to articulate a clear strategy and vision for communications.

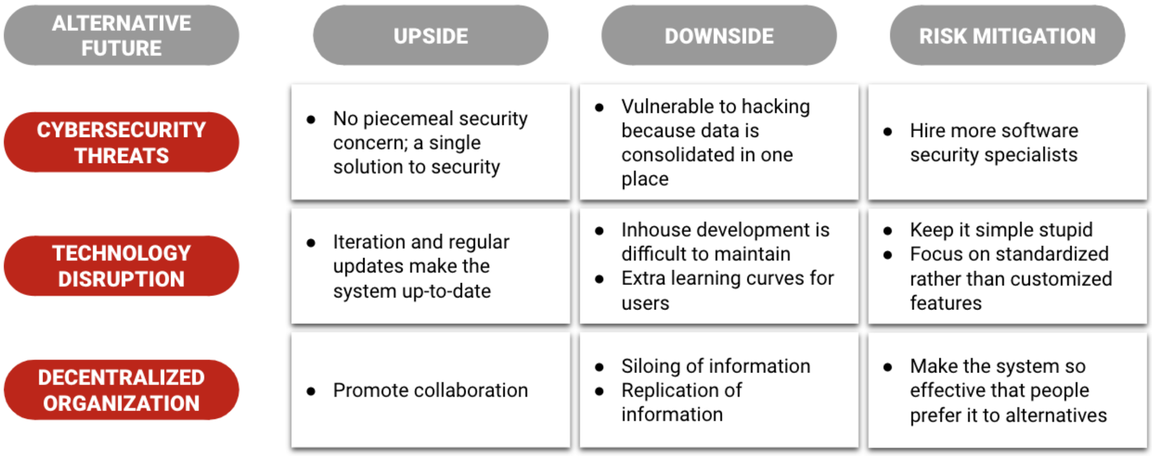
With any large cultural change, especially when including software, resistance is inevitable. To maximize the success of the process, three foci will run parallel to the SLDC throughout implementation: risk mitigation, change management, and training. These three foci will provide consistency throughout the project and help ensure cultural acceptance of the architecture change.

Risk mitigation will identify potential risks to the implementation of the architecture and develop a mitigation plan to deal with them. This process will be ongoing and will continually work to identify new risks as the project progresses.

To minimize internal resistance, a change management team will work to identify project champions and change leaders. A project champion is someone in a leadership role who is responsible for supporting the project both within the project team and externally to the rest of the organization. This person's leadership gives them the credibility and power to influence the organization to support the project, which significantly increases the probability of success and acceptance. One recommended project champion would be the Deputy Director of JPL. Since an enterprise architecture change would affect how JPL operates, this project would fall under the Deputy Director's responsibility of overseeing all business operations. Previous Deputy Director of JPL, Larry James, for example, has already led key initiatives during his tenure at JPL, including a signed open data policy that would make JPL data available to all employees. Previously, an employee could only access data for the projects and lines they were part of. James believed that an organization cannot stay static and be successful, so he worked on making the enterprise actively change in ways that would bolster its success. In addition to a project champion, the change management team would identify change leaders, who are people with natural or structural leadership within the organization that can champion the project and influence their groups to support it. These people play a key role in ensuring cultural acceptance of the project.

The final focus throughout implementation would be on training. Training is vital to a change becoming sustainable because people will have to adapt to new processes and, in this case, new tools. Training would include both how to operate the new tools, as well as how to follow the new processes such as strategic communications. Including risk mitigation, change management, and training throughout the implementation process will support the success of the project.

4.2.8 Future-Proofing



ALTERNATIVE FUTURE	UPSIDE	DOWNSIDE	RISK MITIGATION
CYBERSECURITY THREATS	• No piecemeal security concern; a single solution to security	• Vulnerable to hacking because data is consolidated in one place	• Hire more software security specialists
TECHNOLOGY DISRUPTION	• Iteration and regular updates make the system up-to-date	• Inhouse development is difficult to maintain • Extra learning curves for users	• Keep it simple stupid • Focus on standardized rather than customized features
DECENTRALIZED ORGANIZATION	• Promote collaboration	• Siloing of information • Replication of information	• Make the system so effective that people prefer it to alternatives

Figure 39. Upsides, Downsides and Risk Mitigation for Alternative Futures.

To test how the Chaotic 2.0 architecture would adapt to different futures, we did a future-proofing analysis based on three different envisioned futures, each featuring cybersecurity threats, technology disruption, or decentralized organization respectively, as shown in *Figure 39*.

In the first scenario of cybersecurity threats—a problem that JPL is already concerned about in security management of their data— the Chaotic 2.0 architecture will provide an upside of being a platform for a single solution security with no piecemeal security concerns. On the downside, however, since Chaotic 2.0 would be heavily dependent on digital engineering transformations, it would be vulnerable to hacking, especially because the data is consolidated in one place. One method of mitigating this risk in the future is hiring more software security specialists who could better handle the potential problems involved. In fact, JPL is already working to hire more security specialists in an attempt to mitigate growing cybersecurity threats.

The second scenario of technology disruption involves a case where, for example, a new software is developed that could make the implemented software either less effective or completely obsolete. This future scenario is a significant concern because obsolescence is a concern in all software implementations. The Chaotic 2.0 architecture will have an upside of providing the ability to implement regular updates to continuously update the capabilities of the system, which is becoming a standard offering in the current software implementation market as more companies move to cloud-based software. However, on the downside, this architecture will introduce two main complexities: the difficulty of maintaining the in-house development of the digital programs, in addition to the complexity of the additional learning curves and training required for users. JPL is already working on an in-house software for MBSE, which may incur significant cost, be difficult to update, and be difficult to learn. Mitigating such a future risk could potentially involve following the software engineering motto of "keep it simple, stupid"— focusing on standardized rather than customized features in the software. This means that if 20 teams at JPL are performing integration testing, they would all use the same process rather than customized processes for each team, because it would minimize complexity in the system and minimize the learning curve needed as new members joined the team.

The final scenario we considered involved having a more decentralized organization. Currently, JPL has a relatively flat hierarchy, since they are an R&D-focused technology organization. However, a possible decentralization in the organization is very possible in the future, since the organization prioritizes creativity. In such a future scenario, the Chaotic 2.0 architecture will provide an upside of being able to promote collaboration throughout its platform. However, on the downside, this architecture might risk siloing or replicating information if handled wrongly, since a decentralized organization could lead to individual teams moving data from the centralized storage location and the centralized software. The ideal mitigation of such a risk would be trying to make the system as effective as possible to the point that staff would prefer it to alternatives. While this mitigation would be difficult to ensure, if done properly, it would prevent teams from siloing their data.

4.2.9 Epochs

The epochs outline future phases of JPL's enterprise architecture. In our analysis presented in *Figure 40,* we decided to start with the Chaotic 2.0 architecture for the first epoch, since it was the most favored architecture as determined by previous analysis. This first epoch would focus on data, IT development and digital engineering, in addition to the communications within divisions at JPL. In the next phase, the second epoch would build upon the Chaotic 2.0 and add the PM of PMs architecture to it. Thus, this epoch will involve, on top of the digital engineering implementation, an addition of high-level financial and management power to better allocate resources in a way that forces projects to be better aligned with JPL's strategic goals. Finally, the third epoch will involve the addition of the Partnership Manager architecture on top of the Chaotic 2.0 and PM of PMs architecture, forming the full "Perfect Architecture" at JPL. This last epoch will thus capture the commercial and academic partners as well.

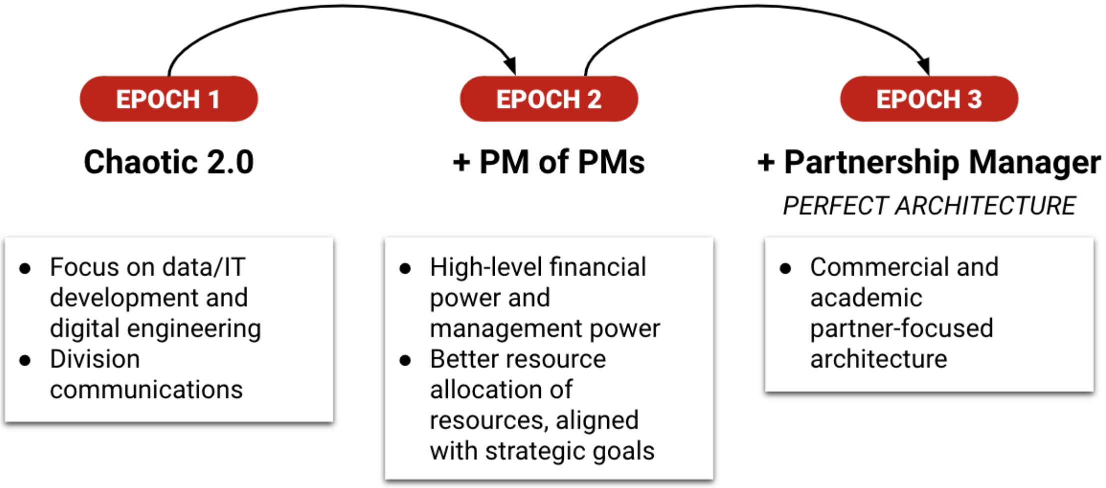


Figure 40. Future Planning of Epochs.

Chapter 5: Conclusions

5.1 Findings and Implications

This research has provided a comprehensive understanding of the challenges and opportunities for innovation in planetary exploration technology at NASA, from various perspectives such as institutional, strategic, policy, and legal. Throughout a deep-dive analysis of six technology case studies, this research analyzed NASA's enterprise architecture and its technology investment, development, and maturation frameworks through different eras, and uncovered its current management and program challenges for the efficient development and integration of innovative planetary exploration technologies.

The challenges were categorized into two main groups: policy and structural challenges and cultural challenges. The policy and structural challenges include issues of oversight, pipeline between technology development and mission needs, technology development process, relationship to industry, instrument selection, mission process, technology demonstration infusion and scaling, technology representation, etc. The cultural challenges fall under the theme of "failure is not an option," taxpayer money, public image, employee environment of fear, and lack of appetite for institutional change. The identified challenges include a lack of strong system of systems engineering, a lack of connection between projects and technologies, political baggage associated with technology offices, difficulty in assessing technology needs, funding uncertainty with multiple different technology pushes and mission pulls, power of the science community relative to technologists, paradoxical order driven by the ecosystem around instruments, and the need for the right review teams. The thesis highlights the need for a fundamental shift in philosophy to incorporate new technology, incentives for inserting new capabilities and risk into the call for proposals.

The research also assessed the specific difficulties for NASA's Jet Propulsion Laboratory (JPL) and suggested the changes to its enterprise architecture in order reinstill innovation at JPL as a "60-year-old startup". The research identified three pain points at NASA JPL—financial architecture, communication (internal, external, and IT-related), and cybersecurity—which were addressed with the proposed architectures. Four potential architectures were conceptualized, and each was submitted to a SWOT analysis and scored based on various metrics such as implementability, cultural acceptance, responsiveness, flexibility, affordability, innovation/creativity, strategy, and mission readiness. The Chaotic 2.0 architecture was found to provide more flexibility than other architectures due to increased coordination, allowing different entities to make changes without worrying about time and communication frictions. A pain point analysis was conducted using a X-matrix to identify potential issues within the proposed Chaotic 2.0 architecture. An implementation strategy was provided based on the software development lifecycle. Future-proofing analysis was conducted based on three different envisioned futures, and the epochs were used to outline future phases of JPL's enterprise architecture. This research's findings provide valuable insights and recommendations for enhancing technology innovation and management within NASA and the broader space sector.

5.2 Sources of Error and Plans to Mitigate Error

There are several potential sources of error that could threaten the validity and reliability of the research—where "reliability" refers to whether the research findings are reproducible by the researcher or others and “validity” refers to whether the research findings accurately reflect reality (Campbell & Stanley, 2015).

One threat to the construct validity—the quality of operational approaches used to measure a concept—of the study is the lack of access to multiple sources of evidence on some of the collected data, or receiving different answers on certain topics, which is in turn was used in the analysis section of this research (Campbell & Stanley, 2015; LeCompte, Analyzing Qualitative Data, 2000; Creswell & Miller, 2000; LeCompte & Goetz, Problems of reliability and validity in ethnographic research, 1982). This issue was observed, for example, when high-level executives did not often identify the same process problems as the lower-level employees throughout the interviews. To address these potential sources of error, the research kept information input diverse to identify the most salient problems. The research also identified the cases with more limited access and consulted respective experts to support the work’s validity by reviewing existing evidence and providing any additional needed documentation and detail for triangulation.

Another possible source of error that may threaten the internal and external validity of the research is that the process entails finding emerging patterns and generalizing from specific technology case studies to the general context of NASA’s planetary exploration technologies (Campbell & Stanley, 2015; LeCompte, Analyzing Qualitative Data, 2000; Creswell & Miller, 2000; LeCompte & Goetz, Problems of reliability and validity in ethnographic research, 1982). Other sources of error could include access to inaccurate versions or interpretations of some of the policy or legal documents. To mitigate that, the research has mainly relied on official international and governmental documents, in addition to peer-reviewed and published papers and books.

Regarding the reliability of the research, one potential source of error is the potential personal bias of the researcher while compiling interviews to identify NASA’s challenges or while proposing the new proposed architectural changes for JPL, given different levels of involvement with JPL before the research (Campbell & Stanley, 2015; LeCompte, Analyzing Qualitative Data, 2000; Creswell & Miller, 2000; LeCompte & Goetz, Problems of reliability and validity in ethnographic research, 1982). However, the research has relied on methodological analysis and evaluation tools, in addition to thorough documentation of the process to omit potential personal bias, keeping targets clear to remove subjectivity as much as possible.

There are additionally a number of limitations to this work, such as whether the choice of the case studies was adequately representative of the remaining planetary exploration technologies that could be considered and studied. An additional limitation is the scope of the enterprise architecture analysis for JPL and the drawn system boundary, in addition to the complexity of involved stakeholders for picking the weights of the “ilities” used in the down selection process of proposed architectures. Expanding the number of interviews used to get the weighted values could potentially yield different results. The analysis tools used were only helpful to an extent, as they themselves would not present the best solution, which could only be identified through thorough discussion and deep understanding of the organization. Utilizing the tools, thus, involves a level of subjectivity. Finally, this research does not include all NASA’s centers and themes of work—but rather is focused on JPL and NASA’s planetary exploration technologies.

5.3 Future Work

The main next steps for future research continuing this work are incorporating additional interviews, documents, and expanding the work outside of a JPL focus. Moreover, the CLPS program and other upcoming NASA missions and programs present a myriad of new case studies that can be further expanded upon. Once CLPS missions start flying, it will be possible to evaluate their successes and shortcomings. Furthermore, pilot studies could be conducted on the proposed architectures for JPL to evaluate their impact in the laboratory and assess their effectiveness. Such an evaluation would inherently create new opportunities for future research that builds up on previous architectures and proposes new ones, based on more informed studies.

PART II: A Policy Framework for Sustainable and Equitable Space Resource Utilization

Chapter 6: Introduction and Background

This chapter provides an introduction to space resources and their importance, followed by a literature review and recap on colonial and imperial practices on Earth and their impact on perpetuating current global inequity. Then, the current parallels of this colonial mindset in the space dialogue are reviewed, especially using specific examples for resource utilization. The goal is to show how scientific endeavours for pushing our limits of understanding of the universe can come into conflict with the current solely colonial narrative surrounding space exploration and resource exploitation plans and policies. This chapter draws on various sources in literature to define the notions of sustainability and equity as they pertain to this research. It then outlines the defined research objective, questions, and motivation. This chapter stresses the importance of involving history, philosophy, socio-economic studies, and political evolution in the space discourse. Furthermore, this chapter highlights some of the opposing ideas to this approach from those who perceive that the concerns raised will hinder the future of human space exploration.

6.1 Problem Statement and Objectives

6.1.1 Problem Statement

6.1.1.1 Introduction to Space Resources

“Mining the Sky”, a catchy science fiction notion, is now becoming a reality and the topic of a heated debate in the space sector. Space offers a rich and diverse set of resources that could be utilized for both astronaut life support systems and space structures, and for mining and bringing valuable materials back to Earth.

In space, the concept of in-situ resource utilization (ISRU), "living off the land," is crucial for future missions, especially for human exploration of celestial bodies like Mars. By utilizing Martian resources, for example, ISRU can produce resources for long-term missions instead of carrying resources from Earth. Multiple ideas for ISRU exist, including using atmospheric carbon dioxide to produce oxygen, ice beneath the surface for water, or combining the two to produce methane and oxygen for rocket propellant (Rapp, 2018; Drake, 2009; Nier & McElroy, 1997; Muscatello, et al., 2016; Ash, Dowler, & Varsi, 1978; Gilbert, 2021). In addition to rocket propellants, sub-surface ice and water on planets and asteroids can be crucial for life support activities such as drinking and radiation protection, at a lower price than the estimated $3 million per ton on water to Low Earth Orbit (and significantly higher to other locations) with the currently cheaper commercial launches (Elvis, 2021; Gilbert, 2021). Moreover, space resources such as iron (Fe) and nickel (Ni) metals can be very valuable for in-space manufacturing, construction or maintenance activities of satellites, space stations, and launch infrastructure (Elvis, 2021; Sanchez, et al., 2021; Sivolella, 2019).

Most recently, the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE), aboard the Mars 2020 mission Perseverance rover, has demonstrated, for the first time, In-Situ Resource Utilization

(ISRU) on another planet by creating oxygen from the Martian atmosphere (Hecht, et al., 2020). This is a major step, setting the path forward to larger ISRU endeavours in space.

The other major use of space resources is to be mined and brought back to Earth. John S. Lewis explores that in detail in his book on the "Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets" (Lewis, 1997). Planets and asteroids provide a richness of resources from metals to rare-earth elements. Asteroids can provide access to gold, iron, nickel, cobalt, platinum group metals (PGMs), ruthenium, rhodium, palladium, osmium, iridium, and platinum (Sanchez, et al., 2021; Paikowsky & Tzezana, 2018), in addition to rare-earth elements such as lanthanum, neodymium, and yttrium (Gilbert, 2021). Similarly, studies have found celestial bodies like the moon to contain helium-3 deposits (Gilbert, 2021), in addition to iron, aluminum, silicon, calcium, magnesium, titanium, sodium, oxygen, thorium and uranium (Elvis, Krolikowski, & Milligan, 2020; Sivolella, 2019).

In a study done by Sanchez et al. in 2021 on metal-rich near-Earth asteroids (NEAs), the researchers presented near-infrared (NIR) spectroscopic data of NEAs 6178 (1986 DA) and 2016 ED85, estimating that "the amounts of Fe, Ni, Co, and the platinum group metals present in 1986 DA could exceed all worldwide reserves" (Sanchez, et al., 2021). Farther away from Earth, the "Main Belt" between Mars and Jupiter contains some of the largest metal-rich (M-type) asteroids (Sanchez, et al., 2021), and it is estimated that the asteroids in that region in total may contain up to 10 million times the amount of iron on Earth (Elvis, 2021).

Despite the crucial role that space resources can play in human exploration beyond Earth, their great potential value may increase conflicts regarding resource ownership and utilization (Hobe, 2018; Tronchetti, 2007), especially when mined with the purpose of being returned to Earth, potentially disrupting the current global economy. This issue is creating a ripple of concerns globally on the future of space mining and resource utilization and shows the need for a policy framework for conducting such activities. As US Senator Bernie Sanders notes (Sanders B. , 2022),

> "According to the Silicon Valley entrepreneur Peter Diamandis, "There are twenty-trillion-dollar checks up there, waiting to be cashed!" . . . The questions we must ask are: who will be cashing those checks? Who will, overall, be benefiting from space exploration? Will it be a handful of billionaires, or will it be the people of our country and all of humanity?
>
> Space exploration is very exciting. Its potential to improve life here on planet Earth is limitless. But it also has the potential to make the richest people in the world incredibly richer and unimaginably more powerful. When we take that next giant leap into space let us do it to benefit all of humanity, not to turn a handful of billionaires into trillionaires."

In keeping with this theme, Part II of this thesis seeks a sustainable and equitable (as later defined in Chapter 6.1.1.4 Sustainability and Equity) policy framework for space exploration and natural resource utilization. The research begins with a detailed review of currently existing national and international policies, laws and guidelines to identify the gaps and inadequacies of policy and governance for space resource utilization. Analysis of lessons learned from history, politics, and resource governance regimes for space analogs on Earth provides guidance on best approaches for policy and governance related to space resources. These will be adapted to the special circumstances of space, leading to an improved plan for international management of space resources in an era of increased multinational exploration and ISRU.

6.1.1.2 Historical Overview of Colonialism and the Parallels in Space

"Turns out MCT can go well beyond Mars, so will need a new name…," tweeted Elon Musk in 2016 about changing the name of his company's, SpaceX, personnel transport craft from the "Mars Colonial Transporter" *only because* it can travel "well beyond Mars" (Etherington, 2016; Mann, 2021). Unsurprisingly, nothing else in the craft's name seemed to raise any issues to SpaceX—nor to other keen advocates of space colonization.

A colonial premise for space, however, is problematic on many different levels. This research specifically bases its definition of the Colonial Mindset as stated by (Wood, 2020), "That whoever has the technology, economic means and the will to do so, has the right to claim property, territory and resources, regardless of the past, present and future claims of other people and the claims of environment." In particular, the research focuses on the effect of this Colonial Mindset on (1) global inequality between countries and people and on (2) unsustainable resource use.

Outer space itself has been constantly surrounded by the narrative of being the "Final Frontier, the New Frontier, the Endless Frontier". As former president Trump said in his 2020 State of the Union address describing the United States' renewed ambitions to settle the moon, "We must remember that America has always been a frontier nation. . . . Now we must embrace the next frontier: America's Manifest Destiny in the stars" (Mann, 2021). It's easy to romanticize one's vision of space by using the "frontier" terminology; however, this term carries years' worth of historical, political, ethical, and colonial baggage that cannot be ignored. As Mann explains in his "Is Mars Ours?" article in The New Yorker, "Advocates of space settlement have long borrowed from an old-fashioned version of the American mythos, which holds that conquering the untamed wilderness of the New World made us better and more democratic as we advanced westward. At least symbolically, space, the final frontier, is sometimes presented as a savage land in need of humanity's beneficent influence" (Mann, 2021).

The goal of this research overview is not to throw ethical accusations at scientists and engineers in the space industry. Human space exploration of Mars and beyond is vital for humanity's curiosity and "intangible desire to explore and challenge the boundaries of what we know and where we have been" (NASA, 2013). However, such a curiosity-driven endeavour for scientifically pushing our limits of understanding of the universe clashes with the current colonial narratives surrounding space exploration and resource exploitation plans and policies. The scale and reach of present space plans, particularly for the use of space resources, pushes these questions to the fore. Due to the interdisciplinary nature of this topic, it is critical to involve lessons learned from history, philosophy, socio-economic studies, and political evolution in the space discourse. As Arendt states, "It has been the glory of modern science that it has been able to emancipate itself completely from all such anthropocentric, that is, truly humanistic, concerns" (Arendt, 2007). Natalie Treviño also emphasizes that the "world is vast and complex, as is the cosmos. People can have the best of intentions but the worst of impacts" (Treviño, 2021).

Treviño refers to the frontier narrative in space as the "Cosmic Order of Coloniality". As Treviño further elaborates (Treviño, 2020),

> "This cosmic order, hegemonically superior since the late 1960s, even while losing popular and political power, orders the very essence of Western space exploration, its future, and possibilities. The Final Frontier is a totalizing and finalizing conception of Man and his future. Such an order reduces ways of knowing and being to colonial and capitalist modes, where all

> things are reduced to exploitation. In this, the future of the final frontier is hardly a future; it is a death march masked as salvation."
>
> "[…] there is another way—it is not hegemonic, nor an easy road, but through the decolonization of the American narrative of space exploration lies a way forward: Hope, Cosmic Awe and Cosmic Revolution, the engagement with the unique material conditions of outer space that can impact socio-economic and political forms as well as the oft mentioned feeling of connection with the cosmos. It is through this that humanity can move away from space, as a frontier—a place to be conquered, but to space as an already existing part of the ecological system of which humanity already belongs."

Treviño emphasized this idea stating that, "My point is not that we will 'repeat' colonialism in space but that the logic of coloniality will impact how we see and function in space" (Treviño, 2021). In other words, this "colonial mindset", previously introduced as defined by (Wood, 2020) creates rippling effects globally that will further exacerbate global inequality between countries and people, in addition to carrying on unsustainable resource use practices, but now in space.

Hilding Neilson, a Canadian astronomer, expresses his opinion on this topic saying, "What I see . . . I'm trying to say this in a way that's on the record," he began. "What I see are organizations that view Mars in the same way that colonizers, pioneers, and settlers viewed the early West—that it was *terra nullius*, a land of opportunity for them, and that the land was free to take" (Mann, 2021). It was also argued that the "natives" were not using the land to its full potential, so if Europeans came in and "improved" the land, then they had ownership rights. This improvement argument started with John Locke (Bishop, 1997). This research considers the effects of viewing space resources, in particular, as *terra nullius,* available as first-come, first-serve opportunities, that are free to take.

The topic of decolonizing our narrative, approach and mentality about space, is a currently heavily debated topic in a growing group within the space community. Despite the obvious difference between colonizing other people and their land, historically on Earth, versus settling in an uninhabited region, the colonial premise, as previously defined, can still have drastic impacts in the latter case. The impacts of particular interest to this research work are those relating to resource use structures and the global economic and environmental effects that such structures may have. As Mandelbaum states, "Interplanetary travel is pitched to us as a good thing. Explorers will visit other planets, which settlers will then colonize. But colonization on our own planet led to […] economic inequity and the destruction of environments. What lessons from Earth's colonialist tragedies can we apply to our interplanetary future?" (Mandelbaum, 2018).

In an interview, Lucianne Walkowicz, the NASA/Library of Congress Chair in Astrobiology and an astronomer at the Adler Planetarium, explained her take on human exploration of Mars, saying (Mandelbaum, 2018),

> "There are a variety of scientific reasons why human presence might make certain investigations easier on Mars. But I'm disturbed by the way people talk about going to Mars as if the planet is ours... When we talk about terraforming, that's a planetary-scale strip mining operation. If you transform a planetary environment, even if you think you know how to do it, that represents a total alteration of the chemistry and physics of the planet, which means you may erase the history of life that might be there.

> […] I can't give you an example of what a decolonized Mars looks like, but it starts by having multidisciplinary conversations about the things that happen here on Earth. Private-public partnership isn't a new thing. It's baked into the history of space exploration. There's a matter of inclusion—space exploration is something that we all take part in. That's true of public missions and not private companies. Their aims are often different from what people think about."

Chanda Prescod-Weinstein, an assistant professor of physics at the University of New Hampshire who studies spacetime's origins, adds to Walkowicz's statement (Mandelbaum, 2018),

> "Decolonization in the Martian context requires asking questions about who is entitled to what land. Can we be trusted to be in balance with Mars if we refuse to be in balance with Earth? Can we be trusted to be equitable in our dealings with each other in a Martian context if the U.S. and Canadian governments continue to attack indigenous sovereignty, violate indigenous lands, and engage in genocidal activities against indigenous people?
>
> I think the answer is no. […] Our terrestrial ecosystem is making very clear to us that our old way of doing things has pushed us to the brink of extinction."

When looking back at the painful history of colonialism around the globe and its continued practices and adverse impacts on societies and countries, it is hard not to see the striking parallels in the ongoing narrative about space. To this day, many ongoing colonial practices can be observed around the world, especially in the United States. In her article titled "On Indigenous People's Day, Let's Commit to an Anticolonial Mindset on Earth and in Space", Wood lists some of these ongoing practices, especially in the "Territories", "Commonwealths" and "Miscellaneous Insular or Outlying Areas" that the United Stated holds (Regan, 2014; Redbird, 2020; How are U.S. states, territories, and commonwealths designated in the Geographic Names Information System?; Wood, 2020). Wood further expands on her thoughts on the "Colonial Mindset" in space saying (Wood, 2020),

> "For those of us who benefit from the powerful military and economic superiority of the United States, it is tempting to read the list of Territories and Commonwealths and simply conclude that it is strategically beneficial for the U.S. to hold land to enable economic, scientific and defense activities all over the world. […] As a space engineer and policy scholar, I am concerned that this *Colonial Mindset* is already built into the fabric of thought as space agencies, engineers, scientists, entrepreneurs and explorers contemplate future human activity on the Moon, Asteroids, Mars and beyond. To achieve this, we must understand the historical and ongoing impacts of the *Colonial Mindset* on Earth."

To understand the historical and ongoing impacts of the *Colonial Mindset* on Earth, it is important to draw on historical, socio-economical and ethical literature on the topic. In doing that, there is a critical need to highlight the parts of history that are often omitted in the current narrative around the world. For example, Dunbar-Ortiz, in 2015, published a history of the United States with stories unveiling the centuries of the US regimen and challenges the policies involved (Dunbar-Ortiz, 2015).

Historically, the era of colonialism was shaped by the Western conquest of parts of Asia, Africa, and the Americas for forced labor, slavery, and resource exploitation of gold, sugar, wood, etc. The colonial activity in the Western Hemisphere involved Spain, Portugal, Britain, France and the Netherlands, after Columbus' voyage (Treviño, 2021; Wood, 2020). This allowed Europe to modernize and develop key technologies between the 15th and 19th centuries. Some of these technologies are the ocean navigation vessel (Ajala, 2013; Swanick, 2006), that was used by the Portuguese for slave trade between Europe and Africa and then transatlantically to the Americas and back for plantation farming for crops like sugarcane, cotton and rice (Gudmestad, 2006; Clegg, 2015; Wood, 2020). The series of technological and economical innovations kept growing and included the cotton gin for textile fabrication (Lakwete, 2005). However, that in turn further enforced colonialism and its capitalistic and racist interconnections (Kendi, 2016; Ortiz, 2018; Dunbar-Ortiz, 2015). As Wood points out, "the need for more land […] extended the appetite of colonization; this was highly visible in the United States as the government pushed the bounds of its sovereignty further westward" (Wood, 2020).

The Colonial Mindset described has crawled its way back into the entire current socio-economic global systems (Kendi, 2016; Ortiz, 2018; Rodney, 2018), and as Wood explains, "created the false division of countries into arbitrary categories of "developed" and "developing", while ignoring the fact that a small set of economically powerful countries has created a long term, exploitative relationship (Amsden, 2009) with other countries, especially countries in the Southern Hemisphere, based on extraction of raw materials, encouragement of low-paid labor, dehumanization of non-white people (Kendi, 2019), and long term cycles of debilitating national debt held by foreign lenders – public and private (Walsh & Phillips, 2020)" (Wood, 2020).

6.1.1.3 The New "Gold Rush"

A new, but similar, strong rush is for space resource utilization from private companies and countries around the world. Tepper & Whitehead refer to that as the New "Gold Rush" and "Land Rush". They explain saying, "We are past the beginning of a double rush: a new "gold rush" for space resources and a "land rush" for the establishment of space habitats, notably on the Moon and Mars. The legal basis for each rush is questionable, at best. Even the related economic and business models, as well as the related governance models, are still in their infancy. In the case of each rush, the private sector is heavily involved and even leading the way. Private corporations are executing many of the projects and initiated many of them, with governments having initiated a few but mainly having provided a legal framework and occasionally financial investment" (Tepper & Whitehead, 2018). Despite the fact that—from a technological standpoint—mining resources on asteroids might still be far in the future, space resource use and acquisition on planetary bodies is already happening, with examples including the Mars 2020 Perseverance sample collections and NASA's awarded commercial contracts for lunar regolith collection by 2024 (Gilbert, 2021; Schierholz & Finch, 2020), that will set a legal precedent on the purchase of space resources.

There are many other examples of such efforts and associated laws around the world. In the United States, these examples include the Commercial Space Launch Competitiveness Act (CSLCA) (Ioannou, 2017; Public Law 114 - 90 - U.S. Commercial Space Launch Competitiveness Act, 2015). Globally, the main examples are Japan's space agency JAXA's memorandum with Tokyo-based iSpace, Inc. (Warnock, 2016), Luxembourg's private sector efforts and adopted space resource utilization laws (Bartunek, 2016; Prospector-X: an international mission to test technologies for asteroid mining.; Planetary resources and the Government of Luxembourg partner to advance the space resource industry, 2016; Loi du 20 Juillet 2017 sur l'Exploration et l'Utilisation des Ressources de l'Espace, 2017; Tepper & Whitehead, 2018), and United Arab Emirates (UAE)'s asteroid mining goals (Al Ahbabi, 2016; Barnard, 2016).

There are also views that disagree with the anti-colonial narrative in space and portray the concerns raised as hindering the future of human space exploration. For example, a very strong advocate for Mars colonization, Robert Zubrin, the founder of the Mars Society, argued in an essay for *National Review* against the "wokeists" who are halting space exploration in response to Tavares, et al's white paper submission on "Ethical Exploration and the Role of Planetary Protection in Disrupting Colonial Practices" (Mann, 2021; Tavares, et al., 2020).

However, to people who have been in constant awe and curiosity about space, ensuring a sustained and equitable future for space activities is crucial—especially because many actions are irreversible. It is important to use our knowledge and history on Earth and only carry our best practices with us to space. This line of thought echoes Mann's statement, "Though I worry that we will end up making unforeseen mistakes in space, I nurture some hope that we can avoid the errors of the past—a wish that descends, perhaps, from the old idea that space is some heavenly realm. We see in space the possibility of redemption, which may never come" (Mann, 2021).

Addressing and understanding our past and current Earthly problems in parallel to our efforts in space is critical to ensure the future we hope in space. Treviño very eloquently explained that saying (Treviño, 2021),

> "By considering the impact of coloniality on space exploration, space advocates can better critique and dismantle the negative aspects of space exploration and actively create alternatives. We need not reproduce racism or environmental devastation. That being said, we cannot stop reproducing them until we fully grasp how they are intertwined.
>
> What I have found in my research is that there is a problem with wishful thinking in the space community. There's an idea that, once we're in space, all our problems will be solved. In reality, we should be solving earthly problems at the same time as we are exploring space. By doing that, when we do migrate into space, we can do so conscious of our faults and strengths. If we continue to be in denial about the history of exploration and exploitation, we cannot create a future on Earth or in space that is equitable or bright."

This brief overview of the history of the colonial mindset and its impacts on the current global inequities raises alarming concerns on the parallels observed in the conversation and efforts on space resource utilization and its consequent impacts. Thus, to include more global voices and ensure the sustainability and equity of space resource use, it is critical to note these historical learnings and take an anticolonial approach both in engineering and in law and policy. It is also important to consider the dangers of the postcolonial mentality, especially in believing that "Western thinking can be used in non-Western contexts without causing problems" (Riach, 2017; Morris, 2010).

6.1.1.4 Sustainability and Equity

6.1.1.4.1 Sustainability

In its approach to sustainability, this research refers to the United Nations' Sustainable Development Goals (SDGs) (The 17 Goals) and its definition of sustainable development as follows (United Nations):

- "Sustainable development has been defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs.
- Sustainable development calls for concerted efforts towards building an inclusive, sustainable and resilient future for people and planet.
- For sustainable development to be achieved, it is crucial to harmonize three core elements: economic growth, social inclusion and environmental protection. These elements are interconnected and all are crucial for the well-being of individuals and societies.
- Eradicating poverty in all its forms and dimensions is an indispensable requirement for sustainable development. To this end, there must be promotion of sustainable, inclusive and equitable economic growth, creating greater opportunities for all, reducing inequalities, raising basic standards of living, fostering equitable social development and inclusion, and promoting integrated and sustainable management of natural resources and ecosystems."

The United Nation's 17 Sustainable Development Goals (SDGs) are displayed in *Figure 41* (The 17 Goals). These goals were developed as part of the United Nations' 2030 Agenda for Sustainable Development to present a global partnership from both "developing and developed" countries on an "urgent call of action" to provide "a shared blueprint for peace and prosperity for people and the planet, now and into the future." (The 17 Goals).

Figure 41. The United Nations 17 Sustainable Development Goals (SDGs). *(The 17 Goals)*

Despite some criticism that these SDGs have received, especially on the division between developing and developed countries and on issues of poverty (Alston, 2020), the SDGs still provide a good start for a set of goals and targets that could be helpful for this research. In particular, this research focuses on the following SDGs and their set of targets as defined by the United Nations (The 17 Goals):

- **SDG 10:** Reduce inequality within and among countries. In particular, the set or relevant targets for this SDG are (The 17 Goals):

    - "Target **10.2**: By 2030, empower and promote the social, economic and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or other status.
    - Target **10.3**: Ensure equal opportunity and reduce inequalities of outcome, including by eliminating discriminatory laws, policies and practices and promoting appropriate legislation, policies and action in this regard.
    - Target **10.4**: Adopt policies, especially fiscal, wage and social protection policies, and progressively achieve greater equality.
    - Target **10.5**: Improve the regulation and monitoring of global financial markets and institutions and strengthen the implementation of such regulations.
    - Target **10.6**: Ensure enhanced representation and voice for developing countries in decision-making in global international economic and financial institutions to deliver more effective, credible, accountable and legitimate institutions.
    - Target **10.a**: Implement the principle of special and differential treatment for developing countries, in particular least developed countries, in accordance with World Trade Organization agreements
    - Target **10.b**: Encourage official development assistance and financial flows, including foreign direct investment, to States where the need is greatest, in particular least developed countries, African countries, small island developing States and landlocked developing countries, in accordance with their national plans and programmes."

- **SDG 11:** Make cities and human settlements inclusive, safe, resilient and sustainable. In particular, the set or relevant targets for this SDG are (The 17 Goals):

    - "Target **11.3**: By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries.
    - Target **11.4**: Strengthen efforts to protect and safeguard the world's cultural and natural heritage.
    - Target **11.b**: By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels
    - Target **11.c**: Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials."

- **SDG 12:** Ensure sustainable consumption and production patterns. In particular, the set or relevant targets for this SDG are (The 17 Goals):

  - "Target **12.1**: Implement the 10-year framework of programmes on sustainable consumption and production, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries.
  - Target **12.2**: By 2030, achieve the sustainable management and efficient use of natural resources.
  - Target **12.6**: Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle.
  - Target **12.7**: Promote public procurement practices that are sustainable, in accordance with national policies and priorities.
  - Target **12.a**: Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production"

- **SDG 16:** Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels. In particular, the set or relevant targets for this SDG are (The 17 Goals):

  - "Target **16.3**: Promote the rule of law at the national and international levels and ensure equal access to justice for all.
  - Target **16.6**: Develop effective, accountable and transparent institutions at all levels
  - Target **16.7**: Ensure responsive, inclusive, participatory and representative decision-making at all levels
  - Target **16.8**: Broaden and strengthen the participation of developing countries in the institutions of global governance
  - Target **16.b**: Promote and enforce non-discriminatory laws and policies for sustainable development"

These four goals and their subsequent set targets are very relevant to the discussion of space resource use, as they could be used as set goals to ensure a more inclusive and sustainable benefit sharing regime that would still allow the accessibility of resources to future generations. This research uses the SDGs as a reference when proposing the new system in Chapter 9.3 Proposed Framework.

6.1.1.4.2 Equity

Political science is most famously defined as the study of "who gets what, when, and how" (Lasswell, 1936). In her book, Policy Paradox: The Art of Political Decision Making, Professor Deborah Stone introduces issues of "distributive conflicts in which equity is the goal" (Stone, 2012). Stone draws on the work of Rae et al. on equity (Rae, 1979; Rae , Yates, Hochsch, Morone, & Fessler, 1983) and presents competing visions of an equitable distribution of an example problem of a chocolate cake—the aim is to show the paradox of distributive problems where "equality may in fact mean inequality" and where equity denotes "distributions regarded as fair, even though they contain both equalities and inequalities" (Stone, 2012).

This section draws on literature to tackle the ideas of equality, equity, and fairness in the global justice discussion of space resource ownership and utilization. Stone's analysis on visions of equitable distribution is critical to this research to develop metrics and strategies for ensuring equitable space resource use. Stone presents a systematic description of the dimensions of the previously mentioned "chocolate cake" problem. These dimensions are "the recipients (who gets something?), the item (what is being distributed?), and the process (how is the distribution to be decided upon and carried out?)" (Stone, 2012). *Table 7* presents a summary of the concepts of equality per different dimensions considered, as presented by Stone.

Table 7. Concepts of Equality (adapted from *(Stone, 2012))*

Simple Definition	Same size share for everybody	
Complications in the Polis		
Dimension	**Issue**	**Dilemma**
Recipients	1. Membership (the boundaries of community)	unequal invitations /equal slices
	2. Rank-based distribution (internal subdivisions of society)	equal ranks / equal slices; unequal ranks / unequal slices
	3. Group-based distribution (major internal cleavages of society)	equal blocs/unequal slices
Items	4. Boundaries of the item	equal meals /unequal slices
	5. Value of the item	equal value /unequal slices
Process	6. Competition (opportunity as Starting resources)	equal forks /unequal slices
	7. Lottery (opportunity as statistical chance)	equal chances /unequal slices
	8. Voting (opportunity as political participation)	equal votes /unequal slices

This research addresses these multiple dimensions for the issue of space resource utilization. Stone's first dimension, "recipients", is critical to define the question of membership. In other words, "Among whom are the resources to be equally distributed". For purposes of this research, the recipients include Humankind as whole, including future generations, particularly as represented by their respective States and governments. Afterwards comes the question of societal division and how that affects the discussion of equality. Two divides are presented in *Table 7*, rank-based distribution or group-based distribution. This research focuses on rank-based equity, that can be observed in economics in *horizontal* and *vertical equity*, where, as Stone describes, "*horizontal equity* meaning equal treatment of people in the same rank and *vertical equity* meaning unequal treatment of people in different ranks" (Stone, 2012). This divide could be observed, for example, between the so-called "developing" and "developed" countries in international laws and policies.

Despite the fact that rank-based equity also assigns different people to different groups, it is different from group-based distribution. Group-based distribution relies on “simple demographic criteria” or “ascriptive characteristics of identity” like ethnicity, race, gender, or religion (Stone, 2012). However, rank-based distribution uses “fairly fine-tuned individual measurements”. For the case of “developing” and “developed” countries, the measurements can include rate of industrialization, individual per capita income, infant mortality rate, death rate and birth rate, and life expectancy rate. This research does not consider the “developing” versus “developed” state division to be the best current rank-based distribution of states around the world and urges the development of better metrics for that divide.

In the second dimension of defining the boundaries and value of space resources, this research uses the definition of “space resource” presented by the Hague International Space Resources Governance Working Group in The Building Blocks for the development of an international framework on space resource activities. There, a “space resource” is “an extractable and/or recoverable abiotic resource in situ in outer space” where this includes, “mineral and volatile materials, including water, but excludes (a) satellite orbits; (b) radio spectrum; and (c) energy from the sun except when collected from unique and scarce locations” (Neto, Hofmann, Masson-Zwaan, & Stefoudi, 2020; Masson-Zwaan & Sundahl, 2021; Committee on the Peaceful Uses of Outer Space, 2020). However, in addition to defining the “types” of items, it is important to consider that an additional metric that affects the item boundary is time. This research considers intergenerational equity for access to space resources across time.

Finally, in addition to considering who the recipients are and defining what is being distributed, this research also considers the “process of distribution” in the dimensions for equality. As Stone explains, “commons problems often require distributive solutions based on unequal slices but fair processes” (Stone, 2012).

In the literature of politics and global justice, there are multiple divides on the topic of equity. Stone presents four major divides: the dimensions to be considered (process or end-result), the question of liberty, property as an individual creation or a collective creation, and human motivation (Stone, 2012).

The first major divide on which dimensions should be considered when evaluating equity or developing equitable structures—specifically on whether to judge according to the process or according to recipients and items. One of the biggest advocates of using the process as criteria for equity is Robert Nozick in his book Anarchy, State and Utopia (Nozick, 1974). As Stone discusses, Nozick argues “that a distribution is just if it came about by a voluntary and fair process. It is just if all the holdings in it--what people have--were acquired fairly” (Nozick, 1974; Stone, 2012). This view opposes the so-called “end-result” justice that only looks at “characteristics of recipients or owners and characteristics of items and asks whether there is an appropriate match” (Nozick, 1974; Stone, 2012). However, this process concept of justice is dependent of the definition of “fairness”, and thus requires finding “independent standards for judging distributive processes” (Stone, 2012).

Scholars like John Rawls, however, focus on the dimensions of recipients and items (Rawls, 1971), the “end-result” justice. Rawls, in A Theory of Justice, divides items as social primary goods and natural primary goods and defines the class of recipients as all citizens, and then he proposes a thought experiment of putting one’s self behind a “veil of ignorance” for designing rules for a society one is about to join. Rawls says that “most rational people would want social primary goods to be distributed equally, but we would allow social and economic inequalities if they worked to everyone's advantage and were attached to positions or offices open to everyone” (Rawls, 1971; Stone, 2012). This view on equity could also qualify as a process as it considers the “rules and institutions that govern society” (Stone, 2012). However, the problem that arises here is, once again, defining the characteristics of recipients and items for justice, because there normally is no consensus on such criteria. Rawl suggests going back to “our innate sense of justice as well as our fundamental rationality” and then derives principles of equity by asking us to “deliberate about rules for a just society without being biased by knowing our own situation” (Rawls, 1971; Stone, 2012). This process is only valid however if there exists “a universal logic about distributive justice”, which is a lot more complicated in practice (Stone, 2012).

The other three divides focus on liberty, property creation, and human motivation.

In terms of liberty, there are two different schools of thought on “what kind of interference with liberty one finds acceptable as a price of distributive justice” (Stone, 2012). Liberty can be viewed as (1) “freedom to use and dispose of one’s resources as one wishes, without interference,” aligning with the process view of equity, or (2) as “having enough basic resources to choose out of desire rather than necessity” aligning with the end-result view of equity.

The different views on property creation are also in a sense tied to different ideas on liberty. People who hold the process view of equity and “unconstrained-choice view of liberty” have a more individualistic view on property creation unlike the collective creation belief of property value (Stone, 2012).

Finally, is the divide on human motivation, where social conservatives view people’s motivation to work and create to be derived by need, while social liberal believe that “people have a natural drive to work, produce, and create, and they are inhibited by need” (Stone, 2012).

This research thus follows the school of thought of social liberalism that, as Stone defines, “includes beliefs in distributive justice as fair shares of basic resources, liberty as freedom from dire necessity, property as a social creation, and productivity as stimulated by security” unlike the conservative belief in “distributive justice as fair acquisitions, liberty as freedom to dispose of one's property, property as an individual creation, and work as motivated by financial need” (Stone, 2012). As Kosovo states, “Fairness centers on how people are treated by others, especially the requirement that everyone be treated alike unless there are good reasons to treat particular people differently. Thus, a fair procedure makes decisions or allocates benefits or burdens on the basis of appropriate criteria, which are applied similarly to all cases unless exceptions can be justified” (Kurian, 2011).

In the context of this research, this idea of fairness is critical, as there currently exists a policy and legal gap in knowledge for a procedural anti-colonial framework that can fairly allocate the use of space resources between all interested actors, while ensuring the sustainability and accessibility of said resources to future generations, and the return on investment for entities involved is space resource mining activities. In that sense, this research explores both the “procedural” and “distributive” dimensions of fairness by tackling both the procedural framework in addition to the expected outcome to stakeholders, avoiding a “first-come, first-claim” approach to space resources. Thus, the research aims to achieve just policies of space resource utilization, focusing on both the institutional and the societal impacts of such choices. This work is also more aligned with Sen’s “realization-focused” comparative approach to justice that mainly focuses on the “advancement or retreat of justice” and the “removal of manifest injustice from the world” instead of with Thomas Hobbes’ and Jean-Jacques Rousseau’s “transcendental institutionalism” line of reasoning about justice (Sen, 2009).

6.1.2 Objectives

The main objective of this research is to propose a sustainable and equitable policy framework for space exploration and natural resource utilization. Despite the importance of planetary protection in this discussion (Nasr, et al., 2021), this topic is left outside the scope of the research, and the work is focused on a benefit-sharing regime for space resources.

The research begins with a detailed review of currently existing national and international policies, laws and guidelines to identify the gaps and inadequacies of policy and governance for space resource utilization. A combination of (1) systems engineering tools, (2) governance, law and policy theories, (3) analysis of the lessons learned from history, politics, and (4) our resource governance regimes for space analogs on Earth, provides guidance on best approaches for policy and governance related to space resources. These will be adapted to the special circumstances of space, leading to an improved plan for international management of space resources in an era of increased multinational exploration and ISRU.

6.2 Research Questions and Motivation

This research discusses Question (3) and its series of sub-questions outlined below:

(3) How to implement an equitable and sustainable benefit-sharing regime for space resources?

(3.1) What are the gaps in the existing laws and policies for equitable and sustainable space resource utilization?

(3.2) What is the Systems Architecture for Resource Governance Analogs on Earth?
- High Seas and Deep Seabed
- Antarctic

(3.3) What is the evaluation of the Governance Analogs for space resource utilization using Third World Approaches to International Law (TWAIL)?

(3.4) What are proposed policies for sustainable space resource utilization that address identified legal policy gaps and combine the best of the analog governance systems?

Question (3.1) specifically focuses on reviewing the current existing treaties, national and international guidelines to outline the gaps that exist in the current policy framework when applied to the use and ownership of resources in space.

The research relating to Question (3.2) considers two resource governance analogs on Earth, Antarctica and the High Seas and Deep Seabed, that could provide critical insight to a better way to govern ISRU in space. These Earth-analogs were chosen for being two of the "global commons" with different governance regime approaches. To understand the governance structure in each of the considered Earth-analogs, the research will involve conducting a detailed Systems Architecture study to understand each of the systems' stakeholders, needs, objectives, system functions, and forms.

The research on Question (3.3) evaluates each of the analogs according to the "third world" global south perspective on international law to identify the gaps and strengths of each governance system and assess them accordingly.

Finally, Question (3.4) is the ultimate goal of this research, which uses the knowledge of the identified policy gaps and the analyzed and evaluated governance analogs on Earth to propose policies for exploiting space resources that address these identified gaps by combining effective tools, strategies and structures from the studied governance analogs.

The main motivation behind this work stems from the critical importance of designing a policy framework for space resource utilization prior to our inevitable activities in the future. The research is motivated by the importance of sustainable and equitable resource access for future "explorers", drawing parallels to the devastating impacts of colonial practices on global inequality on Earth and how that can be avoided in space. This topic of research is of immediate importance due to the rapid private sector growth for human space exploration and current plans for unrestrained space resource extraction and utilization.

Chapter 7: Literature Review, Gaps and Contributions

This literature review discusses space resource utilization in the context of resource ownership and use. The review outlines potential limits created by implementing national and international guidelines. In doing so, practical implications of space resource utilization operations are outlined, then existing binding international and national rules, in addition to the Artemis Accords, are analysed for a grounded understanding of the relationship between space resource utilization and resource appropriation. The review also addresses legal aspects of implementing space resource utilization guidelines, followed by a discussion of remaining gaps to address in light of future space resource utilization by public and private actors.

7.1 Treaties

7.1.1 Outer Space Treaty (OST)

The Outer Space Treaty (OST) of 1967 provided the first set of legally binding principles for space activities with a set attitude of peace and cooperation. When it comes to the topic of "resource ownership", Articles I and II of the OST are of particular importance.

Article I OST tells States that they are free to use and explore outer space, including celestial bodies such as Mars, and directs space activities to be carried out **in the interest and for the benefit of all countries.** It specifically states the following (The Outer Space Treaty, 1967):

> "The exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind.
>
> Outer space, including the moon and other celestial bodies, shall be free for exploration and use by all States without discrimination of any kind, on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies.
>
> There shall be freedom of scientific investigation in outer space, including the moon and other celestial bodies, and States shall facilitate and encourage international co-operation in such investigation."

Article II OST specifically discusses prohibiting national appropriation of outer space, stating the following (The Outer Space Treaty, 1967):

> "Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means."

These two articles, however, have wide interpretations when it comes to the legality of owning or using resources from celestial bodies such as Mars, as this question is not clearly answered within the treaty provisions. There exist interpretations of "celestial bodies" in Article II OST as encompassing the territorial aspect only, but not including natural resources (such as water or metals). Other interpretations also question whether Article II OST, which forbids national appropriation, also forbids private appropriation or not (Tronchetti, 2007) due to the lack of explicit mentioning of privatization.

Article III of the OST can be relevant in the "resource ownership" discussions as it states that, "States Parties to the Treaty shall carry on activities in the exploration and use of outer space, including the moon and other celestial bodies, in accordance with international law, including the Charter of the United Nations, in the interest of maintaining international peace and security and promoting international co-operation and understanding" (The Outer Space Treaty, 1967). This is important as it ties State Parties to the Treaty to international law and to international collaboration—both of which are important as principles for any resource governance framework in space.

Lastly, due to the importance of the private sector in the discussion of space resource utilization, Article VI of the OST is critical as it discusses the state responsibility, authorization and supervision of private entities by the appropriate state. In particular, this article states that (The Outer Space Treaty, 1967),

> "States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty. The activities of non-governmental entities in outer space, including the Moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty."

7.1.2 Moon Agreement

The Moon Agreement is important to our discussion on the topic of "resource ownership," despite the fact that this treaty is currently legally ineffective and does not have a sufficient number of ratifications and signatories, especially from the major space-faring countries like the United States, China and Russia (Moon Agreement, 1979).

The 1979 Moon Agreement was a follow-on to the 1967 Outer Space Treaty, intended to establish a regime for the use of the Moon and other celestial bodies similar to the one established for the sea floor in the *United Nations Convention on the Law of the Sea.* It reaffirms many of OST's provisions including the exclusive use of celestial bodies for peaceful purposes and elaborates on others such as prohibiting national appropriation in detailing the inclusion of natural resources in addition to the land appropriations. Article 11(3) of the Moon Treaty specifically states the following (Moon Agreement, 1979):

> "Neither the surface nor the subsurface of the Moon, nor any part thereof or natural resources in place, shall become property of any State, international intergovernmental or non-governmental organization, national organization or non-governmental entity or of any natural person. The placement of personnel, space vehicles, equipment, facilities, stations and installations on or below the surface of the Moon, including structures connected with its surface or subsurface, shall not create a right of ownership over the surface or the subsurface of the Moon or any areas thereof. The foregoing provisions are without prejudice to the international regime referred to in paragraph 5 of this article."

However, Article 11 is one of the most controversial articles in the Moon Agreement, as it states in paragraph 1 that "The Moon and its natural resources are the common heritage of mankind, which finds its expression in the provisions of this Agreement, in particular in paragraph 5 of this article". Paragraph 5 states that "States Parties to this Agreement hereby undertake to establish an international regime, including appropriate procedures, to govern the exploitation of the natural resources of the moon as such exploitation is about to become feasible" (Moon Agreement, 1979). This international regime is to be facilitated by Article 11(6) stating that "States Parties shall inform the Secretary-General of the United Nations as well as the public and the international scientific community, to the greatest extent feasible and practicable, of any natural resources they may discover on the moon." Additionally, Article 11(7) outlines the main purposes of the international regime to include (Moon Agreement, 1979):

> "(a) The orderly and safe development of the natural resources of the Moon;
> (b) The rational management of those resources;
> (c) The expansion of opportunities in the use of those resources;
> (d) An equitable sharing by all States Parties in the benefits derived from those resources, whereby the interests and needs of the developing countries, as well as the efforts of those countries which have contributed either directly or indirectly to the exploration of the Moon, shall be given special consideration."

Michelle Hanlon, an Associate Director of the National Center for Air and Space Law at the University of Mississippi, explains that, "The Moon Agreement was prepared in the shadow of the Convention of the Law of the Sea. The Convention politicized the notion of common heritage and assured its evolution into an unwieldly, ungainly, overbroad, and divisive term" (Hanlon, 2020). Hanlon further discusses the main two concerns about the concept of "common heritage" to be "(1) All countries share in the management of the area and (2) The benefits derived from exploitation of resources in the area must be shared with all, regardless of participation" (Hanlon, 2020).

This "Common Heritage" doctrine in space was not previously contained in any treaties in the specific language that the Moon Agreement stated. This caused a lot of political concern that, as discussed by Rosenfield & Smith in "The Moon Treaty. The United States Should Not Become a Party" (Rosenfield & Smith, 1980):

> "The then chairman of the Senate Foreign Relations Committee, Senator Frank Church, joined by Senator Jacob Javits, then the ranking minority member of the Committee, wrote the Secretary of State requesting that the United States oppose the opening of this treaty for signature, because this treaty would oppose our interest in free enterprise and free economy as well as our security interest.
>
> In addition, Congressman John B. Breaux, testifying before the House Sub-Committee on Space Science and Applications, of the Committee on Science and Technology, in hearings held during September 1979, has concluded that this treaty is not in the interest of the United States, because it would deprive the United States of opportunities for development of space technology and resources."

Hanlon draws parallels in the national responses to the Moon Agreement back to responses to concepts of international management in the Convention on the Law of the Sea, stating that (Hanlon, 2020):

> “Indeed, in response to implementing provisions in the Convention on the Law of the Sea, President Ronald Reagan criticized the concept of international management, stating that “no national interest of ours could justify handing sovereign control over two thirds of the Earth’s surface over to the Third World”. As to the sharing of benefits? Reagan was definitely set against what he called a “free ride” at the expense of the US.
>
> Reagan cast the Law of the Sea Treaty as being intentionally designed to promote a new world order – a form of global collectivism – that seeks ultimately the redistribution of the world’s wealth through a complex system of manipulative central economic planning and bureaucratic coercion. Reagan blamed this on what he called the distorted interpretation of the noble concept of the Earth’s vast oceans as the common heritage of humankind.
>
> […] Note, though, that Reagan did not suggest that the oceans are NOT the common heritage of humankind. He instead said the Law of the Sea Treaty had distorted the interpretation of that concept.”

From here, the Moon Agreement outlines important, yet very controversial, provisions. Its suggested international regime for resource extraction and required regime purposes are very vague at this point. As Hanlon mentions, “the treaty won’t implement necessary laws until mining is feasible – yet the very structure of the treaty and the uncertainty surrounding it discourages the research and investment necessary to make mining feasible” (Hanlon, 2020).

7.2 Soft Law

Soft law refers to legally non-binding instruments or norms that lack formal enforcement mechanisms but are nevertheless influential in shaping behavior and guiding actions of actors within a particular domain or context (Shelton, Commitment and Compliance: What Role for International Soft Law?, 1999). Soft law may take various forms, such as guidelines, declarations, codes of conduct, or best practices, and are typically adopted by international organizations, governments, professional associations, or industry groups to promote common standards, cooperation, and coordination among stakeholders (Shelton, 2008). While soft law does not have the same legal force as binding treaties or laws, it can nonetheless have significant practical impact by providing a framework for voluntary compliance, setting expectations, and creating normative pressure on actors to align their behavior with shared norms and values (Shelton, Commitment and Compliance: What Role for International Soft Law?, 1999).

Two soft law instruments relevant to space resource utilization are discussed in this section: (1) the Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries of 1996 (Space Benefits Declaration, 1996) and (2) the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) Long-Term Sustainability (LTS) Guidelines adopted in 2019 (A/74/20, 2019).

7.2.1 Space Benefits Declaration

The Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries of 1996 is relevant to the topic sustainable and equitable utilization of space resources. This declaration further elaborates on the interpretation of Article I OST, stating that international cooperation "shall be carried out for the benefit and in the interest of all States, irrespective of their degree of economic, social or scientific and technological development, and shall be the province of all mankind. Particular account should be taken of the needs of developing countries" (Space Benefits Declaration, 1996).

The Declaration further reemphasizes equitable space use and the inclusion of developing countries, stating that (Space Benefits Declaration, 1996),

> "All States, particularly those with relevant space capabilities and with programmes for the exploration and use of outer space, should contribute to promoting and fostering international cooperation on an equitable and mutually acceptable basis. In this context, particular attention should be given to the benefit for and the interests of developing countries and countries with incipient space programmes stemming from such international cooperation conducted with countries with more advanced space capabilities".

However, the Declaration does not introduce any clarifications regarding the non-appropriation principles of space resources, which leaves the legal gap on the different interpretations of this issue in the OST.

7.2.2 United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) Long-Term Sustainability (LTS) Guidelines

The United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) Long-Term Sustainability (LTS) Guidelines adopted in 2019 are another important soft law instrument relating to the topic of this research (A/74/20, 2019). These voluntary guidelines stress on space activities being a tool for "realizing the achievement of the Sustainable Development Goals" and provide guidance on issues such as "the policy and regulatory framework for space activities; safety of space operations; international cooperation, capacity-building and awareness; and scientific and technical research and development" (A/74/20, 2019).

However, few of these Guidelines are of high relevance to the topic of sustainable space resource utilization. Guideline A.3 focuses on States' responsibility on supervising national space activities of non-governmental entities, specifically stating that (A/74/20, 2019),

> "States should ensure that entities under their jurisdiction and/or control that conduct outer space activities have the appropriate structures and procedures for planning and conducting space activities in a manner that supports the objective of enhancing the long-term sustainability of outer space activities, and that they have the means to comply with relevant national and international regulatory frameworks, requirements, policies and processes in this regard."

This guideline is critical for sustainable space resource utilization where a lot of foreseen efforts would be conducted by the commercial sector in countries, and thus require further attention to ensure compliance with long-term sustainability goals.

Guidelines C.1 through C.4 are also relevant as they focus on international cooperation, capacity-building, and awareness efforts—all of which are important for space resource activities. For example, Guideline C.1 specifically focuses on promoting and facilitating international cooperation in support of the long-term sustainability of outer space activities, stating that (A/74/20, 2019),

> "States and international intergovernmental organizations should promote and facilitate international cooperation to enable all countries, in particular developing and emerging spacefaring countries, to implement these guidelines. International cooperation should, where appropriate, involve the public, private and academic sectors, and may include, inter alia, the exchange of experience, scientific knowledge, technology and equipment for space activities on an equitable and mutually acceptable basis".

Guideline D.1 is perhaps the most relevant and important guideline for sustainable space resource utilization, as tackled in this research. This guideline tackles the topic of promoting and supporting research into and the development of ways to support sustainable exploration and use of outer space, stating the following set of five sub-guidelines (A/74/20, 2019),

> "1. States and international intergovernmental organizations should promote and support research into and the development of sustainable space technologies, processes and services and other initiatives for the sustainable exploration and use of outer space, including celestial bodies.
>
> 2. In their conduct of space activities for the peaceful exploration and use of outer space, including celestial bodies, States and international intergovernmental organizations should take into account, with reference to the outcome document of the United Nations Conference on Sustainable Development (General Assembly resolution 66/288, annex), the social, economic and environmental dimensions of sustainable development on Earth.
>
> 3. States and international intergovernmental organizations should promote the development of technologies that minimize the environmental impact of manufacturing and launching space assets and that maximize the use of renewable resources and the reusability or repurposing of space assets to enhance the long-term sustainability of those activities.
>
> 4. States and international intergovernmental organizations should consider appropriate safety measures to protect the Earth and the space environment from harmful contamination, taking advantage of existing measures, practices and guidelines that may apply to those activities, and developing new measures as appropriate.
>
> 5. States and international intergovernmental organizations conducting research and development activities to support the sustainable exploration and use of outer space should also encourage the participation of developing countries in such activities."

Despite their relevance, these guidelines are voluntary and still require more detailed elaboration for their successful implementation.

7.3 National Space Legislation/Policy

The four cases of national space legislations will be discussed in this section in chronological order of their becoming law: the United States, Luxembourg, UAE, and Japan. These cases all follow one, heavily debated, angle of interpretation of the OST provisions on national appropriation of space resources. Each of these states has adopted its own national policy, mainly due to the industry push for space resource commercial use and ownership. However, at the same time, some of these states, like the US, acknowledge the need for a global legal regime, as national law does not bind actors from other states. The subchapters below dive deeper into each of these national laws.

7.3.1 US Commercial Space Launch Competitiveness Act of 2015 and Executive Order on Encouraging International Support for the Recovery and Use of Space Resources of 2020

Chapter 513—Space Resource Commercial Exploration and Utilization in the US Commercial Space Launch Competitiveness Act of 2015 specifically defines an 'asteroid resource' as "a space resource found on or within a single asteroid" and a 'space resource' as "an abiotic resource in situ in outer space" which includes water and minerals. It specifically states some of the goals that the President shall pursue (H.R.1508 - Space Resource Exploration and Utilization Act of 2015, 2015):

> "(1) facilitate commercial exploration for and commercial recovery of space resources by United States citizens;
>
> (2) discourage government barriers to the development in the United States of economically viable, safe, and stable industries for commercial exploration for and commercial recovery of space resources in manners consistent with the international obligations of the United States; and
>
> (3) promote the right of United States citizens to engage in commercial exploration for and commercial recovery of space resources free from harmful interference, in accordance with the international obligations of the United States and subject to authorization and continuing supervision by the Federal Government."

It also details the controversial asteroid resource and space resource rights by stating that "A United States citizen engaged in commercial recovery of an asteroid resource or a space resource under this chapter shall be entitled to any asteroid resource or space resource obtained, including to possess, own, transport, use, and sell the asteroid resource or space resource obtained in accordance with applicable law, including the international obligations of the United States" (H.R.1508 - Space Resource Exploration and Utilization Act of 2015, 2015).

Furthermore, on April 6, 2020, the White House issued an Executive Order on Encouraging International Support for the Recovery and Use of Space Resources (The White House, 2020). Section 1 of this Executive Order specifically declares that the United States does not view space as a global commons, stating the following,

> "Americans should have the right to engage in commercial exploration, recovery, and use of resources in outer space, consistent with applicable law. Outer space is a legally and physically unique domain of human activity, and the United States does not view it as a global commons."

The Executive Order also asserts and stresses the United States' position on not being a party to the Moon Agreement and thus not considering it to be an "effective or necessary instrument" for commercial participation in the long-term space exploration and objecting to "any attempt by any other state or international organization to treat the Moon Agreement as reflecting or otherwise expressing customary international law" (The White House, 2020).

7.3.2 Luxembourg Law on the Exploration and Use of Space Resources 2017

The second interesting example of national legislation is the Luxembourg Law on the Exploration and Use of Space Resources 2017. In Article 1 of the Draft Law, it is declared that "[s]pace resources are capable of being appropriated in accordance with international law", thus permitting ownership over asteroids for the purposes of exploration and commercial exploitation (Loi du 20 Juillet 2017 sur l'Exploration et l'Utilisation des Ressources de l'Espace, 2017; Bergstresser, 2021).

Despite not providing a specific definition of "space resources", the Luxembourg law provides the details on the required process of obtaining a mission authorization that contains information on the mission, risk assessment and responsibilities, in addition to governance and organization. These applications are authorized by the minister(s) or ministers in charge of the economy and space activities (Loi du 20 Juillet 2017 sur l'Exploration et l'Utilisation des Ressources de l'Espace, 2017).

7.3.3 UAE Federal Law No. (12) of 2019

The UAE has published a National Space Policy stating that "a safe, sustainable and stable space environment, free from impediments to access and utilization" is an important national interest (National Space Policy of the United Arab Emirates, 2016). In 2019, the UAE passed a space legislation to facilitate its space sector growth (Federal Law No. (12), 2019). UAE's space legislation is a binding legal instrument. It endorses sustainable activities under Article 2 and Article 7 (12), thus enabling interpretation in the spirit of such endorsement (Federal Law No. (12), 2019).

Under Article 1, space resources are defined as "Any non-living resources present in outer space, including minerals and water" which would appear to include those found on celestial bodies. Moreover, "Space Activities" are defined as: "Activities that target the Specified Area, including its discovery, making an impact thereon, using, or utilising it, in accordance with the provisions of Article (4) of this Law" (Federal Law No. (12), 2019).

Under Article 18, the Council of Ministers can control conditions relating to the permit for exploration and exploitation of resources. The permit can be varied and is not limited to just acquisition or transportation regulation and is granted by the decision of the Board of Directors at the Emirates Space Agency (Federal Law No. (12), 2019).

7.3.4 Japan Space Resource Act of 2021

Being the fourth country in the world to pass a space resources law, Japan enacted the Space Resource Act in 2021, stipulating the private citizen's right to ownership of space resources and the license regarding space resource exploration and development (Japan: Space Resources Act Enacted, 2021). Under Article 2(1) of this Act, space resources are defined as "water, minerals, and other natural resources that exist in outer space, including on the moon and other celestial bodies" (Japan: Space Resources Act Enacted, 2021).

The Act also describes the process needed to obtain a permit license to pursue space resources extraction activities, providing a business activity plan that defines the purpose and other details such as the location, term, and method. Applications are reviewed by the prime minister, with possible consultation with the minister of economy, trade and industry. In its Article 5, the Act also provides that "the person who obtained the permit owns the space resources that the person exploits in accordance with the approved activity plan" (Japan: Space Resources Act Enacted, 2021).

7.4 Building Blocks for the Development of an International Framework for the Governance of Space Resource Activities (by Hague International Space Resources Governance Working Group)

The Building Blocks for the development of an international framework on space resource activities developed by the Hague International Space Resources Governance Working Group are critical for space resource utilization (Neto, Hofmann, Masson-Zwaan, & Stefoudi, 2020; Masson-Zwaan & Sundahl, 2021; Committee on the Peaceful Uses of Outer Space, 2020). This working group was formed to "create an enabling environment for space resource activities that takes into account all interests and benefits all countries and humankind" and "to promote international cooperation and multi-stakeholder dialogue" (Committee on the Peaceful Uses of Outer Space, 2020; Neto, Hofmann, Masson-Zwaan, & Stefoudi, 2020).

Complementing other national, regional, and international efforts, the Building Blocks consist of 20 provisions that are designed to "serve as the basis for a possible international framework, without prejudice to its form and structure." They are guided by the principle of adaptive governance in space stating that "space resource activities should be incrementally addressed at the appropriate time on the basis of contemporary technology and practices" (Neto, Hofmann, Masson-Zwaan, & Stefoudi, 2020).

In particular, Building Block 4.3 (b) states that the international framework should provide that "Space resource activities shall be carried out for the benefit and in the interests of all countries and humankind irrespective of their degree of economic and scientific development". The Building Blocks also define priority rights in addition to resource rights. Building Block 8 specifically discusses the resource rights being lawfully "acquired through domestic legislation, bilateral agreements and/or multilateral agreements" with "mutual recognition between States of such resource rights". Building Block 8 also asserts that "the utilization of space resources is carried out in accordance with the principle of non-appropriation under Article II OST" (Building Blocks for the Development of an International Framework on Space Resource Activities, 2019).

In the discussion of benefit sharing regime for all humankind that this research is particularly interested in, Building Blocks 9 and 13 are important. Building Block 9 discusses the "Due regard for corresponding interests of all countries and humankind". Building Block 13 is the most relevant to this work as it discusses the "Sharing of benefits arising out of the utilization of space resources", specifically stating (Building Blocks for the Development of an International Framework on Space Resource Activities, 2019),

> "13.1 Bearing in mind that the exploration and use of outer space shall be carried out for the benefit and in the interests of all countries and humankind, the international framework should provide that States and international organizations responsible for space resource activities shall provide for benefit-sharing through the promotion of the participation in space resource activities by all countries, in particular developing countries. Benefits may include, but not be limited to, enabling, facilitating, promoting, and fostering:
>
> a) The development of space science and technology and of its applications;
> b) The development of relevant and appropriate capabilities in interested States;
> c) Cooperation and contribution in education and training;
> d) Access to and exchange of information;
> e) Incentivization of joint ventures;
> f) The exchange of expertise and technology among States on a mutually acceptable basis;
> g) The establishment of an international fund.
>
> 13.2 The international framework should not require compulsory monetary benefit-sharing.
> 13.3 Operators should be encouraged to provide for benefit-sharing."

It is interesting, however, that Building Block 13 specifically does not require "compulsory monetary benefit-sharing" arguing that benefit sharing is to be done through instruments "that do not threaten the commercial aspect of space resource activities, which are fundamental to sustain the development of the industry in the first place." The mechanisms for benefit sharing regime shown in the non-exhaustive list in paragraph 13.1 include incentivization of joint ventures with different nations, in addition to exchange of technology and expertise "within the limits of applicable domestic regulation". This Building Block also discusses the role of the Socio-Economic Panel in capacity building especially for nations without current involvement and access to the space resource sector in addition to those aware of this sector but "isolated by decision-makers" (Neto, Hofmann, Masson-Zwaan, & Stefoudi, 2020).

Throughout the development of Building Block 13, it is noted that sharing revenues from space resource activities was a topic of debate and discussion among both members and observers, resulting in a decision favoring against the inclusion of such a mechanism among its provisions. The reasoning behind that was provided to be that "currently compulsory monetary sharing does not represent a suitable solution, due to the very early stage of space resource activities. It was also pointed out that in the short and medium term, the space resource activities of the operators are not expected to return sufficient or significant profit" (Neto, Hofmann, Masson-Zwaan, & Stefoudi, 2020). The alternative included in subparagraph (g), however, was the international fund concept where States can provide funding to support the various other benefit sharing instruments. The details of how such fund would be operated and managed are still undecided and left until there is a better ability to assess space resource activities in the future, following the adaptive governance principles" (Neto, Hofmann, Masson-Zwaan, & Stefoudi, 2020).

The problem with such an open-ended provision regarding monetary benefit sharing is that it provides a very vague and non-mandatory sentiment with no guidance for space mining investors and/or sponsoring States. This vagueness, in turn, leaves it to the national legislatures to provide investors with the details according to their own domestic laws, creating precedent that might be difficult to argue against in the future. Moreover, this Building Block explicitly excludes non-participatory nations in space resource activities from the shared benefits, even if their economies became subject to further global economic inequities. This notion can lead to a dangerous increase in global economic divide between nations, in favor of participating stakeholders.

7.5 Artemis Accords

The US-led Artemis Accords are a non-binding interagency agreement introduced by NASA in May 2020. Section 10 of the Accords is of particular interest to space resource ownership and use, stating the following (The Artemis Accords, 2020):

1. "The Signatories note that the utilization of space resources can benefit humankind by providing critical support for safe and sustainable operations.
2. The Signatories emphasize that the extraction and utilization of space resources, including any recovery from the surface or subsurface of the Moon, Mars, comets, or asteroids, should be executed in a manner that complies with the Outer Space Treaty and in support of safe and sustainable space activities. The Signatories affirm that the extraction of space resources does not inherently constitute national appropriation under Article II of the Outer Space Treaty, and that contracts and other legal instruments relating to space resources should be consistent with that Treaty.
3. The Signatories commit to informing the Secretary-General of the United Nations as well as the public and the international scientific community of their space resource extraction activities in accordance with the Outer Space Treaty.
4. The Signatories intend to use their experience under the Accords to contribute to multilateral efforts to further develop international practices and rules applicable to the extraction and utilization of space resources, including through ongoing efforts at the COPUOS."

Despite Section 10(2)'s affirmation "that the extraction of space resources does not inherently constitute national appropriation under Article II of the Outer Space Treaty", several space law experts argue differently about whether the Accords are in fact in line with the OST. Some worry that it is a just a means for the United States controlling space activity (Rothermich, 2020; Buono, 2020), and others have concerns with bilateral and multilateral agreements undermining some of the main provisions of the OST, potentially causing conflict over mining sites (Wall, 2020; Shackelford, 2020).

Furthermore, as Rothermich states, "There is no international space agency to coordinate national regulation efforts or oversee the emerging space economy. In addition, the accords lack an enforcement provision. Instead, the accords require signatories to make a "political commitment" to upholding the accords' principles" (Rothermich, 2020).

7.6 UN Committee on the Peaceful Uses of Outer Space (COPUOS) Developments

The Working Group on Potential Legal Models for Activities in Exploration, Exploitation and Utilization of Space Resources was established under the Legal Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) (UNOOSA). The co-chairs of this Working Group proposed a five-year workplan and methods of work for the working group that has been adopted and would allow in 2027 the "finalization of a set of initial recommended principles for such activities for the consideration of and consensus agreement by the Committee, followed by possible adoption by the United Nations General Assembly as a dedicated resolution or other action" (Co-Chairs' Proposed Five Year Workplan as of 5 April 2022, 2022).

The five-year plan is mainly focused on a series of planned activities, summarized as follows (UNOOSA, 2023):

- 2022: Agreeing on a detailed workplan and methods of work for the Working Group and undertaking initial administrative and information-collection tasks.
- 2023: Focusing on collating and disseminating submissions by States, collecting relevant information concerning activities in the exploration, exploitation, and utilization of space resources, and preparing a preliminary summary of the information collected.
- 2024: Reviewing additional responses received from States and convening an international conference under the auspices of the United Nations.
- 2025: Continuing the exchange of views and developing a set of initial recommended principles for space activities.
- 2026: Finalizing the summary of discussions on the legal framework and developing a draft set of initial recommended principles.
- 2027: Finalizing and adopting the initial recommended principles and producing a final report of the Working Group.

7.7 Gaps and Conflict Summary

In summary, there are many current existing gaps on the topic of resource ownership. The Outer Space Treaty prohibits "the appropriation of outer space including celestial bodies by claim of sovereignty, by means of use or occupation, or by any other means", but as OST was intended as a set of "Principles", it lacks specific definitions for full effectiveness under certain interpretations (The Outer Space Treaty, 1967). There exist interpretations of "celestial bodies" in Article II OST as encompassing the territorial aspect only, but not including natural resources (such as water or metals). Other interpretations also question whether Article II OST, which forbids national appropriation, also forbids private appropriation or not (Tronchetti, 2007) due to the lack of explicit mentioning of privatization.

The Moon Agreement discusses, in more detail, resource ownership issues under the umbrella of "common heritage for mankind", however it is currently an ineffective treaty. The soft law instruments lack the specificity and the binding ability for space resources issues. The Artemis Accords provide non-binding and non-specific provisions about resource ownership, national appropriations, and the national commercial sector.

Finally, on a national level, the case studies of the United States and Luxembourg, UAE, and Japan discussed above contradict some interpretations of the OST, which raises a policy gap requiring a less vague framework for resource utilization and ownership. These countries passed laws that give commercial companies the rights to extracted space resources. However, some space law experts disagree with that OST interpretation. One example is Stephan Hobe, the director of the Institute of Space Law at Germany's University of Cologne, who said that under 1967 Outer Space Treaty, "outer space and all non-man-made objects it entails are subject to international regulation, I repeat international regulation, not national regulation" (Werner, 2018). In his article "Why national space laws on the exploitation of resources of celestial bodies contradict international law", Hobe further elaborates saying that (Hobe, 2018),

> "It is true that Article II of the Outer Space Treaty explicitly prohibits the national appropriation of outer space and the celestial bodies by means of sovereignty, by means of use or by any other means. Thereby only the notion of sovereignty is fully clear. Article II prohibits in fact the taking of areas of celestial bodies as well as in outer space. The idea behind this is that the Outer Space Treaty tries to avoid any claim to exclusivity.
>
> Exclusive claims of states are not in line with the legal nature of outer space as a legal common, which means that outer space and the celestial bodies cannot be appropriated by a single country. And then this provision continues that appropriation also by means of use is prohibited. Here, it is unclear where the Outer Space Treaty exactly stands. Only through a systematic interpretation it may become clear that two contradictory provisions cannot have been the intention of the founders of the Outer Space Treaty."

This is worrisome as the national appropriation conversations have rippled concerns globally, especially about the United States gaining access and ownership over key space resources and locking other nations out. For example, from a Chinese perspective, in a famous interview in 2017 with Ye Peijian, the head of the Chinese lunar exploration program, he said (Davis, 2018),

> "The universe is an ocean, the moon is the Diaoyu Islands, Mars is Huangyan Island. If we don't go there now even though we're capable of doing so, then we will be blamed by our descendants. If others go there, then they will take over, and you won't be able to go even if you want to. This is reason enough."

Malcolm Davis, a senior analyst at The Australian Strategic Policy Institute (ASPI) explains Peijian's statement saying, "His reference to the Senkaku Islands (Diaoyu Islands) and Huangyan Island (Scarborough Shoal) suggests that China sees space in terms of astrostrategic terrain: the moon and Mars are places of astropolitical importance, rather than simply the focus of scientific exploration. Just as China sees control of the 'first island chain' in East Asia as vital to its maritime security, Ye's comment suggests that these high grounds in space will bear directly on Chinese strategic interests in the coming decades" (Davis, 2018).

Similar concerns from the Chinese side were voiced in China's deep space exploration forum and in an interview with the co-CEO of Ospace, Yao Song, who stated that, "Space resources are first-come, first-served, first-occupied, first-served. If we don't go now, the sky will be locked up in the future" (Curcio & Deville, 2021).

These gaps and conflicts raise very important problems that will affect the future of space exploration and resource utilization. One example arising from the current lack of agreement on current policy and legal interpretations of the existing treaties was raised by van Eijk, in his article titled "Sorry, Elon: Mars is not a legal vacuum – and it's not yours, either" (van Eijk, 2020). There, van Eijk discusses the "Governing Law" section in SpaceX's published Terms of Services for the beta test of its Starlink broadband megaconstellation that states (van Eijk, 2020):

> "Services provided to, on, or in orbit around the planet Earth or the Moon… will be governed by and construed in accordance with the laws of the State of California in the United States. For Services provided on Mars, or in transit to Mars via Starship or other colonization spacecraft, the parties recognize Mars as a free planet and that no Earth-based government has authority or sovereignty over Martian activities. Accordingly, Disputes will be settled through self-governing principles, established in good faith, at the time of Martian settlement."

This statement clearly disregards the current existing system of international law that governs space exploration, with the concept of Mars as a "free planet" possibly breaching Article II of the OST (van Eijk, 2020; Tronchetti, 2007). It additionally explicitly uses the "colonization" terminology within its description of the future Mars activities. As Thomas Cheney, quoted in van Eijk, points out, "this is all just words until it isn't – but there is cause for concern" (van Eijk, 2020).

In conclusion, there are many currently remaining policy gaps and unclear legal interpretations to the non-appropriation principle—but it is critical to address these issues as the non-appropriation principle is a critical basis of space law, as described by Tronchetti, "namely to prevent a colonial competition in outer space and to create the conditions and premises for an exploration and use of outer space carried out for the benefit of all States… Therefore, the need to protect the non-appropriative nature of outer space emerges in all its relevance" (Tronchetti, 2007).

7.8 Research Contributions Summary

As a summary, after identifying the gaps and inadequacies of policy and governance for sustainable and equitable space resource utilization, Chapter 8: Research Design and Methods and Chapter 9: Results and Discussion of this research use Systems Architecture analysis for governance analogs on Earth for space resource utilization. These analogs are then evaluated before finally proposing a policy framework that addresses the identified legal policy gaps and that combines the best of the studied analog governance systems for sustainable and equitable space exploration and natural resource utilization.

Chapter 8: Research Design and Methods

8.1 Research Design Overview

This research proposed policies for sustainable and equitable future human space exploration and natural resource utilization, addressing the identified lack thereof previously outlined in Chapter 7: Literature Review, Gaps and Contributions. This was done through exploratory work examining two resource governance analog case studies on Earth, the Seabed and Antarctica, to identify effective tools, strategies and structures from existing terrestrial frameworks that could aid resource governance in space. The research design integrated a technical approach in the use of Systems Architecture tools and methods outlined in Chapter 8.3.1 Systems Architecture Analysis (Crawley, Cameron, & Selva, 2015), in addition to theoretical frameworks drawn from the fields of international law, space policy, economics, and social science. The research design uses (Yin, 1984)'s and (Langley, 1999)'s process-based case study methods in addition to (Eisenhardt, 1989)'s process of building theory from case studies (previously described in Chapter 3: Research Design and Methods) as a guide for the data collection and analysis and for proposing the final governance framework for Research Question (3.4).

This work of using Earth governance analogs for space applications was a follow-up to the *Res Lunae* work collaboration between Open Lunar Foundation and the Space Generation Advisory Council (SGAC), which systematically analyzed governance systems of terrestrial resources and investigated how these governance practices could inform sustainable and equitable management of lunar resources—studied as separate social-ecological systems (Kuhn & Schingler, 2021). However, the approach that was taken in this previous research is based on polycentric governance of the Moon and its resources as global commons. By definition, "polycentricity offers a framework through which to think about resource governance in space, not as a monolithic system, but as multiple, targeted governance regimes specific to different resources and emerging use cases" (Kuhn & Schingler, 2021; Kuhn, Polycentricity for Governance of the Moon as a Commons, 2021).

8.2 Data Collection

This research collected data on two analog governance systems on Earth, specifically regarding the involved stakeholders, decision-making procedures, property rights, allocation mechanisms, access to the governance system, resource management, and regime enforcement for each. This data was collected from a series of peer-reviewed publications, in addition to treaties, documents and statements published by the United Nations (UN), legal and governance statements, and from government and specific council websites. Once the data on each of these systems was collected, it was organized in spreadsheets and analyzed using Systems Architecture tools and methods outlined in Chapter 8.3.1 Systems Architecture Analysis, below. Following that, a theoretical framework detailed in Chapter 8.3.2 Governance System Evaluation was used for data evaluation to identify the gaps and strengths that each governance systems has relative to these theories and assess each accordingly.

Chapters 8.2.1 High Seas and Deep Seabed and 8.2.2 Antarctic briefly introduce each of the chosen governance analogs and provide a literature background discussing the governance framework and relevant legal procedures for each.

8.2.1 High Seas and Deep Seabed

Historically, the seventeenth century "freedom of-the-seas" doctrine has governed the High Seas and Deep Seabed operations, framing the seas as "free to all and belonging to none", except for the narrow areas surrounding States' coastlines. However, various concerns started prevailing by mid-twentieth century about issues that include offshore resource claims both of fish stocks and of those in the seabed, in addition to spreading pollution in the oceans. These concerns were starting to create threats to the stability between States and more room for conflict (United Nations - Office of Legal Affairs, 2012).

In a speech to the United Nations General Assembly in 1967, Malta's Ambassador to the United Nations, Arvid Pardo, raised these issues and concerns stating that, "an effective international regime over the seabed and the ocean floor beyond a clearly defined national jurisdiction…It is the only alternative by which we can hope to avoid the escalating tension that will be inevitable if the present situation is allowed to continue". This call led to efforts for updating the "freedom of-the-seas" doctrine into a more regulated regime, leading to the Third United Nations Conference on the Law of the Sea in 1973 and the United Nations Convention on the Law of the Sea (UNCLOS) in 1982—nine years of marathon negotiations later (United Nations - Office of Legal Affairs, 2012).

The United Nations Convention on the Law of the Sea (UNCLOS) is an international treaty that codified customary international law and created new laws and institutions to govern the ocean environment and its natural resources. UNCLOS is different from yet related to, both maritime law and admiralty law and, as described by Hoagland, Jacoby, & Schumacher, the development of these laws "can be conceptualized as a tree with UNCLOS as its trunk. Its roots are historical customs, some centuries old, and agreements that emerged mostly after World War II. Its branches are customs, agreements, and soft law that is only now beginning to take shape" (Hoagland, Jacoby, & Schumacher, 2001).

UNCLOS was signed by 117 States in 1982, entering into force in 1994, yet is still not ratified by some major States, notably not by the USA (Maritime Space: Maritime Zones and Maritime Delimitation, 2011), although the USA has recognized it as customary international law. Some of UNCLOS's underlying principles are general international environmental law, some principles of customary international law for sovereignty over resources, in addition to "precautionary action, the common heritage of mankind, the duty to conserve the environment, sustainable development, and international cooperation" (Hoagland, Jacoby, & Schumacher, 2001).

According to the UNCLOS, one of the divided maritime zones is the High Seas & Deep Ocean Floor. "High Seas" is defined as the ocean surface and the water column beyond the Exclusive Economic Zone (EEZ), while the seabed beyond a coastal State's EEZs and Continental Shelf claims is known as the Area (United Nations Convention on the Law of the Sea, 1982; Chapter 2: Maritime Zones). Recognizing this Area as "the common heritage of all mankind" that is beyond national jurisdiction, any conducted activities in the Area have to be for peaceful purposes, such as scientific undersea exploration (United Nations Convention on the Law of the Sea, 1982).

When discussing the natural resources in the high seas and deep seabed, these resources can be divided into two categories, living and non-living resources, with different and more complicated regulations for each. UNCLOS allows any State to fish in the high seas and to exploit living resources without any limitations except for an encouragement for cooperation for purposes of conservation and sustainability of these exploited resources. From here spring various "branches"—conventions and fisheries management organizations for governing international fishing activity. However, the second category of non-living resources in the Area carries additional complexity. These resources include seabed mineral deposits, where projects are "capital intensive to build and administer" unlike fishing (Chapter 2: Maritime Zones). There are three main categories for these seabed mineral deposits: (1) Polymetallic Nodules (PMN), mainly composed of Manganese (Mn), Iron (Fe), Silicates and hydroxides, in addition to trace metal contents of Nickel (Ni), (Copper) Cu, (Cobalt) Co, Manganese (Mn) and Rare Earth Elements (REE); (2) Polymetallic Sulphides (PMS), containing large amounts of copper, zinc, lead, iron, silver and gold; and (3) Cobalt-rich Ferromanganese Crusts (CFC), which are similar to PMN's in composition but have "higher cobalt percentage (up to 2 %), platinum (0.0001 % = 10 ppm) and Rare Earth Elements (REE) besides Nickel and Manganese" (International Seabed Authority, 2022).

In the process of establishing the exploitation regime for the seabed mineral deposits, developing and developed countries had different needs and priorities for the legal framework. Developed countries, the minority who are more likely to develop the mining technologies first, had the view that an international authority should grant licenses to mining companies that can conduct the commercial resource exploitation in consortia. However, the majority of remaining States, constituting the developing countries, raised their objections about such a regime, especially in question of these resources being the "common heritage of mankind". These objections proposed a "strong international authority" with "exclusive rights to mine the common heritage area, involving States or private groups only as it saw fit". Thus, the middle-ground solution to accommodate the needs and requests of both developed and developing states was to include the public and private enterprises, but to also have a "parallel system" responsible for collective mining (United Nations - Office of Legal Affairs, 2012).

This middle-ground solution formally established the seabed mineral deposits to be maintained via UNCLOS's International Seabed Authority, ISA, (the Authority), which is an international intergovernmental body whose main responsibility is the administration of resource projects in the Area. The ISA is headquartered in Jamaica and organized like a public-traded corporation, with a business unit referred to as the Enterprise, in addition to the Assembly, Council and Secretariat. The Authority's Assembly consists of representatives of all nations, and it is the "the supreme body for setting policy in the Authority". The Council is an executive organ consisting of 36 members elected from among the members of the Authority with specified powers over specific key policies responsible for the decision-making. The work of the Authority is supported by the Legal and Technical Commission in addition to the Secretariat headquartered in Jamaica. The Finance Committee is responsible for implementing cost-effective running of the organization. Lastly, and very importantly the Enterprise is the mining arm of the authority responsible for resource mining (United Nations Convention on the Law of the Sea, 1982; Chapter 2: Maritime Zones; Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982, 1994).

The International Seabed Authority (ISA) Mining Code (Draft Regulations) was developed within the legal framework of the Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea (UNCLOS) of 10 December 1982 (Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982, 1994; Draft regulations on exploitation of mineral resources in the Area (ISBA/25/C/WP.1), 2019). These draft regulations aim to regulate the "prospecting, exploration and exploitation of marine minerals in the international seabed Area, or the ‘Area’” (The Mining Code, n.d.). Despite not allowing any state to “claim or exercise sovereignty or sovereign rights over any part of the Area or its resources”, these regulations emphasize that they “shall not in any way affect the freedom of scientific research, pursuant to article 87 of the Convention, or the right to conduct marine scientific research in the Area pursuant to articles 143 and 256 of the Convention. Nothing in these regulations shall be construed in such a way as to restrict the exercise by States of the freedom of the high seas as reflected in article 87 of the Convention” (Draft regulations on exploitation of mineral resources in the Area (ISBA/25/C/WP.1), 2019).

However, in the “Fundamental policies and principles”, the regulations “recognize that the rights in the Resources of the Area are vested in mankind as a whole, on whose behalf the Authority shall act”, and they state a view that ensures various principles including (Draft regulations on exploitation of mineral resources in the Area (ISBA/25/C/WP.1), 2019):

> (vii) “The enhancement of opportunities for all States Parties, irrespective of their social and economic systems or geographical location, to participate in the development of the resources of the Area and the prevention of monopolization of activities in the Area;
>
> (viii) The protection of developing countries from serious adverse effects on their economies or on their export earnings resulting from a reduction in the price of an affected Mineral or in the volume of exports of that Mineral, to the extent that such reduction is caused by activities in the Area;
>
> (ix) The development of the common heritage for the benefit of mankind as a whole; and
>
> (x) That conditions of access to markets for the imports of minerals produced from the resources of the Area and for imports of commodities produced from such minerals shall not be more favourable than the most favourable applied to imports from other sources.”

The Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area make the distinction between “exploitation”, “exploration”, and “prospecting” as follows (Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area / proposed by the Legal and Technical Commission, 2013):

- “exploitation” means the recovery for commercial purposes of polymetallic nodules in the Area and the extraction of minerals therefrom, including the construction and operation of mining, processing and transportation systems, for the production and marketing of metals;
- “exploration” means searching for deposits of polymetallic nodules in the Area with exclusive rights, the analysis of such deposits, the testing of collecting systems and equipment, processing facilities and transportation systems, and the carrying out of studies of the environmental, technical, economic, commercial and other appropriate factors that must be taken into account in exploitation;
- “prospecting” means the search for deposits of polymetallic nodules in the Area, including estimation of the composition, sizes and distributions of polymetallic nodule deposits and their economic values, without any exclusive rights;

The regulations on prospecting specifically state that, "Prospecting shall not confer on the prospector any rights with respect to resources. A prospector may, however, recover a reasonable quantity of minerals, being the quantity necessary for testing, and not for commercial use" (Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area / proposed by the Legal and Technical Commission, 2013).

Seabed mining is fragmented and different rights depend on the locations. The Draft regulations on exploitation of mineral resources in the Area discuss details about exploitation contracts, where it defines a specific "Contract Area", where the Contractor shall implement a Plan of Work in accordance with Good Industry Practice. In Annex X, two sections further lay out important details about the rights of Contractors to the minerals exploited (Draft regulations on exploitation of mineral resources in the Area (ISBA/25/C/WP.1), 2019):

> **"Section 4**
> **Security of tenure and exclusivity**
> 4.1 The Contractor is hereby granted the exclusive right under this Contract to Explore for and Exploit the resource category specified in this Contract and to conduct Exploitation activities within the Contract Area in accordance with the terms of this Contract. The Contractor shall have security of tenure and this Contract shall not be suspended, terminated or revised except in accordance with the terms set out herein.
> 4.2 The Authority undertakes not to grant any rights to another person to Explore for or Exploit the same resource category in the Contract Area for the duration of this Contract.
> 4.3 The Authority reserves the right to enter into contracts with third parties with respect to Resources other than the resource category specified in this Contract but shall ensure that no other entity operates in the Contract Area for a different category of Resources in a manner that might interfere with the Exploitation activities of the Contractor.
> 4.4 If the Authority receives an application for an exploitation contract in an area that overlaps with the Contract Area, the Authority shall notify the Contractor of the existence of that application within 30 Days of receiving that application.
>
> **Section 5**
> **Legal title to Minerals**
> 5.1 The Contractor will obtain title to and property over the Minerals upon recovery of the Minerals from the seabed and ocean floor and subsoil thereof, in compliance with this Contract.
> 5.2 This Contract shall not create, nor be deemed to confer, any interest or right on the Contractor in or over any other part of the Area and its Resources other than those rights expressly granted in this Contract."

One very important aspect in this governance regime is the concept of "Reserved Areas" in the international seabed area and its mineral resources that can be either accessed by developing countries or by the Enterprise. According to Article 8 of UNCLOS, Annex III. Basic Conditions of Prospecting, Exploration and Exploitation (Reserved Areas; United Nations Convention on the Law of the Sea, 1982),

> "Each application, other than those submitted by the Enterprise or by any other entities for reserved areas, shall cover a total area, which need not be a single continuous area, sufficiently large and of sufficient estimated commercial value to allow two mining operations. The

> applicant shall indicate the coordinates dividing the area into two parts of equal estimated commercial value and submit all the data obtained by him with respect to both parts. Without prejudice to the powers of the Authority pursuant to article 17 of this Annex, the data to be submitted concerning polymetallic nodules shall relate to mapping, sampling, the abundance of nodules, and their metal content. Within 45 days of receiving such data, the Authority shall designate which part is to be reserved solely for the conduct of activities by the Authority through the Enterprise or in association with developing States. This designation may be deferred for a further period of 45 days if the Authority requests an independent expert to assess whether all data required by this article has been submitted. The area designated shall become a reserved area as soon as the plan of work for the non-reserved area is approved and the contract is signed."

The reservation of areas is one of UNCLOS's strategies to "ensure that developing countries can access deep sea mineral resource" (Reserved Areas). This process involves the applicant for exploration rights to "divide the total area into two parts of equal estimated commercial value and provide survey data and information to substantiate the estimated values", which is then reviewed by the ISA Legal and Technical Commission (Current Status of the Reserved Areas with the International Seabed Authority, 2019).

Currently, the ISA has 15-year contracts with 22 contractors, and it generally has a total of 31 contracts, including 19 for PMN in the Clarion-Clipperton Fracture Zone and Central Indian Ocean Basin and Western Pacific Ocean, 7 for PMS in the South West Indian Ridge, Central Indian Ridge and the Mid-Atlantic Ridge, and 5 for CFC in the Western Pacific Ocean (International Seabed Authority, 2022). Out of these contracts, *Table 8* and *Table 9* show the current status of the "reserved areas" with the International Seabed Authority and the six "developing countries" who were given exploration contracts. One important note is that the first six contractors in *Table 8*, including India and China, had contributed reserved areas in the 1980s-1990s, before UNCLOS came into force, under the "pioneer inverstor regime" (Current Status of the Reserved Areas with the International Seabed Authority, 2019).

Table 8. Reserved areas available with the International Seabed Authority (as of January 2019) (adapted from *(Current Status of the Reserved Areas with the International Seabed Authority, 2019)*)

Polymetallic nodules contractors	**Original reserved areas (sq. km)**	**Remaining reserved areas (sq. km) (as of 2019)**	**Final area allocated to contractors (sq. km)**
Government of India – MOES	150,000	150,000	75,000
Deep Ocean Resources Development Co. Ltd. (DORD) (Japan)	150,000	123,901	75,000
Institut français de recherche pour l'exploitation de la mer (IFREMER) (France)	155,440	139,677	75,000

Yuzhmorgeologiya (Russian Federation)	132,328	87,531	75,000
China Ocean Mineral Resources Research and Development Association (COMRA) (China)	150,000	118,518	75,000
Interoceanmetal Joint Organization (IOM) (Bulgaria, Cuba, Czechia, Poland, Russian Federation and Slovakia)	150,000	93,898	75,000
Government of the Republic of Korea	150,000	68,008	75,000
Federal Institute for Geosciences and Natural Resources of the Federal Republic of Germany (BGR)	72,744	31,766	77,230
UK Seabed Resources Ltd I (United Kingdom)	58,280	0	57,720
Global Sea Mineral Resources NV (GSR) (Belgium)	71,937	0	76,728
UK Seabed Resources Ltd II (United Kingdom)	74,904	74,904	74,919
Total	**1,315,633**	**888, 218**	**811,597**

Table 9. Reserved areas allocated to developing countries (adapted from *(Current Status of the Reserved Areas with the International Seabed Authority, 2019)*)

Contractor	**Sponsoring State**	**Reserved areas allocated (sq. km)**
Tonga Offshore Mining Limited	Tonga	74,713
Nauru Ocean Resources Inc.	Nauru	74,830
Marawa Research and Exploration Ltd.	Kiribati	74,990
Ocean Mineral Singapore PTE Ltd.	Singapore	58,280
Cook Islands Investment Corporation	Cook Islands	71,937
China Minmetals Corporation	People's Republic of China	72,745
Total	**888, 218**	**427,495**

Finally, and very importantly, the Authority has the responsibility for the protection of the marine environment and of underwater cultural heritage in the Area. From here, Section 7 of the draft regulations specifically holds the Contractor liable to the Authority for "for the actual amount of any damage, including damage to the Marine Environment, arising out of its wrongful acts or omissions, and those of its employees, subcontractors, agents and all persons engaged in working or acting for them in the conduct of its operations under this Contract, including the costs of reasonable measures to prevent and limit damage to the Marine Environment, account being taken of any contributory acts or omissions by the Authority or third parties" (Draft regulations on exploitation of mineral resources in the Area (ISBA/25/C/WP.1), 2019). More recently, a historic agreement was achieved on the text of theHigh Seas Treaty to advance the protection and management of the High Seas' marine biodiversity (HSA/Civil Society, 2023). The treaty still needs to be adopted, followed by 60 ratifications to enter into force (HSA/Civil Society, 2023).

Although not yet adopted, the ISA Mining Code in this governance analog is very interesting to analyze in the context of space resources, due to the parallels in the various stakeholders of interest, the high scientific and economic benefit, the harsh operating conditions, and the limited knowledge about the wide variety of resources available.

8.2.2 Antarctic

Sovereignty over the Antarctic has historically been a very heavily conflicted political topic. There are three groups with interest in the Antarctic pre-1959. Chile and Argentina, the "South American claimants", are the first group casting their territorial rights and claims back to the Alexander VI's 1493 papal bull granting the Arctic pole territory to Spain and its successors, which Chile and Argentina qualify as (Scott, 2010). The second group consisted of the United Kingdom, France, Norway, New Zealand, and Australia, where they negotiated how the continent would be divided between them, despite unresolved overlapping claims between the United Kingdom and the South American claimants (Scott, 2010). The third group consisted of the United States, the Soviet Union, Japan, South Africa, and Belgium, all of which showed active interest in the Antarctic but had not formally made territorial claims there (Scott, 2010).

After various conflicting claims, in 1948, the United States proposed a draft agreement assigning the Antarctic authority to Argentina, Australia, Chile, France, Norway, New Zealand, the United Kingdom, and the United States. In the same year, Julio Escudero Buzman, a Chilean law professor, suggested that "existing legal rights and interests in Antarctica be frozen for a period of five or ten years, during which activities in Antarctica would have no legal effect" (The Ambassador in Chile (Bowers) to the Secretary of State, 1948; Memorandum of Conversation, by the Under Secretary of State (Lovett), 1948; Scott, 2010). After this strategy proved to be effective between governments in the year of 1957 to 1958, they "reached a sort of gentleman's agreement not to engage in legal or political argumentation during that period, in order that the scientific program might proceed without impediment" (Daniels, 1973). This proven success culminated in the Antarctic Treaty proposed by the United Sates in 1959.

The Antarctic governance framework is one of the most interesting Earth-analogs to look at when considering governance frameworks for space, as the two share parallels in terms of their harsh environments, opportunities for scientific exploration, international cooperation, potential for resource exploration, and remote and isolated nature. The Antarctic—a non-sovereign territory including its land and resources—is currently governed by the Antarctic Treaty System (ATS).

This Treaty entered into force on June 23, 1961, and it currently has 54 Parties to the Treaty (Antarctic Treaty, 1961). This Treaty, according to Article VI, defines the scope of its application to be on "to the area south of 60° South Latitude, including all ice shelves, but nothing in the present Treaty shall prejudice or in any way affect the rights, or the exercise of the rights, of any State under international law with regard to the high seas within that area" (Antarctic Treaty, 1961).

The first three articles of the Treaty are important as they restrict the use of the Antarctic for peaceful purposes only, emphasize the freedom of scientific investigation in Antarctica and cooperation toward that end, and state that the "scientific observations and results from Antarctica shall be exchanged and made freely available". In its other provisions, the Treaty also prohibits any measures of military nature or nuclear explosions and radioactive waste material (Antarctic Treaty, 1961).

The signatories of the Treaty included nation states with territorial claims (Argentina, Australia, Chile, France, New Zealand, Norway, and the United Kingdom) and others who do not recognize any claims. Article IV and Article VII of the Treaty are important in this context, as they state that (Antarctic Treaty, 1961):

> "No acts or activities taking place while the present Treaty is in force shall constitute a basis for asserting, supporting, or denying a claim to territorial sovereignty in Antarctica or create any rights of sovereignty in Antarctica. No new claim, or enlargement of an existing claim to territorial sovereignty in Antarctica shall be asserted while the present Treaty is in force." (Article IV)
>
> "To promote the objectives and ensure the observance of the provisions of the Treaty, "All areas of Antarctica, including all stations, installations and equipment within those areas … shall be open at all times to inspection" (Article VII)

In the current regime, any member of the United Nations can accede to the Treaty. The signatories include Consultative Parties, who get decision-making powers based on being original signatories or by "*conducting substantial scientific research there*" (The Antarctic Treaty Explained, 1999). Non-Consultative Parties do not participate in the decision-making but are invited to attend the Consultative Meetings. Decision-making is consensus-based, using voting from the Consultative Parties.

According to the Treaty, it is illegal to claim ownership or have jurisdiction over any land in the Antarctic, but nation states can establish research stations (Antarctic Treaty, 1961). Every nation would then have the rights and obligations to manage their "land", facilities, and people—in a concept of "what you bring is what you own", similar to the framework on the International Space Station (ISS) (International Space Station Intergovernmental Agreement (IGA), 1998).

However, when discussing the Antarctic mineral resources, The Protocol on Environmental Protection to the Antarctic Treaty, provides a very important legal basis for the current regime in the Antarctic. The Environment Protocol was signed in 1991 and entered into force in 1998 (The Protocol on Environmental Protection to the Antarctic Treaty, 1998; Recommendation XI-1 (ATCM XI - Buenos Aires, 1981), 1989). Article 2 of this Protocol on "Objective and Designation" designates Antarctica as a "natural reserve, devoted to peace and science". Article 3 lays out the "Environmental

Principles" for human activities in Antarctica, specifically stressing on the "protection of the Antarctic environment and dependent and associated ecosystems and the intrinsic value of Antarctica, including its wilderness and aesthetic values and its value as an area for the conduct of scientific research, in particular research essential to understanding the global environment, shall be fundamental considerations in the planning and conduct of all activities in the Antarctic Treaty area". Article 8 afterwards focuses on the environmental impact assessment (The Protocol on Environmental Protection to the Antarctic Treaty, 1998).

Article 7 of the Environment Protocol is of particular importance, however, as it states, "Any activity relating to mineral resources, other than scientific research, shall be prohibited." This prohibition can only be removed if a binding legal agreement among parties on mineral exploitation is reached as prescribed under Article 25.5 of the Environment Protocol (The Protocol on Environmental Protection to the Antarctic Treaty, 1998). It is important to note, however, that this Environmental Protocol and the Antarctic Treaty are on a ticking clock to expire in 2048. Until then, unanimous agreement of all Consultative Parties to the Antarctic Treaty is needed to do any modifications to the Articles of the Environmental Protocol. It will be very interesting to see how the future of the Antarctic will look like after the expiration of the Treaty.

Being one of the four global commons, the Antarctic region is an important analog for outer space. Since entering into force in 1961, the Antarctic Treaty has been recognized as one of the most successful international agreements, and scientific research has been proceeding unhindered. (The Antarctic Treaty Explained, 1999). Thus, the Antarctic governance regime can help safeguard space and "maintain it as one of the four commons for humankind under international law and to defuse political tensions" (Salazar, 2015). However, the philosophical and ethical "dilemma" occurs when one starts to question the balance needed between the current Antarctic model, especially to mineral resources, and the importance of not hindering innovation in space.

8.3 Data Analysis Methods

The data analysis process used three main steps to answer the research questions:

(1) The first step was organizing the collected data on the two analog governance systems on Earth, specifically regarding the involved stakeholders, decision-making procedures, property rights, allocation mechanisms, access to the governance system, resource management, and regime enforcement for each, into a database spreadsheet. In this spreadsheet, the evidence on each of the considered governance analogs, along with redundant confirming sources on each of the listed dimensions were organized in a traceable manner.

(2) The next step, after the data was organized, was to implement Systems Architecture analysis tools and methods on the collected data for each of the governance analogs outlined in more detail in Chapter 8.3.1 Systems Architecture Analysis. The goal of using these methods was to analyze the stakeholders, functions, and forms that emerge in each of the governance analogs considered, to meet different stakeholder objectives, thus, supporting Research Question (3.2) of this thesis work. To do this analysis, the collected and organized facts on each system were standardized and categorized under each of the dimensions listed above (involved stakeholders, decision-making procedures, property rights, allocation mechanisms, access to the governance system, resource management, and regime enforcement for each) to easily compare the architecture of each of the systems.

(3) Following that, the next step involved evaluating each of the governance systems using TWAIL as detailed in Chapter 8.3.2 Governance System Evaluation to identify the gaps and strengths that each system has and to assess each accordingly. This analysis involved using the findings of the Systems Architecture analysis to see the alignment of each of the governance analogs with the principles of the considered theoretical frameworks and to draw conclusions.

8.3.1 Systems Architecture Analysis

To analyze each of the considered governance systems and understand the intricacy of their structures, this research conducted Systems Architecture analyses that involve an "embodiment of concept, the allocation of physical/informational function to the elements of form, and the definition of relationships among the elements and with the surrounding context" (Crawley, Cameron, & Selva, 2015).

The analysis for each system involved six steps outlined in *Figure 42* that were based on the methodologies work of Maier et al, Crawley et al., de Weck et al. and (Maier, 2009; Crawley, Cameron, & Selva, 2015; de Weck, Roos, & Magee, Engineering Systems: Meeting Human Needs in a Complex Technological World, 2011). These steps were previously used in Joseph & Wood's work on the "Analysis of the Microgravity Research Ecosystem and Market Drivers of Accessibility" (Joseph & Wood, 2021).

The first step of this process focused on defining the system boundaries and understanding the context of the system operation. This context can be analyzed at different levels including the organizational, supporting, national and international contexts, while considering Technology, Policy, Collaboration and Economics factors at each of these levels (Crawley, Cameron, & Selva, 2015).

The next two steps involved conducting a stakeholder analysis for each of the systems which was carried out in three steps starting with identifying the stakeholders and relationships, then categorizing these stakeholders and finally identifying their needs and desired outcomes. Stakeholders are the people, groups, and organizations that impact a system or are impacted by a system (Freeman & Mcvea, 2001) and they can fall into multiple categories. Primary Stakeholders are the ones making decisions to shape the system; Secondary Stakeholders influence decisions of Primary Stakeholders, and Tertiary Stakeholders are the Beneficiaries of the System (Crawley, Cameron, & Selva, 2015).

Following that was the last and key part of the analysis, which was focused on identifying and studying the form-function relationship—where functions are the actions and activities performed to achieve the stakeholder objectives, and these functions are executed by the so-called "forms". This ties to the principle of emergence where "the functionality of these system entities and their relationships as a whole is greater than the sum of the individual entities" (Maier, 2009; Crawley, Cameron, & Selva, 2015; Joseph & Wood, 2021).

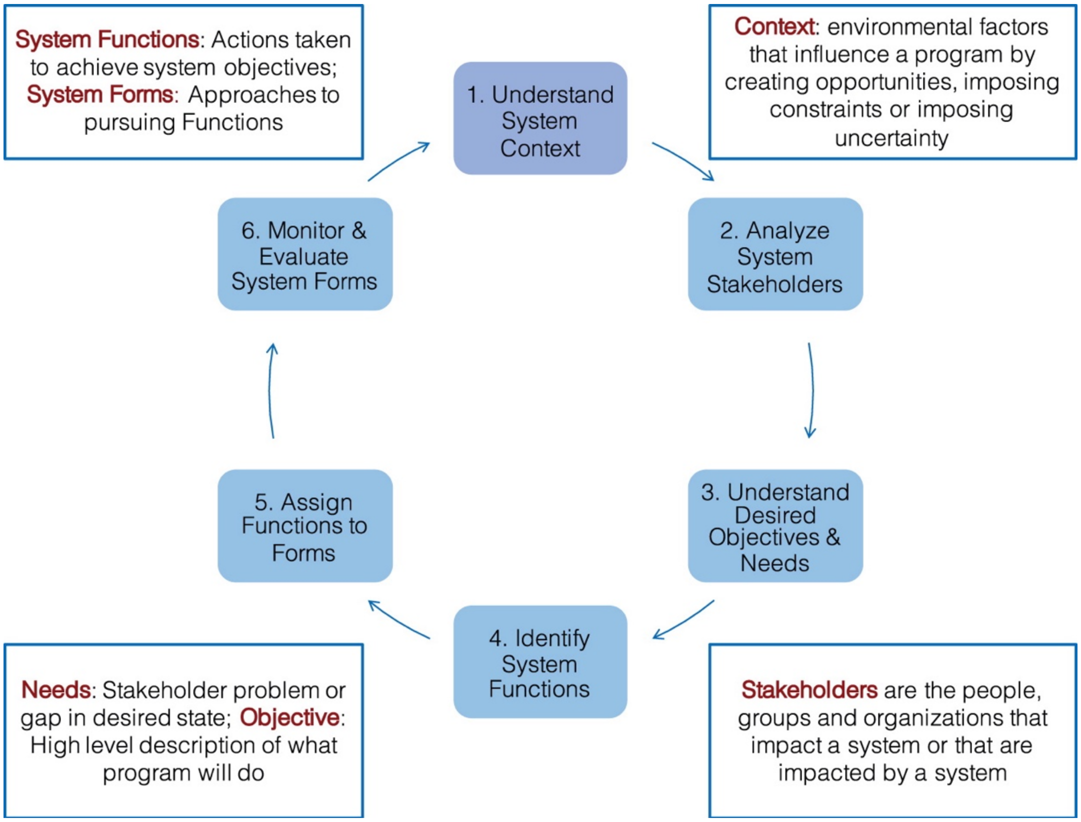


Figure 42. Systems architecture processes. Image credit: Danielle Wood. *(Joseph & Wood, 2021)*

8.3.2 Governance System Evaluation using Third World Approaches to International Law (TWAIL)

In the discussion of equitable and ethical governance framework for space exploration, Third World Approaches to International Law (TWAIL) plays a critical role in the system analysis and evaluations. As defined by Natarajan et al., "Third World Approaches to International Law (TWAIL) is a movement encompassing scholars and practitioners of international law and policy who are concerned with issues related to the Global South. The scholarly agendas associated with TWAIL are diverse, but the general theme of its interventions is to unpack and deconstruct the colonial legacies of international law and engage in efforts to decolonise the lived realities of the Global South" (Natarajan, Reynolds, Bhatia, & Xavier, 2016).

It's noteworthy to point that the concept of "Third World" has a complex history and a lot of post-colonial heritage. However, as defined by TWAIL-ers, this term refers to the "group of states, which are politically, economically, and culturally diverse, but are simultaneously united in their common history of colonialism" (Mutua & Anghie, 2000; Chimni, 2006). Some TWAIL-ers consider the "Third World" term without a pejorative connotation, but rather a continuing political reality aggregated by the economic diversification of states, thus increasing the importance of the unity of the so-called "Third World" to face the continuing imperial practices, politically and economically, by the "First World" states (Mutua & Anghie, 2000; Chimni, 2006).

One of the goals of TWAIL is to "reconcile international law's promise of justice with the proliferation of injustice in the world it purports to govern" (Natarajan, Reynolds, Bhatia, & Xavier, 2016). Mutua further explains TWAIL as the "broad dialectic of opposition to international law", specifically stating that the reason is because "the regime of international law is illegitimate. It is a predatory system that legitimizes, reproduces and sustains the plunder and subordination of the Third World by the West. Neither universality nor its promise of global order and stability make international law a just, equitable, and legitimate code of global governance for the Third World. The construction and universalization of international law were essential to the imperial expansion that subordinated non-European peoples and societies to European conquest and domination" (Mutua & Anghie, 2000).

As a response to decolonization, Mutua details TWAIL's three interrelated objectives to be (Mutua & Anghie, 2000):

1. "The first is to understand, deconstruct, and unpack the uses of international law as a medium for the creation and perpetuation of a racialized hierarchy of international norms and institutions that subordinate non-Europeans to Europeans.
2. Second, it seeks to construct and present an alternative normative legal edifice for international governance.
3. Finally, TWAIL seeks through scholarship, policy, and politics to eradicate the conditions of underdevelopment in the Third World."

To achieve these objectives, however, TWAIL does not have a singular doctrine but rather a number of diverse methodologies used by different scholars such as Marxism, feminism, and critical race theory. In this research, we consider these different methodologies in the governance system evaluations.

8.4 Summary of Data Collection and Analysis Methods

In summary, this research used a series of peer-reviewed publications, treaties, UN documents and statements, legal and governance statements, in addition to government and specific council websites to collect data on two analog governance systems on Earth: (1) High Seas and Deep Seabed and (2) Antarctica. The data was specifically collected regarding the involved stakeholders, decision-making procedures, property rights, allocation mechanisms, access to the governance system, resource management, and regime enforcement for each. Once the data on each of these systems was collected, it was organized in spreadsheets and analyzed using Systems Architecture tools and methods followed by governance system evaluation using the Third World Approaches to International Law (TWAIL) lens to identify the gaps and strengths of each of the governance systems. The results of this analysis, as they guide proposing the new policy framework for sustainable and equitable space resource utilization, are presented in Chapter 9: Results and Discussion.

Chapter 9: Results and Discussion

9.1 Systems Architecture Analysis

This sub-chapter provides the results of the Systems Architecture analyses conducted on the High Seas and Deep Seabed in addition to Antarctica, as outlined in Chapter 8.3.1 Systems Architecture Analysis. For each of these systems, the system boundaries and context of operation is studied, and then followed by a detailed stakeholder analysis and an exploration of the system form-function relationship.

9.1.1 High Seas and Deep Seabed

9.1.1.1 System Context

The first step in analyzing the governance regime of the High Seas and Deep Seabed is to understand its context of operations, considering the Technology, Policy, Collaboration and Economics factors at the organizational, supporting, national and international levels. Outlining these factors is critical for understanding the constraints, opportunities and uncertainties that they create, in addition to defining the boundaries of the system analyzed.

For this analysis, the main focus of the studied system is on the governance regime for the non-living natural resources of the deep seabed. Environmental concerns are briefly considered in the stakeholder analysis and contextual study, but the detailed analysis of the environmental protection of the marine life and deep seabed is outside the scope of this research. Similarly, tourism is briefly mentioned but not considered in the studied focus of the system.

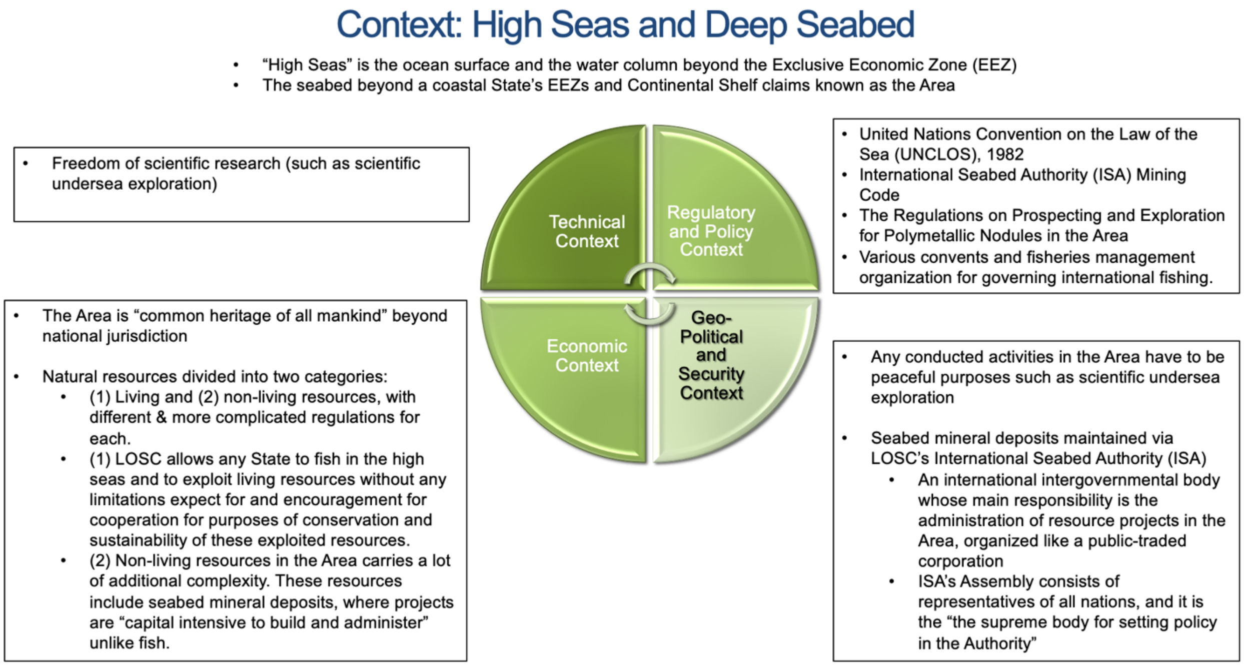
From a technical standpoint, the current technology status for the ability to conduct deep seabed mining, in addition to fully understanding the marine environment is critical. However, there is an overall acknowledgment of the importance of freedom of scientific research (such as scientific undersea exploration).

On a regulatory and policy level, the legal framework of this system is mainly defined by the United Nations Convention on the Law of the Sea (UNCLOS), 1982, the International Seabed Authority (ISA) Mining Code draft, The Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area, in addition to various convents and fisheries management organization for governing international fishing.

From a geopolitical and security standpoint, the seabed mineral deposits are maintained via UNCLOS's International Seabed Authority (ISA), which as previously discussed, is an international intergovernmental body whose main responsibility is the administration of resource projects in the Area. It is organized like a public-traded corporation, where the ISA's Assembly consists of representatives of all nations, and it is "the supreme body for setting policy in the Authority". Any conducted activities in the Area have to be for peaceful purposes such as scientific undersea exploration.

Economically, the Area is considered "common heritage of all mankind" beyond national jurisdiction. The natural resources divided into two categories: (1) Living and (2) non-living resources, with different & more complicated regulations for each. It is allowed to fish in the high seas and to exploit living resources without any limitations expect for and encouragement for cooperation for purposes of conservation and sustainability of these exploited resources. However, non-living resources, including seabed mineral deposits, in the Area carry a lot of additional complexity.

A summary of these contextual factors considered for the High Seas and Deep Seabed is available in *Figure 43*. A number of constraints arise from these factors including the physical amount of available resources in the deep seabed and level of scientific knowledge affecting the status of understanding the marine and deep seabed environment. Additionally, since this system is mainly legally bounded by treaties like UNCLOS, a direct constraint is that the framework only applies to states that are parties to the treaty, unlike the United States for example, who only views these laws as customary international law but has not ratified UNCLOS.



Context: High Seas and Deep Seabed

- "High Seas" is the ocean surface and the water column beyond the Exclusive Economic Zone (EEZ)
- The seabed beyond a coastal State's EEZs and Continental Shelf claims known as the Area

- Freedom of scientific research (such as scientific undersea exploration)

- United Nations Convention on the Law of the Sea (UNCLOS), 1982
- International Seabed Authority (ISA) Mining Code
- The Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area
- Various convents and fisheries management organization for governing international fishing.

- The Area is "common heritage of all mankind" beyond national jurisdiction
- Natural resources divided into two categories:
  - (1) Living and (2) non-living resources, with different & more complicated regulations for each.
  - (1) LOSC allows any State to fish in the high seas and to exploit living resources without any limitations expect for and encouragement for cooperation for purposes of conservation and sustainability of these exploited resources.
  - (2) Non-living resources in the Area carries a lot of additional complexity. These resources include seabed mineral deposits, where projects are "capital intensive to build and administer" unlike fish.

- Any conducted activities in the Area have to be peaceful purposes such as scientific undersea exploration
- Seabed mineral deposits maintained via LOSC's International Seabed Authority (ISA)
  - An international intergovernmental body whose main responsibility is the administration of resource projects in the Area, organized like a public-traded corporation
  - ISA's Assembly consists of representatives of all nations, and it is the "the supreme body for setting policy in the Authority"

Figure 43. System Context for the High Seas and Deep Seabed.

9.1.1.2 System Stakeholders Analysis

The next step in this study is conducting a stakeholder analysis for the High Seas and Deep Seabed, where stakeholders are identified and categorized into primary, secondary, and tertiary stakeholders. As previously defined, Primary Stakeholders are the ones making decisions to shape the system; Secondary Stakeholders influence decisions of Primary Stakeholders, and Tertiary Stakeholders are the Beneficiaries of the System (Crawley, Cameron, & Selva, 2015).

In the case of the High Seas and Deep Seabed, the Primary Stakeholders identified are UNLOS's International Seabed Authority (ISA) in addition to governments and governmental agencies, as they currently withhold the highest decision-making powers in shaping the deep seabed system and future. Influencing their decisions, however, are the Secondary Stakeholders that include scientific researchers and organizations, conservationists, non-governmental organizations NGO's (civil society), the commercial sector and industry (including fisheries, etc.), fisheries management organizations, and humankind as a whole. Lastly, the beneficiaries of the system, identified as Tertiary Stakeholders include an overlap of some of the Primary and Secondary stakeholders including UNCLOS' International Seabed Authority (ISA), governments and governmental agencies, scientific researchers and organizations, conservationists, NGO's (civil society), the commercial sector and industry (including fisheries, etc.), fisheries management organizations, and finally once again humankind.

Table 10 shows a summary of the stakeholder needs, outlining what problems or desires they are facing and desired outcomes they would like in the future. These needs and desired outcomes help define the general system objectives. Based on this analysis for the High Seas and Deep Seabed, the main emerging system objectives are ensuring activities for peaceful purposes only, ensuring that the Area is "common heritage of all mankind" beyond national jurisdiction, ensuring free and scientific investigation and cooperation, continuing the environmental protection of the Area, and lastly balancing the needs of governments, science community, civil society, and the commercial sector/industry. The latter objective is particularly complex within this system's framework.

Table 10. Stakeholder Needs, Desired Outcomes and Objectives for the High Seas and Deep Seabed.

Stakeholder Need What problems or desires are stakeholders facing?	• UNCLOS' International Seabed Authority (ISA) need to maintain peaceful activities, ISA mining code, and inter-governmental agreements and domestic agendas. • Scientific researchers/organizations need freedom of scientific investigation and cooperation, funding, and workforce. • Conservationists, NGO's (civil society) need to protect the nature and environment in High Seas and Deep Seabed • Commercial sector/ Industry needs to conduct profitable activities of living and non-living natural resources in the region.
Desired Outcomes What do stakeholders want the world to be like in the future?	• Activities conducted for peaceful purposes only • Freedom of scientific investigation and cooperation • Protected environment of the High Seas and Deep Seabed • Opportunities to make profits our of mineral resources of living and non-living natural resources in the region.
System Objectives What activities will a system do to contribute to the desired outcomes?	• Ensuring activities for peaceful purposes only • Ensuring that The Area is "common heritage of all mankind" beyond national jurisdiction • Ensuring free and scientific investigation and cooperation • Continuing the environmental protection of the area • Balancing the needs of governments, science community, civil society, and the commercial sector/industry.

9.1.1.3 System Forms and Functions

The last and key part of the analysis is focused on identifying and studying the form-function relationship of the system. As previously defined, functions are the actions and activities performed to achieve the stakeholder objectives. These functions are executed by the so-called "forms", which can include organizations, people, processes, programs and objects.

For the High Seas and Deep Seabed, *Table 11* presents a detailed overview of main identified systems functions and sub-functions. These functions can be grouped into four different categories (1) governance and organization, (2) science and research, (3) industry and tourism, and (4) environmental protection. The main system functions outlined follow the previously identified system objectives.

Table 12 shows the current form-function relationship of the system, by analyzing the alternative existing forms to execute functions for the High Seas and Deep Seabed. As previously discussed in the system boundaries and scope, the main focus of this analysis is on the governance and organization for the deep seabed resources. From here, *Table 13* presents a deeper dive in the current forms that execute each of the sub-functions in the governance and organization category's system function "Balancing the needs of governments, science community, civil society and the commercial sector/industry". This section of the analysis in *Table 13* is particularly important for the system forms evaluation conducted in the following chapter of this thesis.

Table 11. System Functions and Sub-Functions for the High Seas and Deep Seabed.

Function Category	**System Functions**	**Detailed System Sub-Functions**
Governance and Organization	Balancing the needs of governments, science community, civil society and the commercial sector/industry.	• Decision making • General policymaking • Supporting the work of the seabed authority • Implementing cost-effective running of the organization • Mining seabed resources • Conducting all of early activities through joint ventures with commercial operators • Facilitating technology transfer for developing states or the authority acquiring required technology where it's not available through the ordinary market on viable commercial terms • Enforcing activities for peaceful purposes only • Monitoring the ongoing activities and concerns of the science community, civil society and the commercial sector/industry. • Inspecting all activities in the areas of the system • Monitoring the practice of the right of innocent passage.

	Governing the Area as “common heritage of all mankind” beyond national jurisdiction	• Administering resource projects in the Area • Prohibiting national jurisdiction claims **Using Draft regulations on exploitation of mineral resources in the Area (ISBA/25/C/WP.1), 2019:** • Enhancing “opportunities for all States Parties, irrespective of their social and economic systems or geographical location, to participate in the development of the resources of the Area and the prevention of monopolization of activities in the Area” • Protecting “developing countries from serious adverse effects on their economies or on their export earnings resulting from a reduction in the price of an affected Mineral or in the volume of exports of that Mineral, to the extent that such reduction is caused by activities in the Area” • Developing of the common heritage for the benefit of mankind as a whole • Defining “conditions of access to markets for the imports of minerals produced from the resources of the Area and for imports of commodities produced from such minerals shall not be more favourable than the most favourable applied to imports from other sources.”
Science and Research	Conducting free and scientific investigation and cooperation	• Conducting scientific investigation • Promoting and encouraging the conduct of marine scientific research in the international seabed area • Facilitating effective participation by developing States in deep sea exploration and research programmes. • Promoting international cooperation to advance marine scientific research in the deep seabed
Industry and Tourism	Fishing in the high seas	• Fishing in the high seas • Exploiting living resources without any limitations expect for an encouragement for cooperation for purposes of conservation and sustainability of these exploited resources.

	Utilizing of non-living seabed resources	• Regulating the "prospecting, exploration and exploitation of marine minerals in the international seabed Area, or the 'Area'" • Creating contracts for exploitation of mineral resources in the Area
	Conducting touristic activities	• Marine tourism, diving-tourism
Environmental Protection	Continuing the environmental protection of the area	• Protecting the High Seas and Deep Seabed environment and dependent and associated ecosystems • Ensuring conservation and sustainability of exploited resources

Table 12. Analysis of Alternative Forms to Execute Functions for the High Seas and Deep Seabed.

Function Category	**Analysis of Alternative Forms to Execute Functions**	
Governance and Organization	**Balancing the needs of governments, science community, civil society and the commercial sector/industry.** - UNCLOS's International Seabed Authority (ISA) - UNCLOS, ISA mining code, and inter-governmental agreements and domestic agendas	**Governing the Area as "common heritage of all mankind" beyond national jurisdiction** - UNCLOS's International Seabed Authority (ISA) - UNCLOS, ISA mining code, and inter-governmental agreements and domestic agendas - Draft regulations on exploitation of mineral resources in the Area (ISBA/25/C/WP.1), 2019
Science and Research	**Conducting free and scientific investigation and cooperation** - UNCLOS's International Seabed Authority (ISA) - UNCLOS, ISA mining code, and inter-governmental agreements and domestic agendas - Scientific researchers/organizations	

Industry and Tourism	**Fishing in the high seas** - Fisheries	**Utilizing of non-living seabed resources** - Scientific researchers/organizations - Industry and commercial sector - ISA's Enterprise	**Conducting touristic activities** - Tourism companies, cruises, etc.
Environmental Protection	**Continuing the environmental protection of the area** - UNCLOS's International Seabed Authority (ISA) - UNCLOS, ISA mining code, High Seas Treaty draft - Conservationists, NGO's (civil society) - Scientific researchers/organizations - Industry and commercial sector		

Table 13. Detailed Analysis of Alternative Forms to Execute Governance and Organization Functions for the High Seas and Deep Seabed.

Forms Functions	UNCLOS	International Seabed Authority (ISA) & ISA mining code	The Council	The Assembly	The Secretariat	Legal and technical commission	Finance Committee	The Enterprise	Inter-governmental agreements and domestic agendas
Decision making	X	X	X						X
General policymaking	X	X		X					X
Supporting the work of the seabed authority	X				X	X			
Implementing cost-effective running of the organization	X	X					X		
Mining seabed resources	X	X						X	X
Conducting all of early activities through joint ventures with commercial operators	X	X						X	X
Facilitating technology transfer for developing states or the authority	X	X							X
Enforcing activities for peaceful purposes only	X	X							
Monitoring & inspecting the ongoing activities	X	X							

9.1.1.4 Summary

Figure 44 is a Systems Architecture Analysis Summary for the High Seas and Deep Seabed. The figure highlights the external context, inputs, system stakeholders, system objectives, system functions, system forms, and emergent properties of the system. The figure is divided into four main sections.

The first section illustrates the external context of the system, which includes the United Nations Convention on the Law of the Sea (UNCLOS), International Seabed Authority (ISA) Mining Code, The Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area, and the notion of "common heritage of all mankind".

The second section shows the inputs to the system, which are constraints and opportunities. The constraints include the amount of available resources, the status of scientific knowledge on seabed resources and the marine environment, and the States that are not parties to UNCLOS.

The third section of the figure illustrates the system stakeholders, system objectives, system functions, and system forms. The system stakeholders are divided into three categories: primary, secondary, and tertiary. The primary stakeholders include UNLOSC's International Seabed Authority (ISA) and governments/governmental agencies. The secondary stakeholders include scientific researchers/organizations, conservationists, NGO's (civil society), commercial sector/industry (including fisheries, etc.), and fisheries management organizations. The tertiary stakeholders include governments/governmental agencies, scientific researchers/organizations, conservationists, NGO's (civil society), commercial sector/industry (including fisheries, etc.), fisheries management organizations, and humankind.

The system objectives are met by the system functions, which are executed by the system forms. The system functions include balancing the needs of governments, science community, civil society, and the commercial sector/industry; governing the Area as "common heritage of all mankind" beyond national jurisdiction; conducting free and scientific investigation and cooperation; fishing in the high seas; utilizing non-living seabed resources; conducting touristic activities; and continuing environmental protection of the area. The system forms include scientific researchers/organizations, fisheries, industry and commercial sector, tourism companies, cruises, conservationists, NGO's (civil society), and deep seabed resources (polymetallic nodules (PMN), polymetallic sulphides (PMS), and cobalt-rich ferromanganese crusts (CFC)).

The fourth section of the figure shows the emergent properties of the system, which is a governance regime for the deep seabed that ensures a balanced peaceful use of seabed resources under the notion of "common heritage of all mankind" while environmentally protecting the Area. Overall, *Figure 44* provides a comprehensive overview of the stakeholders, needs, functions, forms, constraints, and emergent properties of the High Seas and Deep Seabed system.

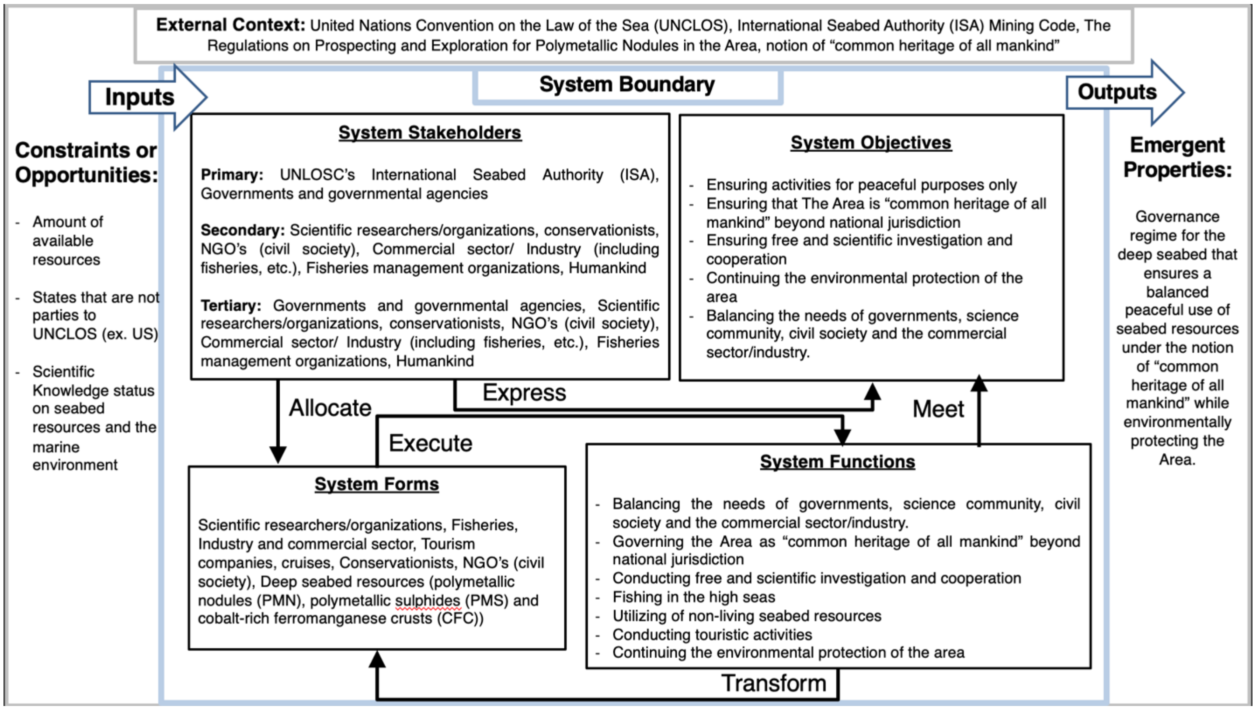


Figure 44. Systems Architecture Analysis Summary for the High Seas and Deep Seabed.

9.1.2 Antarctic

9.1.2.1 System Context

Similar to the analysis done for the High Seas and Deep Seabed, the first step in analyzing the governance regime of Antarctica is to understand its context of operations, considering the Technology, Policy, Collaboration and Economics factors at the organizational, supporting, national and international levels.

The system boundary chosen for this analysis is similar to that for the High Seas and Deep Seabed, where the main focus of the studied system is on the governance regime for the non-living natural resources of the Antarctic. Environmental concerns and touristic endeavors are once again briefly considered in the stakeholder analysis and contextual study, but the detailed analysis of the environmental protection of the Antarctic or the economics of tourism is outside the scope of this research.

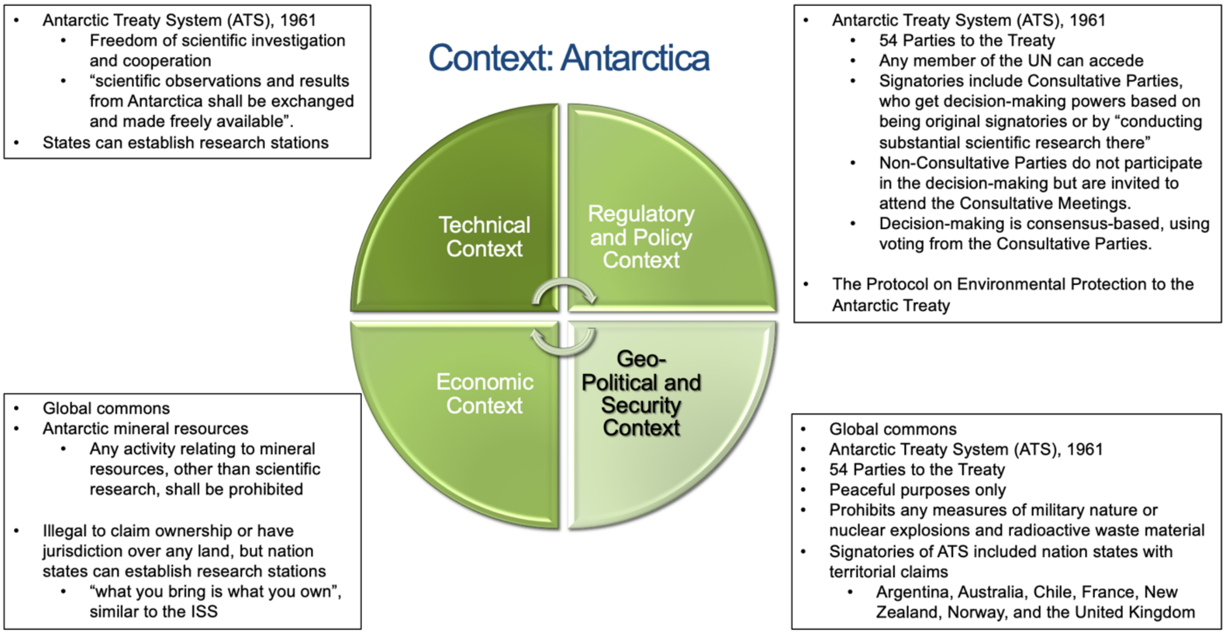
From a technical standpoint, the Antarctic Treaty System (ATS) of 1961 stresses on the freedom of scientific investigation and cooperation, allowing states to establish research stations where scientific results "shall be exchanged and made freely available" (Antarctic Treaty, 1961).

On a regulatory and policy level, the legal framework of this system is mainly defined by the Antarctic Treaty System (ATS) of 1961 in addition to The Protocol on Environmental Protection to the Antarctic Treaty. There are currently 54 parties to the ATS, and any member of the UN can accede. As previously described, the treaty signatories include Consultative Parties, who get decision-making powers based on being original signatories or by "conducting substantial scientific research there" and Non-Consultative Parties do not participate in the decision-making but are invited to attend the Consultative Meetings.

On a geopolitical and security level, the ATS restricts the use of the Antarctic for peaceful purposes only and prohibits any measures of military nature or nuclear explosions and radioactive waste material. The Antarctic is a global commons, however, the signatories of ATS include nation states with pre-treaty territorial claims like Argentina, Australia, Chile, France, New Zealand, Norway, and the United Kingdom.

Economically, once again, as global commons, it is illegal to claim ownership or have jurisdiction over any land in the Antarctic, but nation states can establish research stations. There is a "what you bring is what you own" regime, similar to the International Space Station (ISS). Furthermore, the ATS prohibits any activity relating to mineral resources, other than scientific research.

A summary of these contextual factors considered for Antarctica is available in *Figure 45*. A number of constraints arise from these factors including, once again, the physical amount of available resources there and level of scientific knowledge affecting the status of understanding the Antarctic environment. Similar to the case of the High Seas and Deep Seabed, since this system is mainly legally bounded by the ATS, a direct constraint is that the framework only applies to states that are parties to the treaty, in addition to (and more importantly in this case) the treaty expiration date and the uncertainty of the claims of states afterwards.



- Antarctic Treaty System (ATS), 1961
    - Freedom of scientific investigation and cooperation
    - "scientific observations and results from Antarctica shall be exchanged and made freely available".
- States can establish research stations

- Antarctic Treaty System (ATS), 1961
    - 54 Parties to the Treaty
    - Any member of the UN can accede
    - Signatories include Consultative Parties, who get decision-making powers based on being original signatories or by "conducting substantial scientific research there"
    - Non-Consultative Parties do not participate in the decision-making but are invited to attend the Consultative Meetings.
    - Decision-making is consensus-based, using voting from the Consultative Parties.
- The Protocol on Environmental Protection to the Antarctic Treaty

- Global commons
- Antarctic mineral resources
    - Any activity relating to mineral resources, other than scientific research, shall be prohibited
- Illegal to claim ownership or have jurisdiction over any land, but nation states can establish research stations
    - "what you bring is what you own", similar to the ISS

- Global commons
- Antarctic Treaty System (ATS), 1961
- 54 Parties to the Treaty
- Peaceful purposes only
- Prohibits any measures of military nature or nuclear explosions and radioactive waste material
- Signatories of ATS included nation states with territorial claims
    - Argentina, Australia, Chile, France, New Zealand, Norway, and the United Kingdom

Figure 45. System Context for Antarctica.

9.1.2.2 System Stakeholders and Needs

The next step in this study is conducting a stakeholder analysis for Antarctica, where stakeholders are identified and categorized into primary, secondary, and tertiary stakeholders. The Primary Stakeholders identified here are the Antarctic Treaty System (ATS) original signatories: Argentina, Australia, Chile, France, New Zealand, Norway, and the United Kingdom, and more generally the Consultative parties of the ATS, as they are the main current decision-makers in the Antarctic. Influencing their decisions, however, are the Secondary Stakeholders that include the Non-Consultative parties of the ATS, scientific researchers and organizations, conservationists and international environmental lobbies, civil society, international Non-Governmental Organizations (Greenpeace, etc.), the commercial sector and industry (including tourism, fisheries, etc.), and Humankind as a whole. Lastly, the beneficiaries of the system, identified as Tertiary Stakeholders, once again, include an overlap of some of the Primary and Secondary stakeholders including the Antarctic Treaty System (ATS) original signatories and Consultative parties, scientific researchers and organizations, conservationists, NGO's (civil society), the commercial sector and industry, and Humankind as a whole.

Table 14 shows a summary of the stakeholder needs, outlining what problems or desires they are facing and desired outcomes they would like in the future. Similar to the previous analysis, these needs and desired outcomes help define the general system objectives. Based on this analysis for Antarctica, the main emerging system objectives are ensuring activities for peaceful purposes only, prohibiting any measures of military nature, involving of more states globally in the decision-making power, ensuring free and scientific investigation and cooperation, continuing the environmental protection of the area, and balancing the needs of governments, science community, civil society and the commercial sector/industry. The main difference between this system as compared to the Deep Seabed is the lack of commercial and benefit sharing regimes established for resource mining.

Table 14. Stakeholder Needs, Desired Outcomes and Objectives for Antarctica.

Stakeholder Need What problems or desires are stakeholders facing?	• Antarctic Treaty System (ATS) original signatories and the Consultative parties need to maintain peaceful activities according to the ATS and inter-governmental agreements and domestic agendas. • Non-Consultative parties need to have more decision-making power. • Scientific researchers/organizations need freedom of scientific investigation and cooperation, funding, and workforce. • Conservationists, NGO's (civil society) need to protect the nature and environment in Antarctica. • Commercial sector/ Industry need to conduct profitable activities in the region.

Desired Outcomes What do stakeholders want the world to be like in the future?	• Activities conducted for peaceful purposes only without any measures of military nature or nuclear explosions and radioactive waste material • Change in decision-making power from being limited to original signatories and the Consultative parties of the ATS • Freedom of scientific investigation and cooperation • Protected environment of the Antarctic • Opportunities to make profits our of mineral resources (which is illegal according to the ATS now other than biological prospecting)
System Objectives What activities will a system do to contribute to the desired outcomes?	• Ensuring activities for peaceful purposes only • Prohibiting any measures of military nature • Involving of more states globally in the decision-making power • Ensuring free and scientific investigation and cooperation • Continuing the environmental protection of the area • Balancing the needs of governments, science community, civil society and the commercial sector/industry.

9.1.2.3 System Forms and Functions

As previously done for the High Seas and Deep Seabed, the last and key part of the analysis is focused on identifying and studying the form-function relationship of the Antarctic system. *Table 15* presents a detailed overview of main identified systems functions and sub-functions. These functions can once again be grouped into four different categories, governance and organization, science and research, industry and tourism, and environmental protection. The main system functions outlined follow the previously identified system objectives.

Table 16 shows the current form-function relationship of the system, by analyzing the alternative existing forms to execute functions for Antarctica, with the main focus of this analysis being on the governance and organization of the Antarctic resources. Similar to the previous study, this section of the analysis is particularly important for the system forms evaluation conducted in the following chapter of this thesis.

Table 15. System Functions and Sub-Functions for Antarctica.

Function Category	**System Functions**	**Detailed System Sub-Functions**
Governance and Organization	Enforcing activities for peaceful purposes only	• Monitoring ongoing activities • Prohibiting ownership claims or having jurisdiction over any land in the Antarctic, except for establishing research stations • Inspecting all areas of Antarctica, including all stations, installations and equipment within those areas • Prohibiting any measures of military nature • Inspecting for any measures of military nature or nuclear explosions and radioactive waste material
	Involving of more states globally in the decision-making power	• Inviting Non-Consultative Parties who do not participate in the decision-making to attend the Consultative Meetings.
	Balancing the needs of governments, science community, civil society and the commercial sector/industry.	• Defining the Consultative Parties as the original signatories of the Antarctic Treaty System in addition to those who are "*conducting substantial scientific research there*" • Using voting from the Consultative Parties for consensus-based decision-making • Monitoring the activities and concerns of the science community, civil society and the commercial sector/industry.
Science and Research	Conducting free and scientific investigation and cooperation	• Conducting scientific investigation • Making freely available and exchanging scientific observations and results from Antarctica
Industry and Tourism	Fishing off the coast	• Capturing and off-shore trading of fish

	Conducting touristic activities	• Offering sea- and land-based trips, cruises and expeditions
Environmental Protection	Continuing the environmental protection of Antarctica	• Protecting the “Antarctic environment and dependent and associated ecosystems and the intrinsic value of Antarctica, including its wilderness and aesthetic values and its value as an area for the conduct of scientific research, in particular research essential to understanding the global environment” • Prohibiting any activity relating to mineral resources, other than scientific research

Table 16. Analysis of Alternative Forms to Execute Functions for Antarctica.

Function Category	**Analysis of Alternative Forms to Execute Functions**		
Governance and Organization	**Enforcing activities for peaceful purposes only** - Antarctic Treaty System (ATS) - Original signatories and the Consultative parties	**Involving of more states globally in the decision-making power** - Antarctic Treaty System (ATS) - Original signatories and the Consultative parties - Non-Consultative parties	**Balancing the needs of governments, science community, civil society and the commercial sector/industry.** - Antarctic Treaty System (ATS) - Original signatories and the Consultative parties
Science and Research	**Conducting free and scientific investigation and cooperation** - Antarctic Treaty System (ATS) - Original signatories and the Consultative parties - Scientific researchers/organizations		

Industry and Tourism	**Fishing off the coast** - Fisheries	**Conducting touristic activities** - Tourism companies, cruises, etc.
Environmental Protection	**Continuing the environmental protection of the area** - Antarctic Treaty System (ATS) - Original signatories and the Consultative parties - The Protocol on Environmental Protection to the Antarctic Treaty - Conservationists, NGO's (civil society) - Scientific researchers/organizations - Industry and commercial sector	

9.1.2.4 Summary

Figure 46 is a Systems Architecture Analysis Summary for Antarctica, which provides an overview of the various components and relationships that constitute the Antarctic system. The figure shows the external context of the system, including the Antarctic Treaty System (ATS) and the Protocol on Environmental Protection to the Antarctic Treaty, which establish the legal framework for the management of the region.

The inputs to the system include constraints and opportunities such as the amount of available resources, the status of scientific knowledge about the Antarctic environment and resources, and the territorial claims of nations made before the Treaty was established in 1961.

The system stakeholders are divided into three tiers, with the primary stakeholders being the original signatories of the ATS and the Consultative parties, who allocate system forms and express system objectives. Secondary stakeholders include non-consultative parties, scientific researchers, conservationists, international environmental lobbies, NGOs, the commercial sector, and humankind. Tertiary stakeholders include scientific researchers/organizations, conservationists, NGOs, the commercial sector, and humankind.

The system objectives are met through various system functions, which are executed by system forms. The system functions include enforcing activities for peaceful purposes only, involving more states globally in the decision-making power, balancing the needs of different stakeholders, conducting free and scientific investigation and cooperation, fishing off the coast, conducting touristic activities, and continuing the environmental protection of Antarctica.

The system forms include the ATS, original signatories, and consultative parties, non-consultative parties, scientific researchers/organizations, fisheries, tourism companies and cruises, conservationists, NGOs, industry and the commercial sector, and the Protocol on Environmental Protection to the Antarctic Treaty.

Finally, the emergent properties of the Antarctic system are the governance regime for the region that ensures peaceful activities of the "global commons" while environmentally protecting Antarctica. *Figure 46* provides a comprehensive overview of the Antarctic system and its stakeholders, needs, functions, forms, and emergent properties.

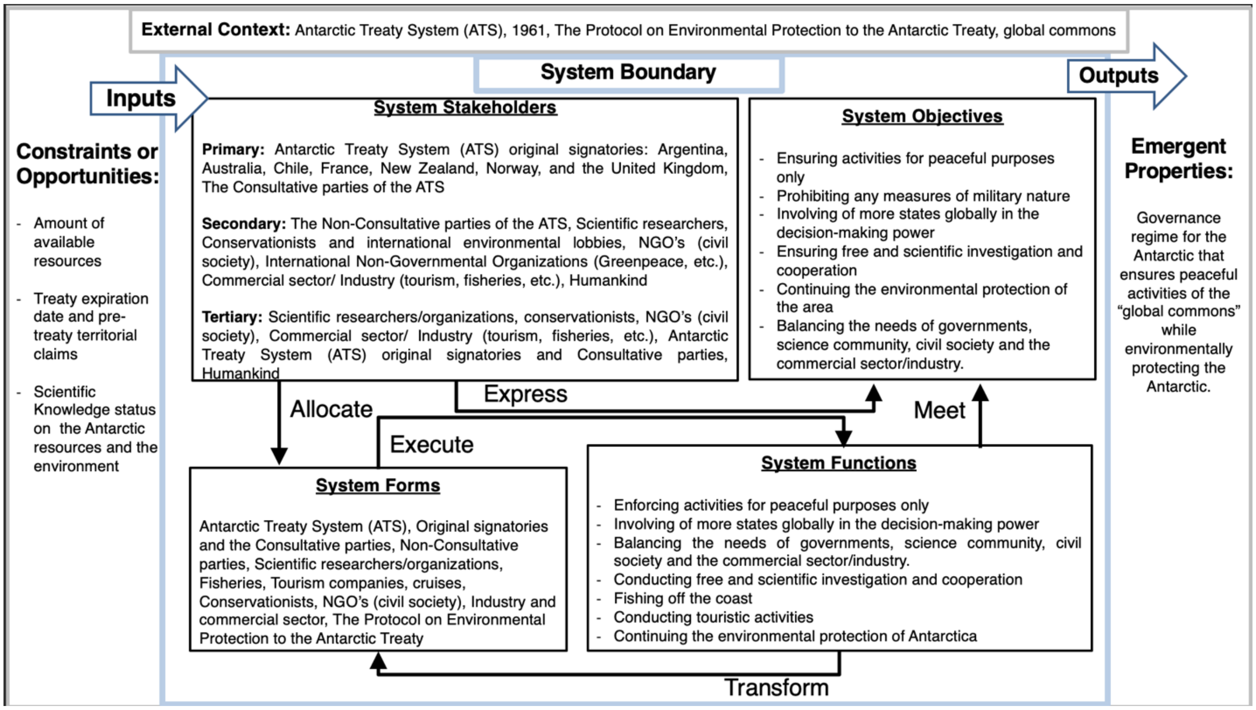


Figure 46. Systems Architecture Analysis Summary for Antarctica.

9.2 Governance System Evaluation in the TWAIL Context

After presenting the Systems Architecture analysis for both the High Seas and Deep Seabed in addition to the Antarctic governance regimes, this sub-chapter focuses on evaluating these systems, with their studied form-function relationships. This evaluation is conducted in the context of Third World Approaches to International Law (TWAIL) to identify the weaknesses and strengths that each governance systems has relative to these theories and assess each accordingly. Each of these strengths and weakness can be traced back to its roots in the form-function relationships previously presented in *Table 12, Table 13,* and *Table 16* for each of the systems in Chapter 9.1 Systems Architecture Analysis.

9.2.1 High Seas and Deep Seabed

The section evaluates the High Seas and Deep Seabed governance regime in the TWAIL lens. Within UNCLOS and the ISA procedures are various attempts to ensure that developing countries can access deep sea mineral resource, especially with the "reserved areas". The Convention, however, is "a club that that one must join to fully share in the benefits", and thus, like other treaties, it "creates rights only for those who become parties to it" (United Nations - Office of Legal Affairs, 2012). This structure currently raises many problems in the nations being represented and accessing the shared benefits, thus providing further disadvantages against nations that are non-participating in deep-sea mining.

In addition to excluding non-participatory nations, the process of "reserved areas" currently does not make any distinctions between the qualifying "developing countries" and their different economic statuses in their ability to apply and have access to these areas. Thus, countries like China and India, being "developing countries", can have equal ability to access reserved areas as much poorer countries. This approach hence provides an equal, but definitely not equitable, opportunity, as it ties into the question of who qualifies as "developing countries" and how the "reserved areas" are equitably allocated among those countries. The Convention also doesn't consider the impact of the mining activities on intergenerational equity.

Moreover, this "parallel system" collective mining regime, involving the Enterprise and "developing states", raises other concerns. Firstly, it gives the Enterprise conflicting goals, leading to questions about the objectivity and transparency of any of the processes given the Enterprise's direct involvement in the mining activities and the conflict of interest arising because of that. This issue becomes of critical importance when discussing sustainability of the marine environment. As the marine biologist Sandor Mulsow, who previously served as the Authority's top environmental official, said, "The ISA is not fit to regulate any activity in international waters. It is like to ask the wolf to take care of the sheep" (Woody & Halper, 2022). The same concern was shared by a senior oceans campaigner for Greenpeace, Arlo Hemphill, saying, "It's extremely concerning" that the ISA "would be in charge of running a business that it is also in charge of regulating" (Woody & Halper, 2022).

Furthermore, this system raises concerns involving the risk for foreign commercial actors looking for developing states with the lowest regulations as sponsors for their activities. An important example here is the case of Nauru and Tonga in the International Tribunal for the Law of the Sea, in 2011, specifically about the liability of a sponsoring state for environmental damage caused by commercial companies. This is an issue that will jeopardize the prospects of many nations that might face that uncertainty in what they sign up for. There currently are several developing countries that are part of such a process, as stated in the (Current Status of the Reserved Areas with the International Seabed Authority, 2019):

> "In 2011, Nauru Ocean Resources Inc (NORI) was given an exploration contract over four sub-areas taken from the reserved areas contributed by BGR (Germany), Yuzhmorgeologiya (Russian Federation) and IOM (Bulgaria, Cuba, Czechia, Poland, Russian Federation and Slovakia). In the same year, Tonga Offshore Minerals Ltd (TOML) was given an exploration contract over six subareas from the reserved areas contributed by BGR (Germany), Deep Ocean Resources Development Co Ltd. (DORD), of Japan, the Government of the Republic of Korea (ROK), and IFREMER (France). In 2012, Marawa Research and Development (sponsored by Kiribati) received a contract covering three regions in three blocks contributed by ROK."

Another concern in this framework is the premise that the two areas divided up by each applicant are of equal estimated commercial value. Despite the requirement to provide "survey data and information to substantiate the estimated values", these estimates are incredibly difficult with the limited knowledge and capabilities of assessing the areas of interest. This difficulty also applies to assessing the environmental and biological environment, as Muslow describes, "It is like going into Central Park in New York with a soda straw, taking one sample and then trying to tell me how many worms are in all of the park" (Woody & Halper, 2022). This lack of statistically credible baseline data and uncertainty in assessing the value of resources a priori to starting the mining work put the "developing states" that are promised an area of equal estimated commercial value facing a possibility of false assessments.

Lastly, UNCLOS was adopted as a "package deal" aiming to achieve "universal participation". The Convention had one aim above all, as explained by the Division for Ocean Affairs and the Law of the Sea in the Office of Legal Affairs of the United Nations, "namely universal participation in the Convention. No State can claim that it has achieved quite all it wanted. Yet every State benefits from the provisions of the Convention and from the certainty that it has established in international law in relation to the law of the sea. It has defined rights while underscoring the obligations that must be performed to benefit from those rights. Any trend towards exercising those rights without complying with the corresponding obligations, or towards exercising rights inconsistent with the Convention, must be viewed as damaging to the universal regime that the Convention establishes" (United Nations - Office of Legal Affairs, 2012). However, the lack of participation of major players like the United States, which are not part of this Convention, in the mining activities can undermine the impact of its benefit sharing premises.

Thus, this framework has a number of strengths and of inadequacies (weaknesses). Its strengths include the acknowledgment of the Area as "common heritage of mankind" in addition to the attempts to increase the accessibility of developing states in the deep seabed resource activities, in an innovative approach unobserved commonly for other similar systems. The weaknesses, however, are regarding the representation of non-participating states in the mining activities, the equitable benefit sharing between the so-called "developing states", the threat to objectivity in the Enterprise's mining role, the risk and liability for developing states sponsoring foreign commercial actors, the difficulty in commercial value assessment of areas, and finally the lack of participation of key states like the USA.

A policy brief article by (Thompson, Miller, Currie, Johnston, & Santillo, 2018) on "Seabed Mining and Approaches to Governance of the Deep Seabed" describes a synthesis of literature approaches to potential policy improvements in the current governance framework in the deep seabed. In the TWAIL lens, some of the helpful improvements include:

- An international monitoring initiative under the United Nations with a more coordinated governance approach (Danovaro, et al., 2017)
- A staged approach to collect baseline data before further mitigation measurements are studied (Niner, et al., 2018), although this could lead to establishing dangerous precedent and might not get the industry's support.
- Placing mining in the context of the UN SDG's and clarifying the interpretation of the "benefit of humankind" with added transparency and global participation (Thompson, Miller, Currie, Johnston, & Santillo, 2018; Kim, 2017)
- Increasing transparency and fully informing the global community about the ongoing processes, reviews, reporting and global distribution of benefits. This could be also coupled with improved independent reviews and accountability measures (Niner, et al., 2018; Ardron, Ruhl, & Jones, 2018).
- Adaptive management that has the "power to halt mining activities" (Halfar & Fujita, 2002)
- Sustainability via implementing circular economy approaches that limit overconsumption (Thompson, Miller, Currie, Johnston, & Santillo, 2018; Ghisellini, Cialani, & Ulgiati, 2016)
- Lastly, "enforced social cost-benefit analyses" that improve benefit sharing and account for fund needed for disasters (Wakefield & Myers, 2016; World Bank, 2017)

The final proposed policy change regarding the "enforced social cost-benefit" is of particular interest to this research in the future proposed framework for space resource utilization. However, as Thompson et al. note, "Such processes would need to include environmental externalities and regular re-appraisal to incorporate relevant technological, cultural, and environmental changes and a mechanism is needed to enforce assessed benefits. The high level of uncertainty associated with seabed mining compounds the difficulties in a cost–benefit analysis" (Thompson, Miller, Currie, Johnston, & Santillo, 2018; World Bank, 2017; Wakefield & Myers, 2016).

9.2.2 Antarctic

Similar to the evaluation of the High Seas and Deep Seabed governance regime, this section evaluates the Antarctic governance regime in the TWAIL lens. As previously discussed in Chapter 8.2.2 Antarctic, the ATS, the Environment Protocol, and the current governance regime are on a ticking clock to expire in 2048, raising a lot of uncertainty for the future of post-treaty claims. Until then, unanimous agreement of all Consultative Parties to the Antarctic Treaty is needed to do any modifications to the Articles of the Environmental Protocol, including regarding the current existing prohibition on mineral exploitation.

Despite the ATS providing a successful example thus far of unhindered peaceful scientific research and operations in the Antarctic, the current framework raises various concerns, from a TWAIL perspective. Firstly, unlike the deep seabed regime, the ATS does not assert the notion of "common heritage of mankind". It operates as an "exclusive club", where the decision-making power is limited to the Consultative Parties, based on being original signatories or by "*conducting substantial scientific research there*" (The Antarctic Treaty Explained, 1999). This is of particular concern on issues of mineral negotiations. For example, several countries including Malaysia claimed that "the ATS was not the best or the fairest way to manage Antarctica" (Scott, 2010). As (Scott, 2010) explains, "The third world referred to the ATS as an "exclusive club". Some believed that Antarctica should be managed by the UN; others argued that the ATS be retained but all states be able to join, and all given equal decision-making status."
The main nuance that members of the ATS used in their arguments defending the current governance and decision-making structure is that Antarctica is being solely "dedicated to science, and all would benefit from the scientific knowledge obtained there" (Scott, 2010). The ATS has so far withstood the debates on this topic.

The second concern is regarding the post-treaty expiration claims. This concern is critical in the TWAIL lens as it challenges the ATS notion of dedicating the Antarctic to peaceful scientific activities without any commercial profits. So far, this concern involves multiple parties, as explained by (Gateway House, 2013):

- "The pre-treaty claimants (PTCs) are nations that have renounced earlier claims after acceding to the ATS. However, Antarctica remains a core issue for each of them and the PTCs are likely to attempt to redeem their lost claims.
- The Reserved Claimants (RCs) did not claim any Antarctic region during or before the 1961 treaties but have reserved the claims that they will forward during the 2048 review.
- The Non-Claimants (NCs) have exploration interests, but none have so far claimed regional rights."

One example of these post-treaty claim concerns is the potential conflict in the mineral-fuel rich area of East Antarctica between Australia, a PTC, in its Australian Antarctic Territory (AAT) and the growing activities of Russia and China, who are an RC and NC respectively (Gateway House, 2013).

Thus, this framework has a number of strengths including its international recognition as one of the most successful international agreements, its proven unhindered scientific research progress, and peaceful operations lacking any recent major political tensions thus far. However, this framework has a number of weaknesses, especially in a TWAIL lens, including the lack of global representation in the decision-making processes and the uncertainty of post-treaty claims.

9.2.3 TWAIL Evaluation Summary and Proposed Criteria

After analyzing in detail each of the governing systems and evaluating them in a TWAIL context, *Table 17* provides a summary of the identified strengths and weaknesses for each of the studied governance frameworks. Each of these strengths and weakness can be traced back to its roots in the form-function relationships previously presented in *Table 12, Table 13,* and *Table 16* for each of the systems. Building upon the evaluation presented in the upper section of *Table 17*, this research used the strengths of each of the previously studied systems and modified the weaknesses observed by adapting the form-function relationships for the new proposed framework. These analyses guided the set of criteria presented in the lower section of *Table 17* that the new framework had to encompass. The new framework is presented in Chapter 9.3 Proposed Framework.

Table 17. Summary of governance frameworks' evaluated strengths and weaknesses in a TWAIL context and proposed framework criteria

<table>
<tr><th></th><th>Strengths</th><th>Weaknesses</th></tr>
<tr><td>High Seas & Deep Seabed</td><td>• The attempts to increase the accessibility of developing states in the deep seabed resource activities, in an innovative approach unobserved commonly for other similar systems.</td><td>• Lack of representation of non-participating states in the mining activities
• The non-equitable benefit sharing between the so-called "developing states"
• The threat to objectivity in the Enterprise's mining role
• The risk and liability for developing states sponsoring foreign commercial actors
• The difficulty in commercial value assessment of areas
• The lack of participation of key states like the USA.</td></tr>
<tr><td>Antarctic</td><td>• International recognition as one of the most successful international agreements
• Its proven unhindered scientific research progress, and peaceful operations lacking any recent major political tensions thus far</td><td>• Lack of global representation in the decision-making processes
• Uncertainty of post-treaty claims</td></tr>
<tr><td colspan="3">Proposed Framework Criteria</td></tr>
<tr><td colspan="2">Reinforces Strengths
• Ensures the accessibility of developing states in space resource activities
• Ensures unhindered scientific research progress and peaceful operations</td><td>Addresses Weaknesses
• Ensures representation of non-participating states in the mining activities in the decision-making processes and in the shared benefits
• Defines more clearly the equitable benefit sharing between the so-called "developing states"
• Separates the governing system from performing any mining role itself
• Addresses the risk and liability for developing states sponsoring foreign commercial actors
• Allocates benefits post obtaining them due to the difficulty in commercial value assessment of resources in advance
• Incentivizes participation of key states like the USA
• No set agreement expiration date that could raise uncertainties</td></tr>
</table>

9.3 Proposed Framework

After analyzing in detail each of the governing systems and evaluating them in Chapter 9.2 Governance System Evaluation in the TWAIL Context, this section is guided by the proposed set of criteria presented in *Table 17* that the new framework has to encompass.

Resources bought back to Earth or used in space may also have great scientific value. However, the main foreseen use of these resources covered by this thesis, and hence by this proposed framework, is for commercial profits. This underscores the importance of recognizing the monetary value in the benefit assessments and sharing. To that end, this research proposes in Chapter Recommendations a set of eleven recommendations for a hybrid top-down and bottom-up framework. The rationale behind each of the recommendations is then further expanded and explained in Chapter 9.3.2 Rationale.

9.3.1 Recommendations

(1) **Governance Entity:** A new independent "Space Resource Benefit-Sharing Council" (SRBSC) shall be established in collaboration with the World Bank, the International Monetary Fund (IMF), and the World Economic Forum. The World Bank already works with developing countries to reduce poverty and increase shared prosperity. The IMF already monitors economic and financial developments of countries, allocates money globally, and helps in building capacity, and the World Economic Forum already specializes in public-private cooperation, sustainability, and quantifying global impact.

(2) **External Consultations:** The SRBSC shall establish a consulting relationship with UNCOPUOS to inform the space policy background of its decisions.

(3) **Decision-making:** The decision-making and processes in the SRBSC shall follow a combination of one-vote per member state and votes per quotas system. Financial contributions of each state shall depend on the State's economic status, while decision-making shall ensure an equal global representation of states with a one-vote-per-member policy (similar to that in the International Telecommunication Union (ITU)).

(4) **Resource Allocation:** Mining companies and/or their sponsoring states shall apply to the Council to receive an allocated exploration license (or other forms of access to space resources) for the resources in areas of celestial bodies of interest.

(5) **Benefit-sharing:** To ensure that the benefits of space resource exploration and utilization are shared fairly among all countries and actors, a **"global tax"** on profits by space mining companies shall be implemented. This tax would be presented in the form of allocating a portion of the shares of space mining companies to global benefits, ensuring that all countries and actors have a stake in the exploration and utilization of space resources, and no resource monopolies are in place. This process shall still allow for a profitable return on investment (ROI) for the mining company. Member states who choose to receive some of the allocated shares would pay a small fee to the mining company and would in return have "skin in the game". This fee shall depend on the state's economic development status.

(6) **Global Tax Allocation:** Global tax, in the form of a portion of the shares of space mining companies, shall be allocated between member states based on their level of economic development according to the UN's Human Development Index (HDI) and their economic dependence on the mined resource. Member states who choose to receive some of the allocated shares would pay a small fee to the mining company and would be allocated a certain percentage of the shares based on their level of economic development and their economic dependence on the mined resource. This means a lower fee and a larger share goes to less developed countries that may have less capacity to participate in these activities or to countries that are economically dependent on the mined resource of interest.

(7) **Restricted &Protected Areas:** Designated protected areas or restricted areas on celestial bodies that are off-limits to mining activities shall be established. These areas could be chosen based on their scientific or astrobiological importance, or on their rarity or scarcity. By establishing protected areas, it may be possible to ensure that these resources are preserved for future generations and that the potential for scientific discovery is not compromised.

(8) **Sustainability:** Sustainability shall be approached in a bottom-up manner. The Space Sustainability Rating (SSR), currently mainly targeted for satellites in Low Earth Orbit (LEO), shall be expanded to apply to sustainable use of space resources. The SRBSC shall still monitor the resource use, raising alerts or adding caps on utilization in case of unsustainable overconsumption of a particular resource. This process shall be done in an adaptive yet conservative manner, based on the best scientific evaluation at the time of the mined area.

(9) **Dispute Resolution:** There shall be transparency and accountability in the allocation and use of space resources, with clear rules and regulations in place to ensure that all actors are held accountable for their activities. This could include the development of liability provisions for space resource activities and the establishment of mechanisms for dispute resolution. Such mechanisms could be adapted from those within the UNCLOS and ISA framework, including but not limited to "proportionate" monetary penalties, sanctions, and an equivalent entity to the Seabed Disputes Chamber (that is part of the International Tribunal for the Law of the Sea (ITLOS)), but for space.

(10) **Incentives for Large Global Players:** Rich countries shall be incentivized to join this Council in multiple ways including: receiving the fees paid for allocated shares, the creation of new markets and opportunities for businesses, the promotion of innovation and competition, the fostering of economic development and prosperity, the uniform measures of dispute resolution, promoting of stability and security in global economy and financial markets, the guaranteed profits, the strengthening of international relationships and partnerships, the fostering of a more positive global reputation, and finally by highlighting a number of other examples of global governance regimes where global benefit allocation is implemented and these countries are participating.

(11) **Expiration Date:** The agreement shall have no set expiration date. However, member states shall be allowed to give notice of withdrawal from the framework, taking effect a year from the receival of the withdrawal notification (similar to the OST withdrawal process).

9.3.2 Rationale

9.3.2.1 Recommendations (1) and (2)

To go into Recommendation (1) in more detail, it is important to start by understanding the historical background of the World Bank and the International Monetary Fund (IMF). In the wake of the Great Depression in the 20th century, from the October 1929 stock market crash until 1939, consumer confidence drastically dropped, as did global spending and investment (History.com Editors, 2022). This caused a 15% collapse in the GDP worldwide, with over 5,000 banks closing in the U.S. alone (Market Business News). This international financial crisis leading up to the Second World War demonstrated the need "to rebuild a more resilient global financial system" (Gray & Wade, 2018).

Efforts to address this economic collapse in 1944, at the Bretton Woods conference, led by the US and British Treasuries, focused on promoting open markets, international cooperation, and ending economic nationalism (Gray & Wade, 2018). The conference resulted in the birth of the two institutions: the IMF and the International Bank for Reconstruction and Development (IBRD). The system was grounded by a system of convertible currencies at fixed exchange rates pegged to gold (Gray & Wade, 2018). It wasn't until 1971, with the so-called "Nixon shock", that the U.S. stopped the dollar peg to gold, causing a "drastic reordering of the global financial system" to a floating exchange rate system of currencies (Lowenstein, 2011).

Since then, the IMF and the World Bank have been supporting the existing financial system. Despite their general similarities, with 189 member countries each, the two institutions are different in their goals and activities. *Table 18* presents the differences between the two institutions as defined by the World Bank (The World Bank). Sudeep Reddy from The Wall Street Journal explains the specific IMF role as follows (Reddy, 2011),

> "The IMF was, in some ways, responsible for making sure that countries stuck to a specific policy of exchange rates and also monitored their economies. And so, a lot of what the IMF does today is it sends people to all 187 countries to monitor their macroeconomic situation. To really track what's going on in their economies, and it does make recommendations that are designed to provide some cohesion to economic policies around the world, whether it's the flow of capital or the management of exchange rates or financial regulation."

Table 18. Differences between the World Bank and the IMF as defined by the World Bank. *(The World Bank)*

World Bank Group	IMF
• Works with developing countries to reduce poverty and increase shared prosperity • Provides financing, policy advice, and technical assistance to governments, and also focuses on strengthening the private sector in developing countries. • Countries must first join the IMF to be eligible to join the World Bank Group.	• Serves to stabilize the international monetary system and acts as a monitor of the world's currencies. • Keeps track of the economy globally and in member countries, lends to countries with balance of payments difficulties, and gives practical help to members.

The World Economic Forum, on the other hand, is critical for quantifying the global impact of activities. After being established in 1971 as a non-profit, independent, and impartial foundation, the Forum's mission has been to "engage the foremost political, business, cultural and other leaders of society to shape global, regional and industry agendas". As stated in the World Economic Forum's mission statement, "The Forum strives in all its efforts to demonstrate entrepreneurship in the global public interest while upholding the highest standards of governance" (World Economic Forum). As a platform for impact, the Forum currently tackles many topics including issues of sustainability and of emerging technologies.

Given the available expertise and already established and existing networks at the IMF and the World Bank, in addition to the alignment in mission and goals with the World Economic Forum, the research suggests in Recommendation (1) establishing a new independent "Space Resource Benefit-Sharing Council" in collaboration with these three institutions. Acknowledging the critical monetary value of obtained resources, it seemed intuitive to utilize those already established global economic institutions for monetary benefit sharing across countries around the world. These institutions, combined, already monitor economic and financial developments of countries, allocate money globally, help in building capacity, work with developing countries to reduce poverty and increase shared prosperity, and quantify the global impact of ongoing activities.

Given the ongoing discussions and meeting development on space resources at UNCOPUOS, Recommendation (2) focuses on establishing a relationship of consulting nature between the Council and UNCOPUOS to exchange expertise on space resources and to inform the space policy background of its decisions.

9.3.2.2 Recommendation (3)

Recommendation (3) is critical to the structure of this new independent "Space Resource Benefit-Sharing Council", especially from a global equity standpoint. The leadership of the World Bank and IMF started as a "gentlemen's agreement" between the U.S. and Europe, where the U.S. took the number one spot at the World Bank as President and the Europeans took that spot at the IMF as

Chairman of the Executive Board (Reddy, 2011). The IMF is headed by a Board of Governors, but the Executive Board has most of the authority. The Executive board consists of 24 Executive Directors, eight of which are fixed permanently (the U.S., China, Germany, France, Japan, Russia, Saudi Arabia, and the U.K.), and the rest of the board members are picked through a geographical rotation, in a fashion similar to the Security Council of the United Nations (Gray & Wade, 2018). Decision-making is done through voting process, where each member's voting share depends on their "quota", relative to the global economy, which is calculated as a function GDP, openness, variability, and reserves (IMF, 2021). This quota-system, however, gives veto power to the U.S. and tremendous power to the European bloc, further extending the discriminatory and colonial power imbalances globally, especially for countries of poorer economies (Bretton Woods Project, 2019). Recommendation (3) thus focuses on ensuring that the new Council operates in combined one-vote per member state and votes per quotas system. A similar process is successfully used in the International Telecommunication Union (ITU) (ITU's election process explained, 2022). Fees and financial contributions of each state shall depend on the State's economic status, while decision-making shall ensure an equal global representation of states with a one-vote-per-member policy.

9.3.2.3 Recommendations (4), (5), and (6)

Recommendations (4), (5), and (6) tackle the logistics of resource allocation and the monetary value assessment and sharing between the mining entity and the remaining States globally. The process would start by the mining companies, through their sponsoring states, applying to the Council to receive an allocated exploration license (or other forms of access to space resources) for the resources in the areas of the celestial body of interest as discussed in Recommendations (4). The Council would then review the application which would include detailed information about the proposed use of the resources, the type of activities that will be planned, the area that will be covered, and the amount of resources that will be needed. An allocation decision will be done following the review and evaluation of the application, providing a license for these activities.

However, to ensure that the benefits of space resource exploration and utilization are shared fairly among all countries and actors, Recommendations (5) discusses implementing a **"global tax"** on profits by space mining companies. This tax would be presented in the form of allocating a portion of the shares of space mining companies to global benefits, ensuring that all countries and actors have a stake in the exploration and utilization of space resources, and no resource monopolies are in place. This process shall still allow for a reasonable return on investment (ROI) for the mining company and requires states to pay a small fee to the company for using the allocated shares. The main advantages of this structure are that (1) it bypasses the difficulty in assessing resource values and economic profits a priori in contracting proposals as observed in the ISA process for deep seabed resources, (2) it protects the larger ROI for the mining companies and allows them to receive fees on allocated global shares, and (3) it promotes a fairer global benefit sharing by allowing states to have "skin in the game" in the activities.

The critical question here is: what is the percentage of company shares that should be allocated for global benefits while still allowing for a reasonable return on investment (ROI) for the mining company? The challenge in determining this specific percentage is that it will be dependent on several factors: the size and profitability of the company, the specific risks and costs associated with the space resource exploration and extraction activities, and the overall economic and regulatory environment. The Council could determine the appropriate percentage of company shares allocated for global benefits according to the amount of investment in the company, or by conducting a complex valuation-based financial analysis of the company, to understand the necessary ROI to sustain the company's business and profitability over the long term. The financial analysis should consider the business-associated risk and uncertainties and the overall status of the space resource market. The exact details of these financial analyses are not included in the scope of this research and would be an area for future work for the SRBSC.

Recommendation (6) addresses the approach for allocating the shares in the so-called "global tax" among member states who choose to receive some of the benefits, including states that are non-participating in mining activities but are part of the Council. Generally, there are different approaches for allocating the global tax, in the form of a portion of the shares of space mining companies, between member states. The allocation could be done based on (1) a country's contribution to the exploration and utilization of space resources, (2) based on a country's population, or (3) based on a country's economic development. The first approach would favor member states that have already invested financial and technical resources for space resources and the expertise in the field. Population size is another way of categorizing member states when allocating benefits, but this approach would not consider the State's size or level of economic development. This research recommends the third approach of considering the level of economic development of member states as the basis for benefit allocation as it is more aligned with the TWAIL context. As previously mentioned, member states who choose to receive some of these shares would be required to pay a small fee to the mining company to receive a percentage of shares in return. In practice, considering the level of economic development of member states would mean that a lower fee and a larger share goes to less developed countries that may have less capacity to participate in these activities or to countries that are economically dependent on the mined resource of interest. The level of economic development can be determined according to the UN's Human Development Index (HDI). Following this recommendation would help ensuring that all member states have a stake in space resource activities and that benefits are more equitably distributed between these states.

9.3.2.4 Recommendation (7)

To ensure the proposed framework criteria of unhindered scientific research progress and peaceful operations, Recommendation (7) concentrates on the importance of designating restricted and protected areas on celestial bodies that are off-limits to mining activities. These areas could be chosen based on their scientific or astrobiological importance, or on their rarity or scarcity. By establishing protected areas, it may be possible to ensure that these resources are preserved for future generations and that the potential for scientific discovery is not compromised. The research here recommends following the Antarctic Treaty notion of dedicating resource activities there purely for peaceful scientific purposes. To that end, this research proposes including two rules, verbatim from the ATS and UNCLOS: (1) "Scientific observations and results […] shall be exchanged and made freely available" (Antarctic Treaty, 1961), and (2) resource activities in these areas "shall not confer on the prospector any rights with respect to resources. A prospector may, however, recover a reasonable quantity of minerals, being the quantity necessary for testing, and not for commercial use" (Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area / proposed by the Legal and Technical Commission, 2013).

9.3.2.5 Recommendation (8)

Recommendation (8) focuses on the sustainability aspect of such activities by trying to integrate a bottom-up governance on that front. The SRBSC has the critical role of closely monitoring the resource use activities globally, raising alerts or adding caps on utilization in case of unsustainable overconsumption of a particular resource. Such "caps on utilization" could be implemented differently for different resources. For example, in the case of mining water on the Moon, the real restriction may not be on digging up water, but rather on mandating a certain percentage to be recycled.

The sustainability aspect of space resource actitvities is important to ensure intergenerational equity in the benefit-sharing regime. However, due to the difficulty of conducting such monitoring and assessment of available resources and consumption caps needed (Krolikowski & Elvis, 2018), this process needs to be done in an adaptive yet conservative manner, based on the best scientific evaluation at the time of the mined area. The main mechanism for sustainability recommended is through a bottom-up approach, expanding the Space Sustainability Rating (SSR), currently mainly targeted for satellites in Low Earth Orbit (LEO), to apply for space resources. SSR was designed by the World Economic Forum, ESA, Space Enabled at MIT, BryceTech and the University of Texas at Austin and is currently moving to an operational system at the EPFL (École Polytechnique Fédérale de Lausanne) Space Center (Hillyer, 2021). Having already received a lot of interest from the commercial satellite sector (Hillyer, 2021), SSR can be a very effective tool if expanded to space resources, as a reputational incentive for commercial mining companies. This score shall account for respecting the restricted and protected areas in mining activities, in addition to promoting sustainable mining practices of space resources that minimize the impact of mining on celestial bodies and the surrounding environment.

9.3.2.6 Recommendation (9)

Recommendation (9) tackles the aspects of dispute resolution. Detailed dispute resolution mechanisms fall within the implementation phase of this concept and are not within the scope of this research. However, the recommendation is to is to follow the mechanisms already available within the UNCLOS and ISA framework. These include but are not limited to "proportionate" monetary penalties, sanctions, and an equivalent entity to the Seabed Disputes Chamber. The research also encourages transparency and accountability in the allocation and use of space resources, with clear rules and regulations in place to ensure that all actors are held accountable for their activities.

9.3.2.7 Recommendation (10)

Recommendation (10) is the most challenging part of this framework, as it is notoriously difficult to convince the bigger global players to be part of an equitable global regime. However, this research provides a set of incentives to join the Council, starting by requiring member states to pay a small fee in return to the received shares. This requirement would allow countries to have a "skin in the game", not only receiving a "free ride" on profits. Furthermore, joining this Council allows for rich countries to enhance the economic growth in less developed countries, which in turn leads to the creation of new markets and opportunities for businesses and for the promotion of innovation and competition—factors that are key for the fostering of economic development and prosperity for both sides. This framework could also help in promoting a more positive global reputation for rich countries. It also provides the opportunity for them to attract global cooperation and to generate profits from space resource activities of other rich countries, and to strengthen their international relationships and partnerships with all member states.

Another critical incentive for the bigger global players to join this Council is ensuring stability and security in the global economy and financial markets, which in turn reduces global inequality and associated conflicts, wars, and instabilities. The framework also provides for a uniform set of dispute resolution mechanisms to deal with problems arising between member states in the space resources domain. Lastly, an important incentive is highlighting the other successful examples of global governance regimes where global benefit sharing is implemented, and rich countries are a part of. These regimes include, but are not limited to, the International Telecommunication Union (ITU) for coordinating the use of the radio frequency spectrum and satellite orbits, the United Nations Framework Convention on Climate Change (UNFCCC) to address climate change and its impacts, the Convention on Biological Diversity (CBD) to conserve and sustainably use the world's biological diversity, and the previously studied International Seabed Authority (ISA) for seabed resources.

9.3.2.8 Recommendation (11)

Recommendation (11) specifically addresses this observed weakness of the ATS and suggests that any agreement on space resources shall have no set expiration date that could raise uncertainty of post-agreement claims. However, a withdrawal process similar to that in the OST is recommended, where member states shall be allowed to give notice of withdrawal from the framework, taking effect a year from the receival of the withdrawal notification.

9.4 Example Application of Proposed Framework: Metal-Rich Asteroid

This case study hypothesizes a realistic scenario of a platinum-rich asteroid — encompassing more than the current yearly world output of platinum, with a value ~2.9 trillion US dollars (this estimate is according to a previous estimate done by Planetary Resources, Inc.). A private company, AsteroidCo, in the United States sets about to capture it and deliver the assets to Earth and thereby dominate world markets for platinum. How would this case be handled in new framework?

Under the assumption that the previously discussed "Space Resource Benefit-Sharing Council" in collaboration with the World Bank, the IMF, and the World Economic Forum has already been established and that the United States is a member, the process would proceed as follows:

- AsteroidCo, through its sponsoring state (the United States), would submit an application for an exploration license that grants access to space resources for mining this asteroid. Their application would include details on the mining activity, including using all the platinum of this asteroid over a period of 10 years, for example, to be brought back to Earth.

- The SRBSC would review the application, confirming no conflicts from other applicants are in place and that the area of interest is not one of the designated protected areas that are off-limits to mining activities.

- Following that review, the SRBSC would grant the exploration license to AsteroidCo, allowing them to explore and extract resources from this area over the approved time period.

- As part of its benefit sharing obligations, AsteroidCo would be required to pay a global tax, in the form of a portion of its shares, to help to ensure that the profits from space resource activities are shared fairly among other member states. AsteroidCo would provide a business plan with financial details, which include their income statement (revenues, expenses, and profits) over the projected time period, their cash flow projection and how much ROI would be needed to sustain their business. The SRBSC can then decide the proper percentage of AsteroidCo's shares that should be allocated for global benefits.

- The SRBSC, in its role as trust that holds and manages these shares on behalf of the global community, would then poll which member states are interested in participating in receiving the benefits. Each interested member state would be required to pay a fee to AsteroidCo in return for a percentage of the allocated shares, based on their level of economic development. That would mean that a lower fee and a larger share goes to less developed countries that may have less capacity to participate in these activities or to countries that are economically dependent on the mined resource of interest, which is platinum in this case.

- For example, if two countries like Canada and South Africa who, for the sake of this case study, are both non-participants in the mining activities but are interested in receiving a portion of the benefits, the Council would have to consider each of their development levels and economic dependency on platinum. From an economic development standpoint, using the UN's Human Development Index (HDI), South Africa is less economically developed than Canada. Additionally, South Africa far surpasses Canada's economic dependence on platinum. South Africa has 91.3% of the world's reserves on platinum, thus being the leading source of most of the world's imports of that element (Natural Resources Canada). Previous studies have shown that South Africa exports around 87.5% of its platinum production, which has some direct contributions to the country's GDP, but more importantly has "an impact (known as the multiplier effect) on other sectors of the economy" (Stilwell, 2004). As a result, the Council would have to require from South Africa a lower fee and a larger percentage of the shares compared to Canada. This would ensure a more equitable distribution between the interested member states.

- Finally, from a sustainability standpoint, AsteroidCo can show its compliance to the expanded SSR metrics as applicable to its space resource mining activities. In parallel, there should be efforts in place to closely monitor the amount of platinum use ongoing overall and determine if any caps on utilization shall be put in place in case of unsustainable overconsumption of platinum were observed. This process shall be done in an adaptive yet conservative manner, based on the best scientific evaluation at the time of the mined area.

9.5 Discussion on Sustainability and Equity of the New Framework

This subsection aims to review the new proposed framework in reference to the criteria set in Chapter 6.1.1.4 Sustainability and Equity to evaluate its ability to meet these goals. Starting with sustainability, as previously discussed, this research is guided by the Sustainable Development Goals (SDG's). In particular, Chapter 6.1.1.4 Sustainability and Equity found that these SDGs and their targets were relevant to space resources:

- **SDG 10:** Reduce inequality within and among countries.
- **SDG 11:** Make cities and human settlements inclusive, safe, resilient and sustainable.
- **SDG 12:** Ensure sustainable consumption and production patterns.
- **SDG 16:** Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.

Throughout the recommendations discussed in the proposed framework, this research is aligned with all the targets of SDG 10, including the social, economic and political empowerment of countries, ensuring equal opportunity and reduce inequalities of outcome, specifically by eliminating discriminatory laws, policies and practices, increasing the represented voice of developing countries, and improving the regulation on the global financial market.

The recommendations are also aligned with the targets of SDG 11 and SDG 12 on the topic of sustainable human activities and ensuring sustainable consumption patterns. The recommendations specifically address "sustainable human settlement planning and management in all countries", supporting less developed countries, and encouraging companies to adopt sustainable practices. The combination of all the recommendations in the proposed framework serves SDG 16, as they promote peaceful activities and more just and effective global institutions, with a wider range of participating countries.

From an equity standpoint, this research attempted to accommodate several of the "dimensions of equality" previously presented by (Stone, 2012) in Chapter 6.1.1.4.2 Equity, *Table 7*. The proposed framework recommendations tackle the "recipients" dimensions of membership equity and inclusivity of countries in the decision-making, without the quota-system and veto powers. The framework also addresses the "items" dimension, regarding the boundary and value of the item, in addition to the different steps involved in the process of mining the resources. Lastly, from the "process" dimension, the framework proposed a more equitable voting and distribution structure, while allowing for a margin of profits that permits a level of competition to still exist.

Chapter 10: Conclusions

10.1 Findings and Implications

The research has identified policy gaps between the current regulatory framework for space resources that propagate colonialist structures into space and a proposed sustainable and equitable framework for space resource utilization which is inevitable in the near future. Through identifying these gaps, this thesis has demonstrated that the current framework is inadequate in addressing the demands of the increasing interest in space resources and is incapable of facilitating their equitable and sustainable utilization.

This research has also taken lessons from our history on Earth to promote peaceful and equitable use of space resources in a way that benefits all humanity, while taking into consideration growing governmental and commercial interests globally. The research proposed a framework, based on these lessons learned, that incorporates the interests of both governmental and commercial entities, while still ensuring the sustainable use of space resources and the equitable distribution of their benefits among nations, rather than being monopolized by a few.

Moreover, this research has additional significant academic benefits, as the new proposed framework could be further studied and evaluated using different methodologies. The research could also enable scholars to explore a more detailed implementation plan, as well as adapt the proposed framework to additional space activities that may arise in the future. However, if this framework is negotiated or adjusted in the future, certain non-negotiable factors must be considered. These factors include the incorporation of a monetary benefit-sharing scheme that precludes monopolies and prevents significant global economic disruptions. Additionally, it is imperative to designate restricted and protected zones on celestial bodies where mining activities are prohibited.

In conclusion, after identifying identified policy gaps that need to be addressed to ensure the sustainable and equitable utilization of space resources in a way that could benefit all humanity, the results of this research suggested a framework that could provide a significant step towards achieving this goal.

10.2 Sources of error and plans to mitigate error

There are several potential sources of error that could threaten the validity and reliability of the research—where "reliability" refers to whether the research findings are reproducible by the researcher or others and "validity" refers to whether the research findings accurately reflect reality (Campbell & Stanley, 2015).

One threat to the construct validity—the quality of operational approaches used to measure a concept—of the study is the lack of access to multiple sources of evidence on some of the collected data which is in turn used in the architectural and theoretical concepts in this research (Campbell & Stanley, 2015; LeCompte, Analyzing Qualitative Data, 2000; Creswell & Miller, 2000; LeCompte & Goetz, Problems of reliability and validity in ethnographic research, 1982). To address this potential source of error, the research has identified the cases with more limited access and consulted respective experts to support the work's validity by reviewing existing evidence and providing any additional needed documentation and detail. Another possible source of error that may threaten the internal and external validity of the research is how the process in Research Question (3.4) (Chapter 6.2 Research Questions and Motivation): "What are proposed policies for sustainable space resource utilization that address identified legal policy gaps and combine the best of the analog governance systems?") affects the proposed governance and policy framework, as the process entails generalizing terrestrial governance systems in the context of space (Campbell & Stanley, 2015; LeCompte, Analyzing Qualitative Data, 2000; Creswell & Miller, 2000; LeCompte & Goetz, Problems of reliability and validity in ethnographic research, 1982). Other sources of error could include access to inaccurate versions or interpretations of some of the legal documents. To mitigate that, the research has mainly relied on official international and governmental documents, in addition to peer-reviewed and published papers and books.

Regarding the reliability of the research, one potential source of error is the potential personal bias of the researcher while doing system evaluation or while proposing a new governance analog (Campbell & Stanley, 2015; LeCompte, Analyzing Qualitative Data, 2000; Creswell & Miller, 2000; LeCompte & Goetz, Problems of reliability and validity in ethnographic research, 1982). However, the research has relied on methodological analysis and evaluation tools, in addition to thorough documentation of the process to omit potential personal bias.

There are additionally a number of limitations in this work, including the choice of the two studied analogs for being representative enough of the space applications from a pool of many other Earth governance analogs that could be considered and studied. An additional limitation is the chosen scope of the systems architecture analysis of each of the governance analogs, that involves assumptions on where to draw the system boundary, the complexity of involved stakeholders, and the respective forms and functions. Different scopes of the work could potentially yield different results. Finally, this research does not conduct a detailed polycentric governance approach (Chapter 8.1 Research Design Overview) for different parts of the space resources, but rather focuses on a generic governance framework that could encompass these various resources.

10.3 Future work

The main next steps for future research continuing this work are integrating the latest results from the UN Committee on the Peaceful Uses of Outer Space (COPUOS) meetings into the analysis, in addition to integrating additional relevant governance analogs and interviews with people, governments, etc. to further inform the proposed framework. Furthermore, it's critical to consider more detailed implementation methods specifically regarding the socio-economic evaluation of profits pertaining to states from space resources, in additional to more detailed criteria in the expanded Space Sustainability Rating metrics.

Bibliography

(1996). *51/122. Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries.* UNOOSA. Retrieved from UNOOSA: https://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/space-benefits-declaration.html

Abele, A. E., Rupprecht, T., & Wojciszke, B. (2008). The influence of success and failure experiences on agency. *European Journal of Social Psychology, 38*(3), 436-448.

About JPL. (n.d.). Retrieved from NASA JPL: https://www.jpl.nasa.gov/who-we-are

Adams, W., & Adams, W. J. (1972). The Military-Industrial Complex: A Market Structure Analysis. *The American Economic Review, 62*(1/2), 279-287.

AE/Office of Chief Engineer. (2002). *NASA Procedures and Guidelines.* NASA. Retrieved from https://spacecraft.ssl.umd.edu/design_lib/NPG7120.5B.pdf

(2016). *Agency Risk Management Procedural Requirements.* NASA Office of Safety and Mission Assurance.

Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982. (1994). Retrieved from Division for Ocean Affairs and the Law of the Sea, Office of Legal Affairs, United Nations: https://www.un.org/depts/los/convention_agreements/texts/agreement_part_xi/agreement_part_xi.htm

Aitken, H. G. (1989). *Taylorism at Watertown Arsenal: Scientific Management in Action, 1908-1915.* Princeton, N.J.: Princeton University Press.

Ajala, O. A. (2013). African slave trade and maritime transportation. *The Encyclopedia of Global Human Migration*.

Al Ahbabi, E. (2016, March). *The UAE space program.* Retrieved from Second ICAO/UNOOSA Symposium: www.icao.int/Meetings/SPACE2016/ Presentations/1e%20-%20M.%20AlAhbabi%20-%20Welcome%20Remarks%20-%20 UAE%20Space%20Agency.pdf

Alexander, J., Cheng, Y., Zheng, W., Trawny, N., & Johnson, A. (2012). A Terrain Relative Navigation Sensor Enabled by Multi-Core Processing. *Proc. IEEE Aerospace Conference.* Big Sky, MT: IEEE.

Alibay, F., Koch, J., Verma, V., Bean, K., Toupet, O., Petrizzo, D., . . . Hogg, R. (2022). On the Operational Challenges of Coordinating a Helicopter and Rover Mission on Mars. *2022 IEEE Aerospace Conference (AERO)* (pp. 1-17). Big Sky, MT: IEEE.

Alston, P. (2020). *The parlous state of poverty eradication: Report of the Special Rapporteur on Extreme Poverty and Human Rights.* Human Rights Council.

Amsden, A. H. (2009). Escape from empire: the developing world's journey through heaven and hell. *MIT Press*.

Anderson, P., & Tushman, M. L. (1990). Technological Discontinuities and Dominant Designs: a Cyclical Model of Technological Change. *Administrative Science Quarterly, 35.*

Antarctic Treaty. (1961). Retrieved from U.S. Department of State: https://2009-2017.state.gov/t/avc/trty/193967.htm

Ardron, J., Ruhl, H., & Jones, D. (2018). Incorporating transparency into the governance of deep-seabed mining in the area beyond national jurisdiction. *Mar. Policy*(89), 58–66.

Arendt, H. (2007). *The Conquest of Space and the Stature of Man.* Retrieved from The New Atlantis: https://www.thenewatlantis.com/publications/the-conquest-of-space-and-the-stature-of-man

Argote, L. (1999). *Organizational Learning: Creating, Retaining, and Transferring Knowledge.* Norwell, MA: Kluwer Academic Publishers.

Ash, R. L., Dowler, W. L., & Varsi, G. (1978). Feasibility of rocket propellant production on Mars. *Acta Astronautica, 5*(9), 705-724.

Barnard, L. (2016, March 7). *UAE to finalise space laws soon.* Retrieved from The National: www.thenational.ae/business/aviation/uae-to-finalise-space-laws-soon

Baroff, L. E. (2006). Project-Line Interaction: Implementing Projects in JPL's Matrix. *IEEE Aerospace Conference.*

Bartunek, R. (2016, June 3). *Luxembourg sets aside 200 million euros to fund space mining ventures.* Retrieved from Reuters: www.reuters.com/article/us-luxembourg-space-miningidUSKCN0YP22H

Beard, E. (1976). *Developing the ICBM: A Study in Bureaucratic Policitics.* New York: Columbia University Press.

Bergstresser, J. (2021). To Boldly Go: An Analysis of Luxembourg Space Resources Law in Light of the EU Treaty. *Business Law Review, 42*(3), 143-151.

Bishop, J. D. (1997). Locke's Theory of Original Appropriation and the Right of Settlement in Iroquois Territory. *Canadian Journal of Philosophy, 27*(3), 311–337.

Bonitz, R. G., Nguyen, T. T., & Kim, W. S. (2000). The Mars Surveyor '01 Rover and Robotic Arm. *2000 IEEE Aerospace Conference*, *7*, pp. 235-246. Big Sky, MT, USA.

Boynton, W. V., Bailey, S. H., Hamara, D. K., Williams, M. S., Bode, R. C., Fitzgibbon, M. R., . . . Pathare, A. V. (2001, August 25). Thermal and Evolved Gas Analyzer: Part of the Mars Volatile and Climate Surveyor integrated payload. *Journal of Geophysical Research: Planets, 106*(E8), 17683– 17698.

Bretton Woods Project. (2019, June 4). *What are the main criticisms of the World Bank and the IMF?* Retrieved from Bretton Woods Project: https://www.brettonwoodsproject.org/2019/06/what-are-the-main-criticisms-of-the-world-bank-and-the-imf/

Brown, S. L., & Eisenhardt, K. M. (1998). *Competing on the Edge: Strategy as Structured Chaos.* Cambridge, MA: Harvard Business School Press.

Bugos, G. E. (1993). Manufacturing certainty: Testing and program management for the F-4 Phantom II. *Social Studies of Science, 23*, 265–300.

Building Blocks for the Development of an International Framework on Space Resource Activities. (2019, November). Retrieved from The Hague International Space Resources Governance Working Group: https://www.universiteitleiden.nl/binaries/content/assets/rechtsgeleerdheid/instituut-voor-publiekrecht/lucht--en-ruimterecht/space-resources/bb-thissrwg--cover.pdf

Buono, S. (2020). *For sale: The Moon.* Retrieved from The Hill: https://thehill.com/opinion/technology/521864-for-sale-the-moon

Burgelman, R. A. (2002). Strategy as vector and the inertia of coevolutionary lock-in. *Administrative Science Quarterly, 47*(2), 325-357.

Buthe, T. (2002). Taking Temporality Seriously: Modeling History and the Use of Narratives as Evidence. *American Political Science Review, 96*(3), 481-493.

Caffrey, R. T., Udomkesmalee, G., Hayati, S. A., & Henderson, R. (2004). Initiating the 2002 Mars Science Laboratory (MSL) Technology Program. *2004 IEEE Aerospace Conference.* Big Sky, MT.

Campbell, D. T., & Stanley, J. C. (2015). *Experimental and quasi-experimental designs for research.* Ravenio Books.

Canup, R., & Christensen, P. (2022). *Origins, Worlds and Life. A Decadal Strategy for Planetary Science & Astrobiology 2022-2032.* Retrieved from The National Academies of Science, Engineering and Medicine: https://www.nationalacademies.org/documents/embed/link/LF2255DA3DD1C41C0A42D3BEF0989ACAECE3053A6A9B/file/D5AFB6ADB55E9561F413E585DC8ED0748F738614AF3C?noSaveAs=1

Casani, J. (1991, December 19). NASA's View of JPL. JPL Executive Council Files (JPL 165).

Chapter 2: Maritime Zones. (n.d.). Retrieved from Law of the Sea: A Policy Primer: https://sites.tufts.edu/lawofthesea/chapter-two/

Chen, R. (2022). *VIPER Mission Overview*. Retrieved from NASA: https://www.nasa.gov/viper/overview

Cheng, Y., Clouse, D., Johnson, A., Owen, W., & Vaughan, A. (2011). Evaluation and Improvement of Passive Optical Terrain Relative Navigation Algorithms for Pin-Point Landing. *Proc. AAS Space Flight Mechanics Meeting.* AAS.

Chimni, B. S. (2006). Third World Approaches to International Law: Manifesto. *International Community Law Review 8:*, 3-27, 26.

Christensen, C. (2003). *The Innovator's Dilemma.* New York: Harper Collins.

Clegg, J. J. (2015). Capitalism and slavery. *Critical Historical Studies, 2*(2), 281-304.

Co-Chairs' Proposed Five Year Workplan as of 5 April 2022. (2022, April 5). Retrieved from UNOOSA: https://www.unoosa.org/documents/pdf/copuos/lsc/space-resources/Co-Chairs_Proposed_Workplan_as_at_5_April.pdf

Collier, R. B., & Collier, D. (1991). *Shaping the Political Arena. Critical Junctures, the Labor Movement, and Regime Dynamics in Latin America.* Princeton: Princeton University Press.

Colwell, J., Brisset, J., Dove, A., Jarmak, S., & Q-PACE team. (2019). Q-PACE: the CubeSat Particle Aggregation and Collision Experiment. *EPSC-DPS Joint Meeting 2019.* Geneva, Switzerland.

Committee on the Peaceful Uses of Outer Space. (2020). Building blocks for the development of an international framework on space resource activities: Working paper submitted by Luxembourg and the Netherlands. United Nations General Assembly.

Cooper, L. P. (2008, August). How Project Teams Conceive of and Manage Pre-Quantitative Risk.

Cooper, L. P. (2010). "Experience" as Knowledge: Application of Experience in a New Product Development Team. *Academy of Management 2010 Organizational Communications and Information Systems.*

Cooper, L. P., Hecht, M. H., & Majchrzak, A. (2003). Managing a project's legacy: implications for organizations and project management. *IEEE Aerospace Conference.* Big Sky, MT.

Cooper, L. P., Majchrzak, A., & Faraj, S. (2005). Learning from Project Experiences Using a Legacy-based Approach. *Hawaii International Conference on System Sciences (HICSS).*

Crane, L., & Sparkes, M. (2021, April). First helicopter flight on another planet takes off. *New Scientist*, 13.

Crawley, E., Cameron, B., & Selva, D. (2015). *System architecture: strategy and product development for complex systems.* Prentice Hall Press.

Creswell, J. W., & Miller, D. L. (2000). Determining validity in qualitative inquiry. *Theory Into Practice, 39*(3).

Curcio, B., & Deville, J. (2021). *#SpaceWatchGL Column: Dongfang Hour China Aerospace News Roundup 15 – 21 November*. Retrieved from SpaceWatch.Global: https://spacewatch.global/2021/11/spacewatchgl-column-dongfang-hour-china-aerospace-news-roundup-15-21-november/

Current Status of the Reserved Areas with the International Seabed Authority. (2019). Retrieved from International Seabed Authority: https://www.isa.org.jm/files/files/documents/statusofreservedareas-01-2019-a.pdf

Daniels, P. C. (1973). The Antarctic Treaty. In R. S. Lewis, & P. M. Smith eds., *Frozen Future: A Prophetic Report from Antarctica* (pp. 31-45). New York: Quadrangle Books.

Danovaro, R., Aguzzi, J., Fanelli, E., Billet, D., Gjerde, K., Jamieson, A., . . . Van Dover, C. L. (2017). An ecosystem-based deep-ocean strategy. *Science*(355), 452–454.

Davis, M. (2018, July 12). *China, the US and the race for space*. Retrieved from The Strategist — The Australian Strategic Policy Institute Blog: https://www.aspistrategist.org.au/china-the-us-and-the-race-for-space/

de Weck, O. (2021). *Advanced Space Technology Roadmapping Architecture (ASTRA).* Retrieved from NASA: https://www.nasa.gov/directorates/spacetech/strg/early-stage-innovations-esi/esi2020/astra/

de Weck, O. (2022). *Technology Roadmapping and Development A Quantitative Approach to the Management of Technology.* Springer Cham.

de Weck, O., Roos, D., & Magee, C. L. (2011). *Engineering Systems: Meeting Human Needs in a Complex Technological World.* MIT Press.

de Weck, O., Siddiqi, A., Moraguez, M., Trujillo, A., Lordos, G., & Sarang, M. (2018, October). *Commercial Space Technology Roadmap.* Retrieved from NASA: https://www.nasa.gov/sites/default/files/atoms/files/commercial_space_technology_roadmap.pdf

(2000). *Deep Space 1 Technolow Validation Reports.* JPL Publication, Jet Propulsion Laboratory, Pasadena, CA.

Deutsch, L. J. (2020). Towards deep space optical communications. *Nature Astronomy, 4*(907).

Dezfuli, H., Benjamin, A., Everett, C., Maggio, G., Stamatelatos, M., & Youngblood, R. (2011). *NASA Risk Management Handbook.* National Aeronautics and Space Administration.

Dezfuli, H., Stamatelatos, M., Maggio, G., Everett, C., & Youngblood, R. (2010). *NASA Risk-Informed Decision Making Handbook.* Office of Safety and Mission Assurance NASA Headquarters.

Dillon, R. L., & Madsen, P. M. (2015). Faster-Better-Cheaper Projects: Too Much Risk or Overreaction to Perceived Failure? *IEEE Transactions on Engineering Management, 62*, 141-149.

Draft regulations on exploitation of mineral resources in the Area (ISBA/25/C/WP.1). (2019). Retrieved from International Seabed Authority: https://isa.org.jm/files/files/documents/isba_25_c_wp1-e_0.pdf

Drake, B. G. (2009). *Human Exploration of Mars Design Reference Architecture 5.0.* NASA/SP–2009–566-ADD.

Dunbar, B. (2023). *Commercial Lunar Payload Services Overview.* Retrieved from NASA: https://www.nasa.gov/content/commercial-lunar-payload-services-overview

Dunbar-Ortiz, R. (2015). *An Indigenous Peoples' History of the United States.* Beacon Press.

Eaton, C., Patel, S., Glandon, K. L., Weger, K., Mesmer, B., & Moreland, R. (2022). Legacy of Faster, Better, Cheaper? Cost, Schedule, and Performance Objectives: Understanding the Impact of NASA Policy on Perceptions of Failures. *Space Policy, 62*.

Eisenhardt, K. M. (1989). Building Theories from Case Study Research. *Academy of Management Review, 14*(4), 532-550.

Ellyin, R. (2018). A Technology Infusion Decision Model for Robotic Space Exploration. Northcentral University ProQuest Dissertations Publishing.

Elvis, M. (2021, July 2). *Riches in space.* Retrieved from AEON: https://aeon.co/essays/asteroid-mining-could-pay-for-space-exploration-and-adventure.

Elvis, M., Krolikowski, A., & Milligan, T. (2020). Concentrated lunar resources: imminent implications for governance and justice. *Phil. Trans. R. Soc. A*.

Emes, M. R., Bryant, P., Wilkinson, M. K., King, P., James, A. M., & Arnold, S. (2012). Interpreting "Systems Architecting". *Systems Engineering, 15*(4).

Epp, C., & Smith, T. (2008). The Autonomous Precision Landing and Hazard Detection and Avoidance Technology (ALHAT). *Proc. of the IEEE Aerospace Conference* (pp. 1-7). Big Sky, MT: IEEE.

Escobar, D., Chopra, I., & Datta, A. (2018). Vacuum Chamber Testing of 1.5-Foot Diameter Mars Rotor. *AHS Technical Conference on Aeromechanics Design for Transformative Vertical Flight, American Helicopter Soc.* San Francisco, CA.

Etherington, D. (2016). *SpaceX's Mars Colonial Transporter can go "well beyond" Mars.* Retrieved from TechCrunch+: https://techcrunch.com/2016/09/17/spacexs-mars-colonial-transporter-can-go-well-beyond-mars/

Fagerberg, J., Mowery, D. C., & Nelson Eds., R. R. (2005). The Oxford Innovation Handbook. Oxford University Press.

Falletti, T. (2006). Theory-Guided Process-Tracing in Comparative Politics: Something Old, Something New. *APSA-CP: Newsletter of the Organized Section in Comparative Politics of the American Political Science Association, 17*(1), 9-14.

Farley, K. A., Williford, K. H., Stack, K. M., Bhartia, R., Chen, A., de la Torre, M., . . . Nelessen, A. (2020). Mars 2020 Mission Overview. *Space Science Reviews, 216*(142).

Federal Law No. (12) On The Regulation Of The Space Sector. (2019). Retrieved from UAE Ministry of Justice: https://www.moj.gov.ae/assets/2020/Federal%20Law%20No%2012%20of%202019%20on%20THE%20REGULATION%20OF%20THE%20SPACE%20SECTOR.pdf.aspx

(n.d.). *Flight Opportunities NASA Facts.* National Aeronautics and Space Administration (NASA). Retrieved from NASA: https://www.nasa.gov/sites/default/files/atoms/files/nasa_fact_sheet_flightopportunities-04-11-2019.pdf

Foust, J. (2022, September 11). *Court approves sale of Masten assets to Astrobotic*. Retrieved from Space News: https://spacenews.com/court-approves-sale-of-masten-assets-to-astrobotic/

Foust, J. (2022, September 21). *Lander companies prepare to shoot for the moon*. Retrieved from Space News: https://spacenews.com/lander-companies-prepare-to-shoot-for-the-moon/

Foust, J. (2022, November 10). *NASA to continue Lunar Trailblazer despite cost overrun*. Retrieved from SpaceNews: https://spacenews.com/nasa-to-continue-lunar-trailblazer-despite-cost-overrun/

Foust, J. (2022, November 5). *Psyche review finds institutional problems at JPL*. Retrieved from Space News: https://spacenews.com/psyche-review-finds-institutional-problems-at-jpl/

Frank, E. A. (2019, January 28). *Faster, Better, Cheaper: A maligned era of NASA's history*. Retrieved from Elizabeth A. Frank: http://www.elizabethafrank.com/colliding-worlds/fbc

Frazier, S., & O'Neill, I. J. (2022, June 28). *Deep Space Optical Communications (DSOC)*. Retrieved from NASA: https://www.nasa.gov/mission_pages/tdm/dsoc/index.html

Freeman, E. R., & Mcvea, J. F. (2001). A Stakeholder Approach to Strategic Management. *SSRN Electronic Journal*.

Garcia, M. D., & Fujii, K. K. (2007). Mission design overview for the Phoenix Mars Scout Mission. *AAS/AIAA Space Flight Mechanics Meeting.* Sedona, Arizona: Jet Propulsion Laboratory, National Aeronautics and Space Administration.

Gateway House. (2013, January 17). *Who Will Control the Antarctic?* Retrieved from Fair Observer: https://www.fairobserver.com/region/north_america/who-will-control-antarctic/

Genova, A. L., & Dunham, D. W. (2017). Trajectory Design for the Lunar Polar Hydrogen Mapper Mission. *27th AAS/AIAA Space Flight Mechanics Meeting.* San Antonio TX,.

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.*, 11–32.

Gilbert, A. (2021, April 26). *Mining in Space Is Coming.* Retrieved from Milken Institute Review: https://www.milkenreview.org/articles/mining-in-space-is-coming

Glaser, B. G., & Strauss, A. L. (1967). *The discovery of grounded theory.* New York: Aldine De Gruyter.

Goode, H. H., & Machol, R. E. (1957). *System Engineering: An Introduction to the Design of Large-Scale Systems.* McGraw-Hill.

Gray, G., & Wade, T. (2018, October 23). *U.S. Participation in the International Monetary Fund (IMF): A Primer Read more: https://www.americanactionforum.org/insight/u-s-participation-in-the-international-monetary-fund-imf-a-primer/#ixzz7gqlAj85K Follow us: @AAF on Twitter.* Retrieved from American Action Forum: https://www.americanactionforum.org/insight/u-s-participation-in-the-international-monetary-fund-imf-a-primer/

Greve, H. R. (2007). Exploration and exploitation in product innovation. *Industrial and Corporate Change, 16*(5), 945-975.

Gudmestad, R. (2006). Technology and the world the slaves made. *History Compass, 4*(2), 373-383.

H.R.1508 - Space Resource Exploration and Utilization Act of 2015. (2015). Retrieved from Congress.gov: https://www.congress.gov/bill/114th-congress/house-bill/1508

Halfar, J., & Fujita, R. M. (2002). Precautionary management of deep-sea mining. *Mar. Policy, 26*, 103–106.

Hall, L. (2020). *Lunar Surface Innovation Initiative*. Retrieved from NASA: https://www.nasa.gov/directorates/spacetech/Lunar_Surface_Innovation_Initiative

Hall, L. (2021). *STMD: Space Tech Research Grants*. Retrieved from NASA: https://www.nasa.gov/strg

Hall, L. (2022). *NIAC Overview*. Retrieved from NASA: https://www.nasa.gov/content/niac-overview

Hall, L. (2022). *STMD: Center Innovation Fund*. Retrieved from NASA: https://www.nasa.gov/directorates/spacetech/innovation_fund/index.html

Hall, L. (2022). *STMD: Small Spacecraft Technology*. Retrieved from NASA: https://www.nasa.gov/directorates/spacetech/small_spacecraft/smallsat_overview.html

Hall, P. A. (2003). Aligning Ontology and Methodology in Comparative Politics. In J. Mahoney, & D. Rueschemeyer, *Comparative Historical Analysis in the Social Sciences* (p. Chapter 11). Cambridge, UK and New York: Cambridge University Press.

Handal, J., Surowiec, J., & Buckley, M. (2022, September 14). *DART's Small Satellite Companion Takes Flight Ahead of Impact*. Retrieved from NASA: https://www.nasa.gov/feature/dart-s-small-satellite-companion-takes-flight-ahead-of-impact

Hanlon, M. (2020, January 17). What is the Moon Treaty and is it still useful? (F. Space, Interviewer) Retrieved from Filling Space: https://filling-space.com/2020/01/17/what-is-the-moon-treaty-and-is-it-still-useful/

Hardgrove, C. (2016). The Lunar polar Hydrogen Mapper (LunaH-Map) Mission: Revealing Hydrogen Distributions at the Moon's South Pole with a 6U CubeSat,. *13th Annual CubeSat Developers Workshop, Cal Poly State University.* San Luis Obispo CA.

Hartvigsen, J. J., Elangovan, S., Larsen, D., Elwell, J., Bokil, M., Frost, L. J., & Clark, L. M. (2015). Challenges of solid oxide electrolysis for production of fuel and oxygen from Mars atmospheric CO2. *ECS Transactions, 68*(1), pp. 3563–3583.

Hecht, M. (2003, June 1). ASK Talks with Dr. Michael Hecht. (A. K. Sevices, Interviewer)

Hecht, M., & Saunders, R. S. (2003). CryoScout: A descent through the Mars polar cap. *3rd International Conference on Mars Polar Science and Exploration.* Alberta, Canada.

Hecht, M., Hoffman, J., Rapp, D., McLean, J., Soohoo, J., Schaefer, R., . . . Ponce, A. (2020). Mars Oxygen ISRU Experiment (MOXIE). *Special Mars 2020 Edition of Space Science Reviews*.

Hecht, M., Kounaves, S. P., Quinn, R. C., West, S. J., Young, S. M., Ming, D. W., . . . Smith, P. H. (2009). Detection of Perchlorate and the Soluble Chemistry of Martian Soil at the Phoenix Lander Site. *Science, 325*(5936), 64-67.

Hecht, M., Meloy, T. P., Anderson, M. S., Buehler, M. G., Frant, M. A., Grannan, S. M., . . . Marshall, J. (1999). The MSP 2001 Mars Environmental Compatibility Assessment (MECA). *The Fifth International Conference on Mars.*

Henderson, R., & Clark, K. (1990). Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms. *Administrative Science Quarterly, 35*, 9-30.

Hillyer, M. (2021, June 17). *New Space Sustainability Rating Addresses Space Debris with Mission Certification System.* Retrieved from World Economic Forum: https://www.weforum.org/press/2021/06/new-space-sustainability-rating-addresses-space-debris-with-mission-certification-system

History.com Editors. (2022, May 9). *Great Depression History.* Retrieved from History: https://www.history.com/topics/great-depression/great-depression-history

Hoagland, P., Jacoby, J., & Schumacher, M. E. (2001). Law Of The Sea. *Encyclopedia of Ocean Sciences*, 1481-1492.

Hobe, S. (2018). *Why national space laws on the exploitation of resources of celestial bodies contradict international law.* Retrieved from Room - Space Journal of Asgardia: https://room.eu.com/article/why-national-space-laws-on-the-exploitation-of-resources-of-celestial-bodies-contradict-international-law

Hoffman (Ed.), E. J., & Lawbaugh (Ed.), W. M. (1998, April 1). *Issues in NASA Program and Project Management. Special Edition: A Collection of Papers on NASA Procedures and Guidance 7120.5A.* NASA. Retrieved from NASA: https://ntrs.nasa.gov/citations/20000028280

Hoffman, J. H., Chaney, R. C., & Hammack, H. (2008). Phoenix mars mission—The thermal evolved gas analyzer. *Journal of the American Society for Mass Spectrometry, 19*, 1377–1383.

How are U.S. states, territories, and commonwealths designated in the Geographic Names Information System? (n.d.). Retrieved from The United States Geological Survey: https://www.usgs.gov/faqs/how-are-us-states-territories-and-commonwealths-designated-geographic-names-information-system?qt-news_science_products=0#qt-news_science_products

HSA/Civil Society. (2023, March 4). *Agreement Reached to Advance High Seas Treaty*. Retrieved from High Seas Alliance: https://highseasalliance.org/treatytracker/hsa-civil-society/agreement-reached-to-advance-high-seas-treaty/

Hughes, T. P. (2000). *Rescuing Prometheus: Four Monumental Projects that Changed the Modern World.* Vintage.

Huntress, W. (1992, November 19). Wesley Huntress quoted in JPL executive council off-site meeting. JPL Executive Council Files (JPL 165).

Iannotta, B. (2009, March 5). *Obama Budget Plan Offers Near-Term Boost for NASA.* Retrieved from Space News: https://spacenews.com/obama-budget-plan-offers-near-term-boost-nasa/

IMF. (2021, March 4). *IMF Quotas.* Retrieved from IMF: https://www.imf.org/en/About/Factsheets/Sheets/2016/07/14/12/21/IMF-Quotas

International Seabed Authority. (2022). *https://www.isa.org.jm/exploration-contracts.* Retrieved from International Seabed Authority: https://www.isa.org.jm/exploration-contracts

Ioannou, L. (2017, January 31). *Billionaire closer to mining the moon for trillions of dollars in riches*. Retrieved from CNBC: www.cnbc.com/2017/01/31/billionaire-closer-to-miningmoon- for-trillions-of-dollars-in-riches.html

ISO/IEC JTC 1/SC 7 Software and systems engineering. (2011-12). *ISO/IEC/IEEE 42010:2011 Systems and software engineering — Architecture description.*

ITU's election process explained. (2022 , April). Retrieved from International Communication Union: https://www.itu.int/en/mediacentre/backgrounders/Pages/election-process.aspx

James, L. (2019, March). Speech at the MIT Apollo 50+50 Event.

Jansma, P. A., & Jones, R. M. (2006). Advancing the practice of systems engineering at JPL. *2006 IEEE Aerospace Conference.* Big Sky, MT: IEEE.

Japan: Space Resources Act Enacted. (2021). Retrieved from Library of Congress: https://www.loc.gov/item/global-legal-monitor/2021-09-15/japan-space-resources-act-enacted/

Johnson, A., Aaron, S., Chang, J., Cheng, Y., Montgomery, J., Mohan, S., . . . Zheng, J. (2017). The Lander Vision System for Mars 2020 Entry Descent and Landing. *Proc. AAS Guidance Navigation and Control Conference.* AAS.

Johnson, A., Aaron, S., Cheng, Y., Montgomery, J., Trawny, N., Tweddle, B., . . . Zheng, J. (2016). Design and Analysis of Map Relative Localization for Access to Hazardous Landing Sites on Mars. *Proc. AIAA SciTech Conference.* AIAA.

Johnson, A., Ansar, A., Matthies, L., Trawny, N., Mourikis, A., & Roumeliotis, S. (2007). A General Approach to Terrain Relative Navigation for Planetary Landing. *Proc. AIAA Infotech at Aerospace Conference.* Rohnert Park, CA: AIAA.

Johnson, A., Bergh, C., Cheng, Y., Clouse, D., Gostelow, K., Ishikawa, K., . . . Zheng, W. (2013). Design and Ground Test Results for the Lander Vision System. *Proc. of the AAS Guidance Navigation and Control Conference.* Breckenridge, CO: AAS.

Johnson, A., Cheng, Y., Montgomery, J., Trawny, N., Tweddle, B., & Zheng, J. (2015). Real-Time Terrain Relative Navigation Test Results from a Relevant Environment for Mars Landing. *Proc. AIAA SciTech Conference.* AIAA.

Johnson, A., Villaume, N., Umsted, C., Kourchians, A., Sternberg, D., Trawny, N., . . . Montgomery, J. (2020). The Mars 2020 Lander Vision System Field Test. *Proc. AAS Guidance Navigation and Control Conference.* AAS.

Johnson, A., Willson, R., Cheng, Y., Goguen, J., Leger, C., San Martin, A. M., & Matthies, L. (2007, January 17). Design Through Operation of an Image-Based Velocity Estimation System for Mars Landing. *International Journal of Computer Vision, 74*, 319-341.

Johnson, C. L., & Smith, M. (1989). *Kelly: More Than My Share of It All.* Smithsonian Books.

Johnson, S. B. (2006). *The Secret of Apollo: Systems Management in American and European Space Programs.* Johns Hopkins University Press.

Johnson-Roth, G. (2011). *Mission Assurance Guidelines for A-D Mission Risk Classes.*

Jolly, S. (2002). *The Upside/Downside of Faster, Better, Cheaper.* Retrieved from NASA: https://www.nasa.gov/pdf/456665main_PIF_1_jolly_fbc.pdf

Jordan, J. M. (1994). *Machine-Age Ideology Social Engineering and American Liberalism, 1911-1939.* University of North Carolina Press.

Joseph, C., & Wood, D. (2021). Analysis of the Microgravity Research Ecosystem and Market Drivers of Accessibility. *New Space*.

JPL. (2009). *Phoenix TEGA Door Opening Anomaly.* NASA Lessons Learned System.

JPL and the Space Age: The Pathfinders (2022). [Motion Picture].

Kanigel, R. (2005). *The One Best Way: Frederick Winslow Taylor and the Enigma of Efficiency.* The MIT Press.

Kaplan, D., Baird, R., Flynn, H., Ratliff, J., Baraona, C., Jenkins, P., . . . al, e. (2000). The 2001 Mars In-situ-propellant-production Precursor (MIP) Flight Demonstration - Project objectives and qualification test results. *Space 2000 Conference and Exposition.*

Kendi, I. X. (2016). *Stamped from the Beginning: The Definitive History of Racist Ideas in America.*

Kendi, I. X. (2019). *How to Be an Antiracist.* One World/Ballantine.

Kim, R. (2017). Should deep seabed mining be allowed? *Mar. Policy*, 134–137.

Kimmel, W. M., Beauchamp, P. M., Frerking, M. A., Kline, T. R., Vassigh, K. K., Willard, D. E., . . . Trenkle, T. G. (2020). *Technology Readiness Assessment Best Practices Guide.* NASA Office of the Chief Technologist.

Kingdon, J. W. (1984). *Agendas, Alternatives and Public Policies.* Washington DC.: Addison-Wesley Educational Publishing Inc.

Klein, G. (2003). *The Power of Intuition.* New York: Doubleday.

Kogut, B., & Zander, U. (1992). Knowledge of the firm, combinative capabilities, and the replication of technology. *Organization Science, 3*(3), 383-397.

Kolb, D. A. (1984). *Experiential Learning: Experience as the Source of Learning and Development.* Englewood Cliffs, NJ: Prentice Hall.

Koning, W. J., Johnson, W., & Allan, B. G. (2018). Generation of Mars Helicopter Rotor Model for Comprehensive Analyses. *AHS Specialists' Conference on Aeromechanics Design for Transformative Vertical Flight.* San Francisco, California.

Koppes, C. R. (1982). *JPL and the American Space Program: A History of the Jet Propulsion Laboratory (The Planetary Exploration Series).* New Haven: Yale University Press.

Krolikowski, A., & Elvis, M. (2018). Making policy for new asteroid activities: In pursuit of science, settlement, security, or sales? *Space Policy*.

Kuhn, L. (2021, June 6). *Polycentricity for Governance of the Moon as a Commons.* Retrieved from Open Lunar Foundation: https://www.openlunar.org/library/polycentricity-for-governance-of-the-moon-as-a-commons

Kuhn, L., & Schingler, J. K. (2021, June 5). *Polycentricity for coherent, timely, effective, and equitable governance of lunar activities.* Retrieved from Open Lunar Foundation: https://www.openlunar.org/library/polycentricity-for-governance-of-lunar-activities

Kurian, G. T. (2011). *Fairness. In The Encyclopedia of Political Science.* CQ Press.

Lakwete, A. (2005). *Inventing the cotton gin: machine and myth in Antebellum America.* JHU Press.

Lambright, W. H. (2009). Launching a New Mission: Michael Griffin and NASA's Return to the Moon. *Launching a New Mission: Michael Griffin and NASA's Return to the Moon*. IBM Center for The Business of Government . Retrieved from Launching a New Mission: Michael Griffin and NASA's Return to the Moon

Langley, A. (1999). Strategies for Theorizing from Process Data. *Academy of Management Review, 24*(4), 691-710.

Langley, A., & Truax, J. (1994). A process study of new technology adoption in smaller manufacturing firms. *Journal of Management Studies, 31*, 619-652.

Lasswell, H. (1936). *Politics: Who Gets What, When, How.* New York: Whittlesey House.

Launius, R. D., & McCurdy, H. E. (1997). *Spaceflight and the Myth of Presidential Leadership.* University of Illinois Press.

Launius, R., & McCurdy, Eds., H. E. (2016). *Seeds of Discovery: Chapter in the Economic History of Innovation within NASA.* Retrieved from NASA: https://www.nasa.gov/sites/default/files/atoms/files/seeds_of_discovery_ms-spaceportal.pdf

LeCompte, M. D. (2000). Analyzing Qualitative Data. *Theory Into Practice, 39*(3).

LeCompte, M. D., & Goetz, J. P. (1982). Problems of reliability and validity in ethnographic research. *Review of Educational Research, 52*(1), 31-60.

Lee, S.-H., Lin, W.-C., Rudnik, J., & Rhodes, D. H. (2021). An architecting approach to transformations within the design consulting industry: IDEO case study. *Proceedings of the International Conference on Engineering Design (ICED21).* Gothenburg, Sweden.

Leising, C. J. (2004, March 30-31). *JPL's Approach for Helping Flight Project Managers Meet Today's Management Challenges.* Retrieved from NASA: https://www.nasa.gov/pdf/293241main_62662main_1_pmchallenge_leising.pdf

Lewis, J. S. (1997). *Mining the Sky: Untold Riches From The Asteroids, Comets, And Planets.* Basic Books.

Lindsay, J. (2006). War upon the Map: The Politics of Military User Innovation. MIT.

Linick, D., & Briggs, C. (2014). *Developing the JPL Engineering Processes.* Retrieved from NASA JPL: https://trs.jpl.nasa.gov/bitstream/handle/2014/41036/04-2813.pdf?sequence=1

Locke, K. (2001). *Grounded theory in management research.* SAGE Publications Ltd.

Loff, S. (2022, October 5). *NASA Leadership*. Retrieved from NASA: https://www.nasa.gov/nasa-leadership

Loi du 20 Juillet 2017 sur l'Exploration et l'Utilisation des Ressources de l'Espace. (2017, July 20). Retrieved from http://data.legilux.public.lu/file/eli-etat-leg-loi-2017-07-20-a674-jo-fr-pdf.pdf

Lowenstein, R. (2011, August 4). *The Nixon Shock.* Retrieved from Bloomberg: https://www.bloomberg.com/news/articles/2011-08-04/the-nixon-shock

Maier, M. W. (2009). *The Art of Systems Architecting (Systems Engineering).* CRC Press.

Majchrzak, A., Cooper, L. P., & Neece, O. E. (2004, February). Knowledge Reuse for Innovation. *Management Science, 50*(2), 174–188.

Mandelbaum, R. F. (2018, November 20). *Decolonizing Mars: Are We Thinking About Space Exploration All Wrong?* Retrieved from Gizmodo: https://gizmodo.com/decolonizing-mars-are-we-thinking-about-space-explorat-1830348568

Mann, A. (2021, May 11). *Is Mars Ours?* Retrieved from The New Yorker: https://www.newyorker.com/science/elements/is-mars-ours

March, J. G. (1991). Exploration and Exploitation in Organizational Learning. *Organizational Science, 2*(1, Special Issue: Organizational Learning: Papers in Honor of (and by) James G. March), 71-87.

Maritime Space: Maritime Zones and Maritime Delimitation. (2011). Retrieved from United Nations: https://www.un.org/depts/los/LEGISLATIONANDTREATIES/status.htm

Market Business News. (n.d.). *What is an economic depression? Definition and examples.* Retrieved from Market Business News: https://marketbusinessnews.com/financial-glossary/economic-depression/

Mars Climate Orbiter Mishap Investigation Board. (2000, March). *Report on Project Management in NASA by the Mars Climate Orbiter Mishap Investigation Board.* Retrieved from SpaceRef: https://spaceref.com/press-release/report-on-project-management-in-nasa-by-the-mars-climate-orbiter-mishap-investigation-board/

Mars Exploration Rovers. (n.d.). Retrieved from NASA Mars Exploration Program: https://mars.nasa.gov/mars-exploration/missions/mars-exploration-rovers/

Mars Pathfinder. (n.d.). Retrieved from NASA Mars Exploration Program: https://mars.nasa.gov/mars-exploration/missions/pathfinder/

Mars Polar Lander/Deep Space 2. (n.d.). Retrieved from NASA Mars Exploration Program: https://mars.nasa.gov/mars-exploration/missions/polar-lander/

(1999). *Mars Surveyor 2001 Mission Plan, Revision A.* Pasadena, CA: JPL.

Masson-Zwaan, T., & Sundahl, M. J. (2021). The Lunar Legal Landscape: Challenges and Opportunities. *Air and Space Law, 46*(1), 29-56.

Matousek, S. (2001). Mars Scouts: An Overview. *15th Annual AIAA/USU Conference on Small Satellites.* Logan, Utah.

Matson, J. (2010, February 1). *Phased Out: Obama's NASA Budget Would Cancel Constellation Moon Program, Privatize Manned Launches*. Retrieved from Scientific American: https://www.scientificamerican.com/article/nasa-budget-constellation-cancel/

Maue, A. (2021, November 26). *How NASA chooses its missions (and how you can help).* Retrieved from Astrobites: https://astrobites.org/2021/11/26/nasa-mission-selection/

Maya, I., Rahimi, M., Meshkati, N., Madabushi, D., Pope, K., & Schulte, M. (2005). Cultural Influence on the Implementation of Lessons Learned in Project Management. *Engineering Management Journal, 17*(4), 17-24.

McClean, J. B., Hoffman, J. A., Hecht, M. H., Aboobaker, A. M., Araghi, K. R., Elangovan, S., . . . Voecks, G. E. (2021). Prelanding plans for Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) science operations. *Acta Astronautica*.

McCleese, D., Sander, M., & Barber, T. (1991, December). JPL-NASA HQ, Mutual Perceptions. JPL Executive Council Files (JPL 165).

McCurdy, H. E. (2003). *Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program.* Baltimore, MD: The Johns Hopkins University Press.

McDougall, W. A. (1985). *... the Heavens and the Earth: A Political History of the Space Age.* USA: Basic Books Inc.

McGuinness, J., & Warner, C. (2022, December 13). *NASA's Big 2022: Historic Moon Mission, Webb Telescope Images, More*. Retrieved from NASA: https://www.nasa.gov/press-release/nasa-s-big-2022-historic-moon-mission-webb-telescope-images-more

Memorandum of Conversation, by the Under Secretary of State (Lovett). (1948). In *Foreign Relations of the United States* (p. 1002).

Mercer, C. R. (2019). Small Satellite Missions for Planetary Science. *33rd Annual AIAA/USU Conference on Small Satellites.*

Meyen, F., Hecht, M., Hoffman, J., & Team, M. (2016, December). Thermodynamic model of Mars Oxygen ISRU Experiment (MOXIE). *Acta Astronautica, 129*, 82-87.

Ministry of Defence. (2012, December 12). *MOD Architecture Framework*. Retrieved from gov.uk: https://www.gov.uk/guidance/mod-architecture-framework

Mintzberg, H. (1979). An emerging strategy of "direct" research. *Administrative Science Quarterly, 24*(4), 582–589.

Mitchell, R. K., Agle, B. R., & Wood, D. J. (1997, October). Toward a Theory of Stakeholder Identification and Salience: Defining the Principle of Who and What Really Counts. *The Academy of Management Review, 22*(4), 853-886 .

Mohon, L. (2021). *Technology Demonstration Missions Overview*. Retrieved from NASA: https://www.nasa.gov/mission_pages/tdm/main/overview.html

Mohr, L. B. (1982). *Explaining Organizational Behavior.* San Francisco: Jossy-Bass.

Morris, R. C. (2010). *Can the Subaltern Speak?: Reflections on the History of an Idea.* Columbia University Press.

Mourikis, A., Trawny, N., Roumeliotis, S., Johnson, A., Ansar, A., & Matthies, L. (2009, April). Vision Aided Inertial Navigation for Spacecraft Entry Descent and Landing. *IEEE Trans. on Robotics and Automation, 25*, 264-280.

Muscatello, A. C., Hintze, P. E., Meier, A. J., Bayliss, J. A., Karr, L. J., Paley, M. S., . . . Berggren, a. M. (2016). Mars Atmospheric In Situ Resource Utilization Projects at the Kennedy Space Center. *Earth and Space 2016 : Engineering for Extreme Environments.*

Mutua, M., & Anghie, A. (2000). What is TWAIL? *Proceedings of the Annual Meeting (American Society of International Law), 94*, 31-40.

NASA. (2015 , July). *2015 NASA Technology Roadmaps Introduction, Crosscutting Technologies, and Index.* Retrieved from NASA:

https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_0_introduction_crosscutting_index_final_0.pdf

NASA. (2006). *NASA Administrator Michael Griffin*. Retrieved from NASA: https://www.nasa.gov/centers/ames/about/griffin_bio.html

NASA. (2008). *Phoenix Mars Lander Spacecraft and Instruments*. Retrieved from NASA: https://www.nasa.gov/mission_pages/phoenix/spacecraft/tega.html

NASA. (2013). *Beyond Earth - Expanding Human Presence into the Solar System*. Retrieved from NASA: https://www.nasa.gov/exploration/whyweexplore/why_we_explore_main.html#.YbJAyC2ZMnU

NASA. (2017). *Former Administrator Charles F. Bolden*. Retrieved from NASA: https://www.nasa.gov/about/highlights/bolden_bio.html

NASA. (2018, April 10). *Former NASA Administrator Jim Bridenstine*. Retrieved from NASA: https://www.nasa.gov/about/highlights/bridenstine-biography.html

NASA. (2019). *Planetary Mission Program Overview*. Retrieved from NASA: https://www.nasa.gov/planetarymissions/overview.html

NASA. (2020). *NASA Software Engineering and Assurance Handbook.* National Aeronautics and Space Administration (NASA).

NASA. (2022). *About the Human Exploration and Operations Mission Directorate (Archive)*. Retrieved from NASA: https://www.nasa.gov/directorates/heo/about.html

NASA. (2022, September 30). *Impact Story: Terrain Relative Navigation*. Retrieved from NASA: https://www.nasa.gov/directorates/spacetech/Terrain_Relative_Navigation

NASA. (2022). *NASA 2022 Strategic Plan.*

NASA. (2022, November 4). *Psyche IRB Recommendations.* Retrieved from NASA: https://www.nasa.gov/sites/default/files/atoms/files/psyche_irb_report_and_response_nov_2022.pdf

NASA. (2023, February 25). *Ingenuity*. Retrieved from NASA: https://mars.nasa.gov/technology/helicopter/#Flight-Log

NASA. (2023). *NASA*. Retrieved from https://www.nasa.gov/about/org_index.html

(2015). *NASA Cost Estimating Handbook.* National Aeronautics and Space Administration (NASA).

NASA Headquarters. (2016). *NASA Project Planning and Control Handbook.* National Aeronautics and Space Administration. Retrieved from NASA: https://www.nasa.gov/content/project-planning-and-control-ppc-handbook

NASA History. (2009). *Administrator Daniel S. Goldin's Accomplishments.* Retrieved from NASA History: https://history.nasa.gov/goldin-accomplishments.pdf

NASA History Office Program. (2018, April 2). *NASA History Overview*. Retrieved from NASA: https://www.nasa.gov/content/nasa-history-overview

NASA JPL. (2002, May 28). *Odyssey Finds Water Ice in Abundance Under Mars' Surface.* Retrieved from NASA JPL: https://www.jpl.nasa.gov/news/odyssey-finds-water-ice-in-abundance-under-mars-surface

NASA Office of Safety and Mission Assurance (OSMA). (n.d.). *NASA Software Assurance and Software Safety Standard requirements.* 2022: National Aeronautics and Space Administration.

(2021). *NASA Procedural Requirements NPR 8705.4A Risk Classification for NASA Payloads.* NASA Online Directives Information System (NODIS) Library.

(2018). *NASA Research and Technology Program and Project Management Requirements.* NASA.

NASA SBIR/STTR Program Support Office. (2022). *Small Business Innovation Research (SBIR) / Small Business Technology Transfer (STTR)*. Retrieved from NASA: https://www.nasa.gov/directorates/spacetech/sbir_sttr/index.html#.VQb6MkjJzyE

NASA Science. (2023). *About Us*. Retrieved from NASA Science: https://science.nasa.gov/about-us/leadership/bios

NASA Science. (2023). *Decadal Survey*. Retrieved from NASA Science: https://science.nasa.gov/earth-science/decadal-surveys

NASA Science. (n.d.). *Instruments*. Retrieved from NASA Science: https://mars.nasa.gov/mars2020/spacecraft/instruments/

NASA Science. (n.d.). *Mars 2020 Mission Perseverance Rover*. Retrieved from NASA Science: https://mars.nasa.gov/mars2020/

NASA Science Mission Directorate. (2018). *Small Innovative Missions for PLanetary Exploration (SIMPLEx) Evaluation Plan Third Stand Alone Missions of Opportunity Notice Announcement of Opportunity NNH17ZDA004O, Program Element Appendix J SALMON-3 PEA J.* Retrieved from https://soma.larc.nasa.gov/simplex/pdf_files/SIMPLEx-SALMON3-Evaluation-Plan-rev15.pdf

(2022). *NASA Software Engineering Requirements.* NASA Online Directives Information System (NODIS) Library.

NASA Solve. (n.d.). Retrieved from NASA: https://www.nasa.gov/solve/index.html

(2021). *NASA Space Flight Program and Project Management Requirements.* NASA.

NASA STEM Engagement Highlights . (2021). Retrieved from NASA: https://www.nasa.gov/sites/default/files/atoms/files/edu_nasa_stem_engagement_highlights_2021.pdf

(2016). *NASA Systems Engineering Handbook* . NASA.

(2020). *NASA Systems Engineering Processes and Requirements.* NASA.

NASA, The Artemis Accords: Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids For Peaceful Purposes [Artemis Accords]. (2020, October 13).

NASA/JPL. (2001, September 18). *PIA04496: Artist's Concept of Deep Space 1 Encounter with Comet Borrelly* . Retrieved from NASA/JPL: https://photojournal.jpl.nasa.gov/catalog/PIA04496

NASA/JPL-Caltech/ASU. (2022). *NASA Continues Psyche Asteroid Mission.* Retrieved from NASA: https://www.nasa.gov/feature/nasa-continues-psyche-asteroid-mission

NASA's Technology Transfer Program. (n.d.). Retrieved from NASA's Technology Transfer Program: https://technology.nasa.gov/

Nasr, M., Meyen, F., & Hoffman, J. (2018). Scaling the Mars Oxygen ISRU Experiment (MOXIE) for Mars Sample Return. *2018 IEEE Aerospace Conference*, (pp. 1-7). Big Sky, MT.

Nasr, M., Wiser, L., Talibzade, R., Rotola, G., Fino, I., Grattan, K., . . . Louden, E. (2021). Planetary Protection and Martian ISRU. *Global Space Exploration Conference (GLEX 2021).* St Petersburg, Russian Federation: International Astronautical Federation (IAF).

Natarajan, U., Reynolds, J., Bhatia, A., & Xavier, S. (2016). Introduction: TWAIL - on praxis and the intellectual. *Third World Quarterly, 37*(11), 1946-1956.

National Space Policy of the United Arab Emirates. (2016, September). Retrieved from UAE Space Agency: https://space.gov.ae/Documents/PublicationPDFFiles/UAE_National_Space_Policy_English.pdf

Natural Resources Canada. (n.d.). *Platinum facts.* Retrieved from Natural Resources Canada: https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/platinum-facts/20520

Nelson, ed, D. (1992). *A Mental Revolution: Scientific Management since Taylor.* Columbus, Ohio: The Ohio State University Press.

Nelson, R. M., Stofan, E. R., Raymond, C. A., & Rayman, M. D. (1997). The New Millennium Deep Space One Mission. *28th Annual Lunar and Planetary Science Conference*, (p. 1013). Houston, TX.

Neto, O. D., Hofmann, M., Masson-Zwaan, T., & Stefoudi, D. (2020). *Building Blocks for the Development of an International Framework for the Governance of Space Resource Activities (A Commentary).* Eleven International Publishing.

New Millenium Program. (n.d.). Retrieved from NASA JPL: https://www.jpl.nasa.gov/nmp/TECHNOLOGY/tech-index.php#:~:text=The%20New%20Millennium%20Program%20(NMP,to%20medium%20class%20system%20technologies.

Nguyen, H. T. (2008). Sequence organization as local and longitudinal achievement. *Text & Talk, 28*(4), 501-528.

Nier, A., & McElroy, M. (1997). Composition and structure of Mars' Upper atmosphere: Results from the neutral mass spectrometers on Viking 1 and 2. *Journal of Geophysical Research, 82*(28), 4341-4349.

Nightingale, D. J., & Rhodes, D. H. (2015). *Architecting the Future Enterprise.* The MIT Press.

Niner, H. J., Ardron, J. A., Escobar, E. G., Gianni, M., Jaeckel, A., Jones, D. O., . . . Gjerde, K. M. (2018). Deep-sea mining with no net loss of biodiversity – an impossible aim. *Front. Mar. Sci.*

Niza, C., Silva, S., & Lima, M. (2008). Occupational accident experience: Association with workers' accident explanation and definition. *Safety Science, 46*(6), 959-971.

Nohria, N., Dyer, D., & Dalzell, F. (2002). *Changing Fortunes: Remaking the Industrial Corporation.* New York: Wiley.

Nozick, R. (1974). *Anarchy, State and Utopia.* New York: Basic Books.

NSPIRES NASA PRS. (2015). *Small Innovative Missions for Planetary Exploration Program Abstracts of selected proposals.* Retrieved from NASA Solicitation and Proposal Integrated Review and Evaluation System NASA Research Opportunities: https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=478898/solicitationId=%7B1DDABD1B-6261-1D15-874A-67BB42357C3A%7D/viewSolicitationDocument=1/SIMPLEx14%20Selections_Abstracts.pdf

Nutt, P. (1984). Types of organizational decision processes. *Administrative Science Quarterly, 29*, 414- 450.

OECD. (1992). *Proposed Guidelines for Collection and Interpreting Technological Innovation Data: Oslo Manual.*

Office of Inspector General. (2022). *2022 Report on NASA's Top Management and Performance Challenges.*

Oh, D. Y., Collins, S., Drain, T., Hart, W., Imken, T., Larson, K., . . . Pirkl, Z. (2019). Development of the Psyche Mission for NASA's Discovery Program. *36th International Electric Propulsion Conference University of Vienna.* Vienna, Austria.

O'Reilly, C. A., & Tushman, M. (2007, March). Ambidexterity as a Dynamic Capability: Resolving the Innovator's Dilemma. *Stanford University Graduate School of Business*(Research Paper No. 1963).

Ortiz, P. (2018). *An African American and Latinx History of the United States* (Vol. 4). Beacon Press.

Osborne, T. L. (2022). *NASA Space Flight Program and Project Management Handbook.* Washington, D.C.: National Aeronautics and Space Administration Headquarters.

Paikowsky, D., & Tzezana, R. (2018, January). The politics of space mining – An account of a simulation game. *Acta Astronautica, 142*, 10-17.

Paxton, L. J. (2007). "Faster, better, and cheaper" at NASA: Lessons learned in managing and accepting risk. *Acta Astronautica, 61*(10), 954-963.

Peck, M. J., & Scherer, F. M. (1962). *The Weapons Acquisition Process: An Economic Analysis.* Cambridge: Harvard Business School School Press.

Pettigrew, A. M. (1990). Longitudinal Field Research on Change: Theory and Practice. *Organization Science, 1*(3), 267–292.

Phoenix. (2022). Retrieved from NASA Solar System: https://solarsystem.nasa.gov/missions/phoenix/in-depth/

Planetary resources and the Government of Luxembourg partner to advance the space resource industry. (2016, June 13). Retrieved from Planetary Resources: www.planetaryresources.com/ 2016/06/planetary-resources-and-the-government-of-luxembourg-partner-to-advancethe- space-resource-industry

Podolski, D., & Biswas, A. (2020, December 22). *Deep Space Optical Communications (DSOC).* Retrieved from NASA: https://www.nasa.gov/directorates/spacetech/game_changing_development/projects/archived/DSOC

Posen, B. (1984). *The Sources of Military Doctrine: France, Britain, and Germany between the world wars.* Ithaca: Cornell University Press.

Potter, N. (2020, July). A Mars helicopter preps for launch: The first drone to fly on another planet will hitch a ride on NASA's Perseverance rover - [News]. *IEEE Spectrum, 57*(7), 06-07.

Prospector-X: an international mission to test technologies for asteroid mining. (n.d.). Retrieved from Deep Space Industries : https://deepspaceindustries.com/prospector-x-an-internationalmission- to-test-technologies-for-asteroid-mining

Psyche IRB. (2022). *Psyche Independent Review Board Report.* NASA.

Public Law 114 - 90 - U.S. Commercial Space Launch Competitiveness Act. (2015, November 25). Retrieved from https://www.govinfo.gov/app/details/PLAW-114publ90

Rae , D., Yates, D., Hochsch, J. L., Morone, J., & Fessler, C. (1983). *Equalities.* Harvard University Press.

Rae, D. (1979). The Egalitarian State: Notes on a Contradictory System of Ideals. *Daedalus, 108*(4), 37-54.

Rapp, D. (2018). *Use of Extraterrestrial Resources for Human Space Missions to Moon or Mars* (Vol. 2nd edition). 2018: Springer-Praxis Books.

Rapp, D. (2023). Private Communication.

Rapp, D., Hoffman, J., Meyen, F., & Hecht, M. (2015). The Mars Oxygen ISRU Experiment (MOXIE) on the Mars 2020 Rover. *AIAA SPACE 2015 Conference and Exposition* (pp. 1-12). Pasadena, California: American Institute of Aeronautics and Astronautics.

Rawls, J. (1971). *A Theory of Justice.* Cambridge, Massachusetts: Harvard University Press,.

Rayman, M. D. (2002). Successful Conclusion of the Deep Space 1 Mission: Important Results without a Flashy Title. American Institute of Aeronautics and Astronautics.

Rayman, M. D., Varghese, P., Lehman, D. H., & Livesay, L. L. (2000). Results from the Deep Space 1 technology validation mission. *Acta Astronautica, 47*(2–9), 475-487.

Recommendation XI-1 (ATCM XI - Buenos Aires, 1981). (1989). Retrieved from Secretariat of the Antarctic Treaty: https://www.ats.aq/devAS/Meetings/Measure/133?s=1&from=1/1/1958&to=1/1/2158&cat=0&top=0&type=0&stat

Redbird, B. (2020, February). *What Drives Native American Poverty?* Retrieved from https://www.ipr.northwestern.edu/news/2020/redbird-what-drives-native-american-poverty.html

Reddy, S. (2011, March 23). What Does The IMF Do, Who Should Drive It? *NPR*. (M. Martin, Interviewer) NPR. Retrieved from https://www.npr.org/2011/05/23/136579286/what-does-the-imf-do-who-should-drive-it

Reeves Jr., J. D. (2013, May 19). The Impact of Risk Identification Biases and Trends on Space System Project Performance. George Washington University.

Reeves, J. D., Eveleigh, T., Holzer, T. H., & Sarkani, S. (2013). Risk identification biases and their impact to space system development project performance. *Engineering Management Journal, 25*, 3-12.

Regan, S. (2014, March). *5 Ways The Government Keeps Native Americans In Poverty.* Retrieved from Forbes: https://www.forbes.com/sites/realspin/2014/03/13/5-ways-the-government-keeps-native-americans-in-poverty/#1f68cbe2c274

Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area / proposed by the Legal and Technical Commission. (2013). Retrieved from International Seabed Authority: https://www.isa.org.jm/files/documents/EN/Regs/MiningCode.pdf

Rentsch, J., Heffner, T. S., & Duffy, L. T. (1994). What you know is what you get from experience. *Group & Organization Management, 19*(4), 450-474.

(2019). *Report of the Committee on the Peaceful Uses of Outer Space.* UN COPUOS.

Reserved Areas. (n.d.). Retrieved from International Seabed Authority: https://www.isa.org.jm/minerals/reserved-areas

Riach, G. (2017). *An Analysis of Gayatri Chakravorty Spivak's Can the Subaltern Speak?* Macat Library.

Rich , B. R. (1996). *Skunk Works: A Personal Memoir of My Years at Lockheed.* Back Bay Books.

Roberts, T. G. (2022, September 1). *History of the NASA Budget.* Retrieved from Aerospace Security Project at CSIS: https://aerospace.csis.org/data/history-nasa-budget-csis/

Rodney, W. (2018). *How Europe underdeveloped Africa.* Verso Trade.

Rogers, E. (1983). *Diffusion of Innovations.* New York: The Free Press.

Romohalli, K., Lawton, E., & Ash, R. (1989). Recent Concepts in Missions to Mars: Extraterrestrial Processes. *Journal of Propulsion and Power, 5*(2), 181-187.

Rose, J. R. (2002). Risk management at JPL-practices and promises. *IEEE Aerospace Conference.* Big Sky, MT: IEEE.

Rosen, S. P. (1994). *Winning the Next War.* Ithaca: Cornell University Press.

Rosenfield, S. B., & Smith, D. D. (1980). The Moon Treaty: The United States Should Not Become A Party. *Proceedings of the Annual Meeting (American Society of International Law), 74*, 162–70.

Rothermich, E. (2020, December 23). *NASA's Artemis Accords Boost Commercial Space Activity.* Retrieved from The Regulatory Review: https://www.theregreview.org/2020/12/23/rothermich-nasa-artemis-accords-boost-commercial-space-activity/

Rothwell, R., & Zegveld, W. (1994). Reindustrialization and Technology. In R. Rothwell (Ed.), Towards the Fifth-generation Innovation Process. *International Marketing Review., 11*, 7-31.

Rouse, W. B. (2005). A theory of enterprise transformation. *Systems Engineering, 8*(4), 279-295.

Salazar, J. F. (2015, August 13). *Antarctica may hold the key to regulating mining in space.* Retrieved from DownToEarth: https://www.downtoearth.org.in/news/governance/antarctica-may-hold-the-key-to-regulating-mining-in-space-50717

Salomon, R., & Martin, X. (2008). Learning, knowledge transfer, and technology implementation performance: A study of time-to-build in the global semi-conductor industry. *Management Science, 54*(7), 1266-1280.

Samuels, J. (2021, December 28). *NASA's Perseverance Mars Rover Milestones - 2021 Year in Review*. Retrieved from NASA Science: https://mars.nasa.gov/resources/26463/nasas-perseverance-mars-rover-milestones-2021-year-in-review/

Sanchez, J. A., Reddy, V., Bottke, W. F., Battle, A., Sharkey, B., Kareta, T., . . . Cantillo, D. C. (2021). Physical Characterization of Metal-rich Near-Earth Asteroids 6178 (1986 DA) and 2016 ED85. *The Planetary Science Journal, 2*(5), 2:205.

Sanders, B. (2022, April 22). *Jeff Bezos is worth $160bn – yet Congress might bail out his space company.* Retrieved from The Guardian: https://www.theguardian.com/commentisfree/2022/apr/22/jeff-bezos-space-elon-musk-billionaires-bernie-sanders

Sanders, G. B., & Larson, W. E. (2011). Integration of In-Situ Resource Utilization into lunar/Mars exploration through field analogs. *Advances in Space Research, 47*(1), 20-29.

Sanders, G. B., Paz, A., Oryshchyn, L., Araghi, K., Muscatello, A., Linn, D. L., . . . Peters, T. (2015). Mars ISRU for Production of Mission Critical Consumables–Options, Recent Studies, and Current State of the Art. *AIAA SPACE 2015 Conference and Exposition.*

Sapolsky, H. M. (1972). *The Polaris System Development: Bureaucratic and Programmatic Success in Government.* Cambridge: Harvard University Press.

Schierholz, S., & Finch, J. (2020, December 3). *NASA Selects Companies to Collect Lunar Resources for Artemis Demonstrations*. Retrieved from NASA: https://www.nasa.gov/press-release/nasa-selects-companies-to-collect-lunar-resources-for-artemis-demonstrations

Schumpeter, J. A. (1934). *The Theory of Economic Development.* New York: Harvard University Press.

(2021). *Science Mission Directorate Policy: SMD Standard Mission Assurance Requirements For Payload Classification D.* NASA.

Science-enabling Technology. (2023). Retrieved from NASA Science: https://science.nasa.gov/technology

Scott, S. V. (2010). *International Law in World Politics: An Introduction.* Lynne Rienner Publishers, Inc.

Sen, A. (2009). *The Idea of Justice.* Cambridge, Mass: Harvard University Press.

Shackelford, S. (2020, May 19). *US seeks to change the rules for mining the Moon.* Retrieved from The Conversation: https://theconversation.com/us-seeks-to-change-the-rules-for-mining-the-moon-136665

Sheldrake, J. (1997). *Management theory : from Taylorism to Japanization.* London: International Thomson Business Press.

Shelton, D. (1999, November 22). *Commitment and Compliance: What Role for International Soft Law?* Retrieved from Carnegie Endowment for International Peace: https://carnegieendowment.org/1999/11/22/commitment-and-compliance-what-role-for-international-soft-law-event-47

Shelton, D. (2008). Soft Law. In *Handbook of International Law.* Routledge Press.

Sherwin, C. W., & Isenson, R. S. (1967). Project Hindsight. *Science, 156*(3782), 1571-1577.

Shirbacheh, M., Hecht, M., Bell, J. L., & Mogensen, C. (2005). Microscopy, electrochemistry, and conductivity analyzer (MECA) payload on Mars '07 Phoenix lander. *2005 IEEE Aerospace Conference*, (pp. 279-291). Big Sky, MT, USA.

Shotwell, R. (2005). Phoenix--the first Mars Scout mission. *Acta Astronaut, 57*(2-8), 121-34.

Simon, H. A. (1977). *The New Science of Management Decision.* Prentice Hall.

Sivolella, D. (2019). *Space Mining and Manufacturing: Off-World Resources and Revolutionary Engineering Techniques.* Springer Cham.

Smith, K., & Tushman, M. L. (2005). Managing Strategic Contractions: A Top Management Model for Managing Innovation Streams. *Organization Science, 16*(5), 522-536.

SOMA LaRC. (2018). *Small, Innovative Missions for PLanetary Exploration (SIMPLEx).* Retrieved from SOMA LaRC: https://soma.larc.nasa.gov/simplex/

Sonenshein, S. (2010). We're Changing - Or are We? Untangling the Role of Progressive, Regressive, and Stability Narratives During Strategic Change Implementation. *Academy of Management Journal, 53*(3), 477-512.

(1998, January 29). *Space Station - Agreement Between the United States of America and Other Governments.* Washington.

Space Technology Mission Directorate. (2022). Retrieved from NASA: https://www.nasa.gov/directorates/spacetech/about_us/index.html

Sternberg, D. (2019). MarCO: The First Interplanetary CubeSats. *13th Low-Cost Planetary Missions Conference.* Toulouse, France.

Stilwell, L. C. (2004). Platinum in the South African economy. *International Platinum Conference 'Platinum Adding Value'.* The South African Institute of Mining and Metallurgy.

Stone, D. (2012). *Policy Paradox The Art of Political Decision Making.* New York: W. W. Norton & Company.

Streiffert, B., Starbird, T., & Grenander, S. (2006). A Roadmap for Using Agile Development in a Traditional Environment. *SpaceOps 2006 Conference.* American Institute of Aeronautics and Astronautics (AIAA).

Sutter, B., Ming, D. W., Boynton, W. V., Niles, P. B., Hoffman, J., Lauer, H. V., & Golden, D. C. (2009). Summary of Results from the Mars Phoenix Lander's Thermal Evolved Gas Analyzer. *The New Martian Chemistry Workshop.*

Swanick, L. A. (2006). An analysis of navigational instruments in the Age of Exploration: 15th century to mid-17th century. *Texas A&M University*.

Szajnfarber, Z. (2009). What Drives Spacecraft Innovation? A Quantitative Analysis of Communication Satellite History. *Massachusetts Institute of Technology*.

Szajnfarber, Z. (2011). Innovation Pathways in Technology Intensive Government Organizations: Insights from NASA. *Massachusetts Institute of Technology*.

Szajnfarber, Z., & Gralla, E. L. (2017). Qualitative methods for engineering systems: Why we need them and how to use them. *Systems Engineering, 20*(6).

Szajnfarber, Z., Richards, M. G., & Weigel, A. L. (2011). Challenges to Innovation in the Government Space Sector. *Defense Acquisition Review Journal*(59).

Tavares, F., Buckner, D., Burton, D., McKaig, J., Prem, P., Ravanis, E., . . . Wilhelm, M. B. (2020). Ethical Exploration and the Role of Planetary Protection in Disrupting Colonial Practices. *arXiv: Instrumentation and Methods for Astrophysics*.

Tepper, E., & Whitehead, C. (2018, December 20). Moon, Inc.: The New Zealand Model of Granting Legal Personality to Natural Resources Applied to Space. *New Space, 6*(4), 288-298.

The 17 Goals. (n.d.). Retrieved from United Nations Department of Economic and Social Affairs Sustainable Development: https://sdgs.un.org/goals

The Ambassador in Chile (Bowers) to the Secretary of State. (1948). In *Foreign Relations of the United States* (p. 995).

The Antarctic Treaty Explained. (1999). Retrieved from British Antarctic Survey: https://www.bas.ac.uk/about/antarctica/the-antarctic-treaty/the-antarctic-treaty-explained/

The Martian Autonomous Rotary-wing Vehicle (MARV). (2000, June 1). *Student Design Competition - Graduate Category*. University of Maryland. Retrieved from https://vtol.org/files/dmfile/2000SDC_1stPlaceGraduateProposal_UMD_MARC.pdf

The Mining Code. (n.d.). Retrieved from International Seabed Authority: https://www.isa.org.jm/mining-code

The Protocol on Environmental Protection to the Antarctic Treaty. (1998). Retrieved from Secretariat of the Antarctic Treaty: https://www.ats.aq/e/protocol.html

The White House. (2020, April 6). *Executive Order on Encouraging International Support for the Recovery and Use of Space Resources.* Retrieved from Trump White House Archives: https://trumpwhitehouse.archives.gov/presidential-actions/executive-order-encouraging-international-support-recovery-use-space-resources/

The World Bank. (n.d.). *The World Bank Group and the International Monetary Fund (IMF).* Retrieved from The World Bank: https://www.worldbank.org/en/about/history/the-world-bank-group-and-the-imf

Thomke, S., & Hippel, E. V. (2004). *Customers as Innovators.* Harvard Business Review.

Thompson, K. F., Miller, K. A., Currie, D., Johnston, P., & Santillo, D. (2018, December 11). Seabed Mining and Approaches to Governance of the Deep Seabed. *Frontiers in Marine Science*.

Trawny, N., Benito, J., Tweddle, B., Bergh, C., Khanoyan, G., Vaughan, G., . . . Nietfeld, S. (2015). Flight testing of terrain-relative navigation and large-divert guidance on a VTVL rocket. *Proc. AIAA Space Conference.* AIAA.

Trawny, N., Mourikis, A., Roumeliotis, S., Johnson, A., & Montgomery, J. (2006). Vision-Aided Inertial Navigation for Pin-Point Landing Using Observation of Mapped Landmarks. *Journal of Field Robotics: Special Issue on Space Robotics, 24*(5), 257-278.

Treviño, N. B. (2020). The Cosmos is Not Finished. *Electronic Thesis and Dissertation Repository*.

Treviño, N. B. (2021, February). *What is the Legacy of Colonialism on Space Exploration?* Retrieved from Filling Space: https://filling-space.com/2021/02/19/what-is-the-legacy-of-colonialism-on-space-exploration/

Tronchetti, F. (2007). The Non-Appropriation Principle Under Attack: Using Article II Of The Outer Space Treaty In Its Defence. *International Astronautical Congress (IAC).*

Tushman, M. L., & Romanelli, E. (1985). Organizational evolution: A metamorphosis model of convergence and reorientation. *Research in Organizational Behavior, 7*, 171–222.

Tushman, M. L., & Smith, K. W. (2002). Organizational Technology. In J. Baum (Ed.), *Companion to Organizations* (pp. 386-414). Malden, MA: Blackwell.

Tzanetos, T., Aung, M., Balaram, J., Grip, H. F., Karras, J. T., Canham, T. K., . . . Toupet, O. (2022). Ingenuity Mars Helicopter: From Technology Demonstration to Extraterrestrial Scout. *2022 IEEE Aerospace Conference (AERO)* (pp. 01-19). Big Sky, MT: IEEE.

UN General Assembly, Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, 34/68. (1979, December 18).

UN General Assembly, The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies (Outer Space Treaty), 2222 (XXI). (1967, January 27).

United Nations. (n.d.). Retrieved from United Nations: https://www.un.org/sustainabledevelopment/development-agenda/

United Nations - Office of Legal Affairs. (2012). *The United Nations Convention on the Law of the Sea (A historical perspective)*. Retrieved from United Nations: https://www.un.org/depts/los/convention_agreements/convention_historical_perspective.htm

United Nations Convention on the Law of the Sea. (1982). Retrieved from United Nations: https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf

UNOOSA. (2023, March). *Working Group on Legal Aspects of Space Resource Activities.* Retrieved from UNOOSA: https://www.unoosa.org/oosa/en/ourwork/copuos/lsc/space-resources/index.html

UNOOSA. (n.d.). *Working Group on Legal Aspects of Space Resource Activities*. Retrieved from UNOOSA: https://www.unoosa.org/oosa/en/ourwork/copuos/lsc/space-resources/index.html

Utterback, J. M. (1994). *Mastering the Dynamics of Innovation.* Cambridge, MA: Harvard Business Press.

Utterback, J. M., & Abernathy, W. J. (1975). A Dynamic Model of Process and Product Innovation. *The International Journal of Management Science, 3*.

Van de Ven, A. H., Angle, H. L., & Poole, M. S. (2000). *Research on the management of innovation: The Minnesota studies.* US: Oxford University Press.

Van de Ven, A. H., Polley, D. E., Garud, R., & Venkataraman, S. (1999). *The innovation journey.* New York: Oxford University Press.

van Eijk, C. (2020). Sorry, Elon: Mars is not a legal vacuum – and it's not yours, either. *Völkerrechtsblog*.

Veismann, M., Dougherty, C., Rabinovitch, J., Quon, A., & Gharib, M. (2021). Low-density multi-fan wind tunnel design and testing for the Ingenuity Mars Helicopter. *Experiments in Fluids, 62*(193).

Vertical Flight Society. (2018, May 14). *Vertical Flight Society applauds NASA's Mars Helicopter selection*. Retrieved from Vertical Magazine: https://verticalmag.com/press-releases/vertical-flight-society-applauds-nasas-mars-helicopter-selection/

Vitug, E. (2022). *STMD: Game Changing Development*. Retrieved from NASA: https://www.nasa.gov/directorates/spacetech/game_changing_development/about/index.html

Voytek, M. A. (2023). *PICASSO and MatISSE.* Retrieved from Astrobiology at NASA: https://astrobiology.nasa.gov/research/astrobiology-at-nasa/picasso-and-matisse/

Wakefield, J. R., & Myers, K. (2016). Social cost benefit analysis for deep sea minerals mining. *Mar. Policy*.

Wall, M. (2020, October 8). *US policy could thwart sustainable space development, researchers say.* Retrieved from Space.com: https://www.space.com/us-space-policy-mining-artemis-accords

Walsh, M. W., & Phillips, M. (2020, June 1). *Poor Countries Face a Debt Crisis 'Unlike Anything We Have Seen'.* Retrieved from New York Times: https://www.nytimes.com/2020/06/01/business/coronavirus-poor-countries-debt.html

Warnock, E. (2016, December 16). *Japan joins race for space resources.* Retrieved from Wall Street Journal: www.wsj.com/articles/japan-joins-race-for-space-resources-1481874269

Weiss, A. M., Lurie, N. H., & Macinnis, D. J. (2008). Listening to strangers: Whose responses are valuable, how valuable are they, and why? *Journal of Marketing Research, 45*(4), 425-436.

Wellington, A. M. (1887). *The Economic Theory of the Location of Railways.* New York: J. Wiley.

Werner, D. (2018, April 17). *Space Law Workshop exposes rift in legal community over national authority to sanction space mining.* Retrieved from Space News: https://spacenews.com/space-law-workshop-exposes-rift-in-legal-community-over-national-authority-to-sanction-space-mining/

Westwick, P. J. (2007). Reengineering Engineers: Management Philosophies at the Jet Propulsion Laboratory in the 1990s. *Technology and Culture, 48*(1), 67-91.

Williams, D. R. (2022). *Mars Surveyor 2001 Lander.* Retrieved from NASA Space Science Data Coordinated Archive: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=MS2001L#:~:text=Description,the%20Mars%20Surveyor%202001%20Lander.

Williams, R. (2002). *Retooling: A Historian Confronts Technological Change.* The MIT Press.

Wood, D. (2020, October 12). *On Indigenous People's Day, Let's Commit to an Anticolonial Mindset on Earth and in Space.* Retrieved from MIT Media Lab: https://www.media.mit.edu/posts/Anticolonial_Mindset_Earth_and_Space/#:~:text=Let%20us%20pursue%20this%20work,both%20people%20and%20the%20environment.

Woody, T., & Halper, E. (2022, April 19). *A gold rush in the deep sea raises questions about the authority charged with protecting it.* Retrieved from Los Angeles Times: https://www.latimes.com/politics/story/2022-04-19/gold-rush-in-the-deep-sea-raises-questions-about-international-seabed-authority

World Bank. (2017). *Precautionary management of deep sea minerals. Pacific Possible Background Paper No. 2.* Washington, D.C: World Bank Group.

World Economic Forum. (n.d.). *Our Mission.* Retrieved from World Economic Forum: https://www.weforum.org/about/world-economic-forum

Yin, R. (1984). *Case Study Research.* Beverly Hills, CA: Sage Publications.

Young, L. A. (2000). Vertical Lift – Not Just For Terrestrial Flight. *AHS/AIAA/RaeS/SAE International Powered Lift Conference.* Arlington, VA.

Young, L. A., Aiken, E. W., Derby, M. R., Demblewski, R., & Navarrete, J. (2002). Experimental Investigation and Demonstration of Rotary-Wing Technologies for Flight in the Atmosphere of Mars. *58th Annual Forum of the AHS International.* Montreal, Quebec.

Young, L. A., Aiken, E. W., Derby, M., Johnson, J., Navarrete, J., Klem, J., . . . Torres, R. (n.d.). Engineering Studies into Vertical Lift Planetary Aerial Vehicles. *AHS International Meeting on Advanced Rotorcraft Technology and Life Saving Activities*, (p. 2002). Utsunomiya, Tochigi, Japan.

Young, L. A., Chen, R. T., Aiken, E. W., & Briggs, G. A. (2000). Design Opportunities and Challenges in the Development of Vertical Lift Planetary Aerial Vehicles. *American Helicopter Society International Vertical Lift Aircraft Design Specialist's Meeting.* San Francisco, CA.

Young, T., Arnold, J., Brackey, T., Carr, M., Dwoyer, D., Fogleman, R., . . . Maguire, J. (2000). *Mars Program Independent Assessment Team Report.*

Zubrin, R. (1996). *The Case for Mars.* New York City, NY: Simon & Schuster.