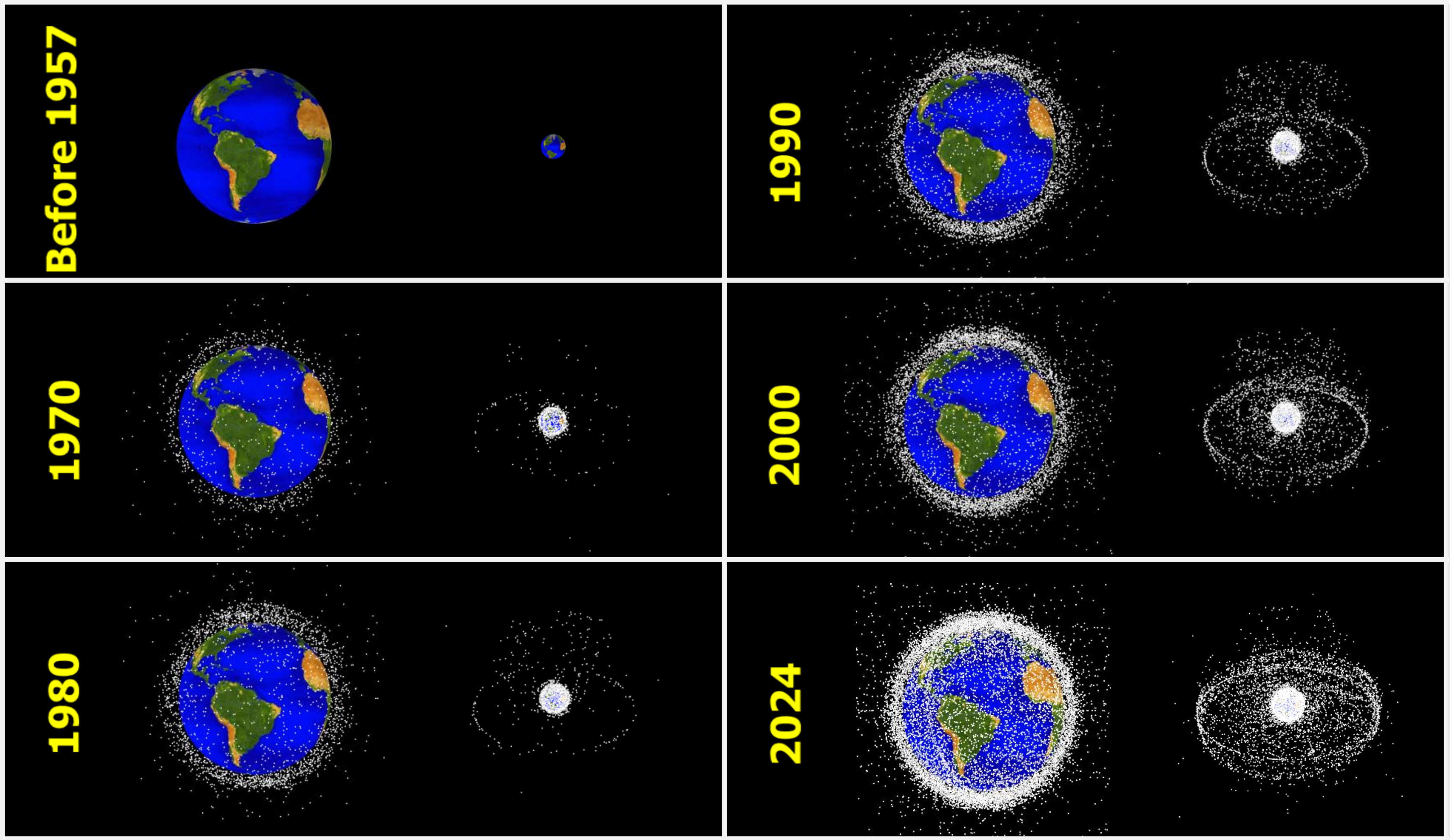
Orbital Debris and the NASA Orbital Debris Program Office

J.-C. Liou, PhD

Chief Scientist for Orbital Debris
National Aeronautics and Space Administration

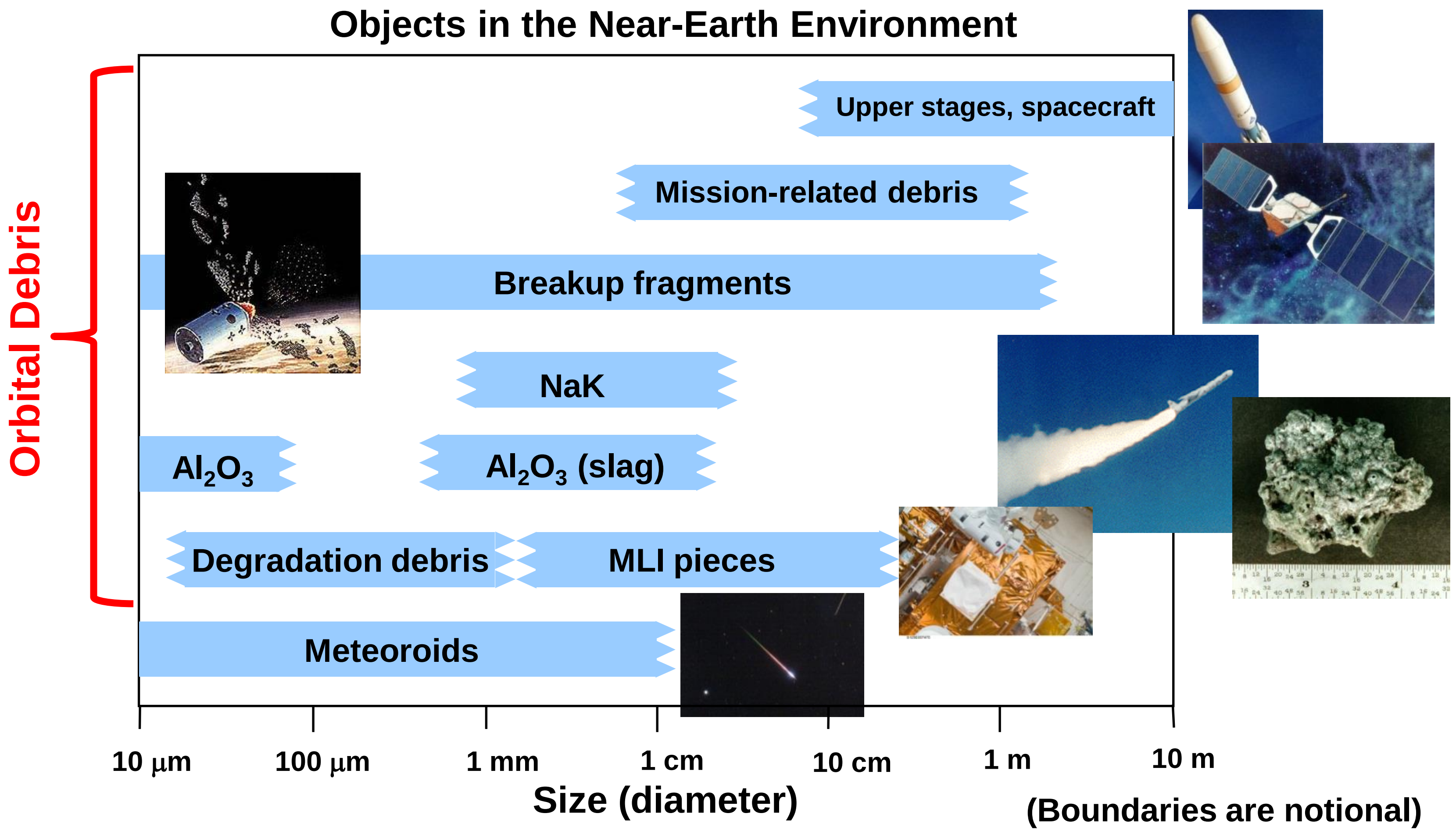
TRISMAC 2024, Frascati (Rome), Italy
24-26 June 2024

The Historical Orbital Debris Environment



- The U.S. Space Force (USSF) uses the Space Surveillance Network (SSN) to track large objects in space and maintain their orbits in the U.S. Satellite Catalog
- Only objects in the Catalog (~10 cm and larger) are shown
  - Sizes of the dots are not to scale

Sources of Orbital Debris



- **<u>Orbital debris</u> is any human-made object in orbit about the Earth that no longer serves any useful function**

Current Orbital Debris Population

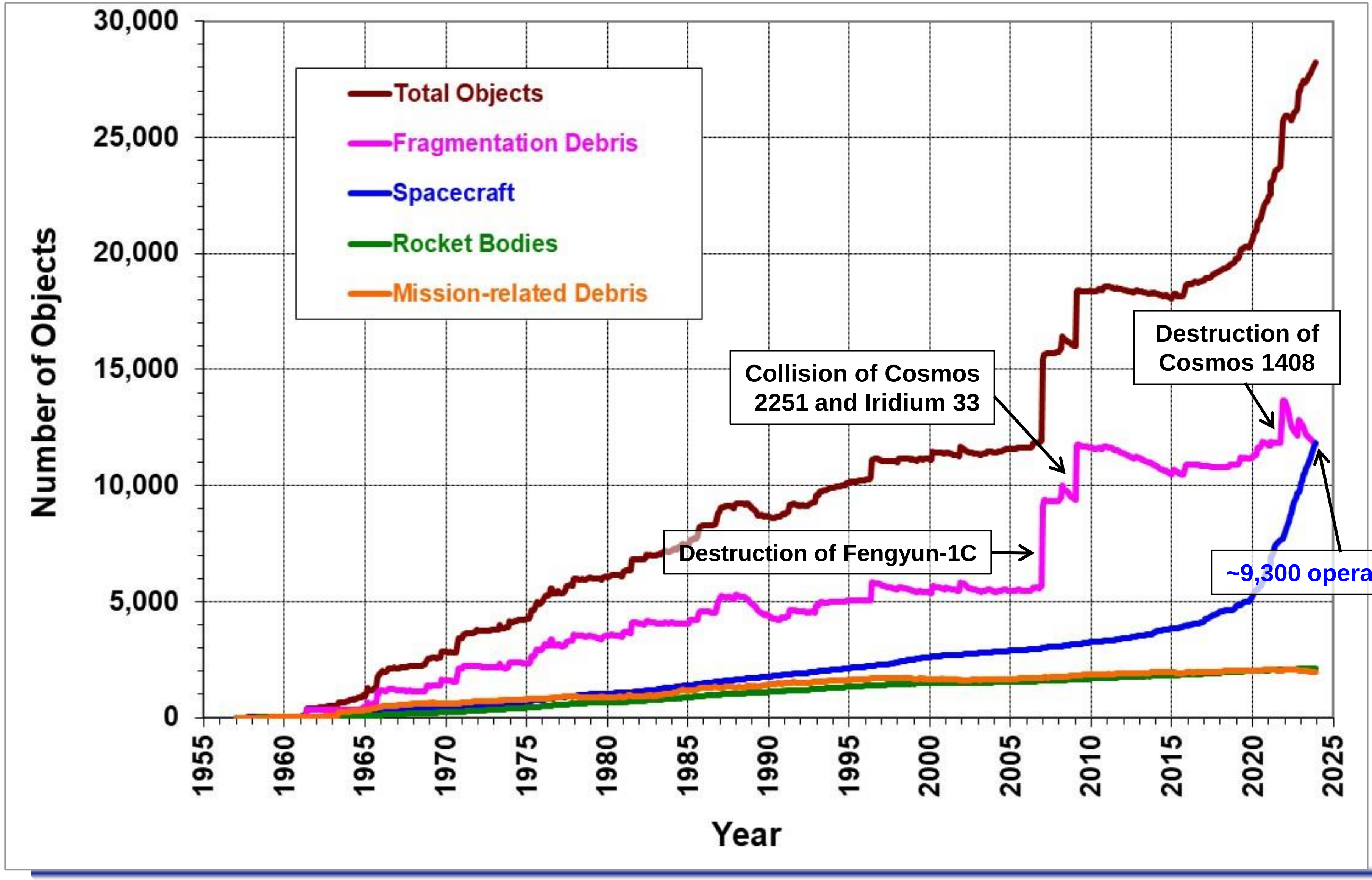
Baseball size or larger (≥10 cm): ~28,000 (tracked/cataloged by the USSF)

Marble size or larger (≥1 cm): ~500,000

Dot or larger (≥1 mm): >100,000,000 (a grain of salt)

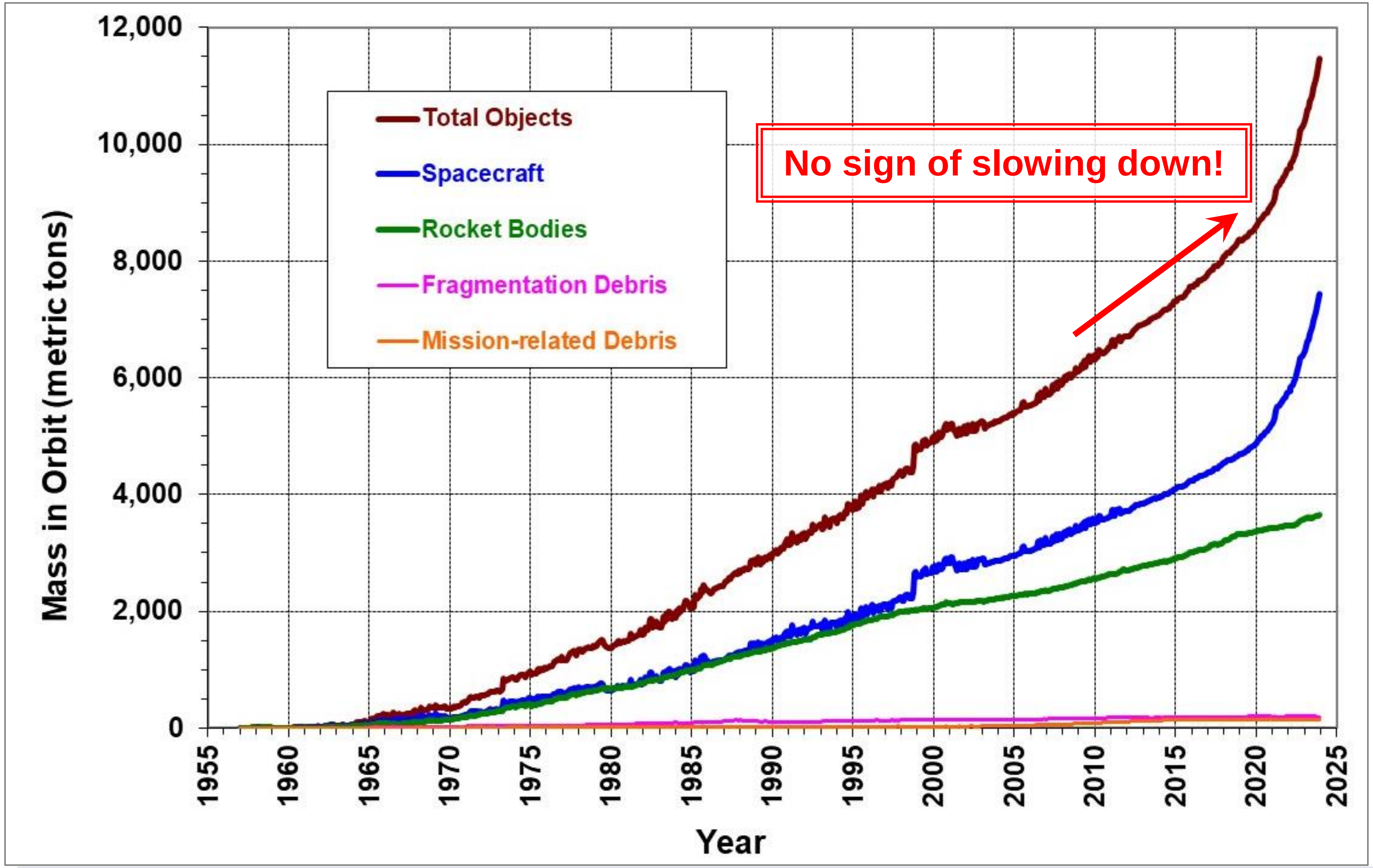
- **Due to high impact speed in space (~10 km/sec in LEO), even sub-millimeter debris poses a realistic threat to human spaceflight and robotic missions**
  - 10 km/sec ~22,000 MPH
  - Speed of a bullet ~1,500 MPH
- **Mission-ending threat is dominated by small (millimeter-sized) debris impacts**

Growth of Cataloged Population



- **The cataloged objects continue to increase**
  - Such large objects only represent the tip of the iceberg for the orbital debris population
  - ~100,000,000 additional debris too small to be tracked but large enough to threaten missions exist in the environment
- **The rapid increase in spacecraft is due to CubeSats and large constellations**

Mass in Orbit Continues to Increase

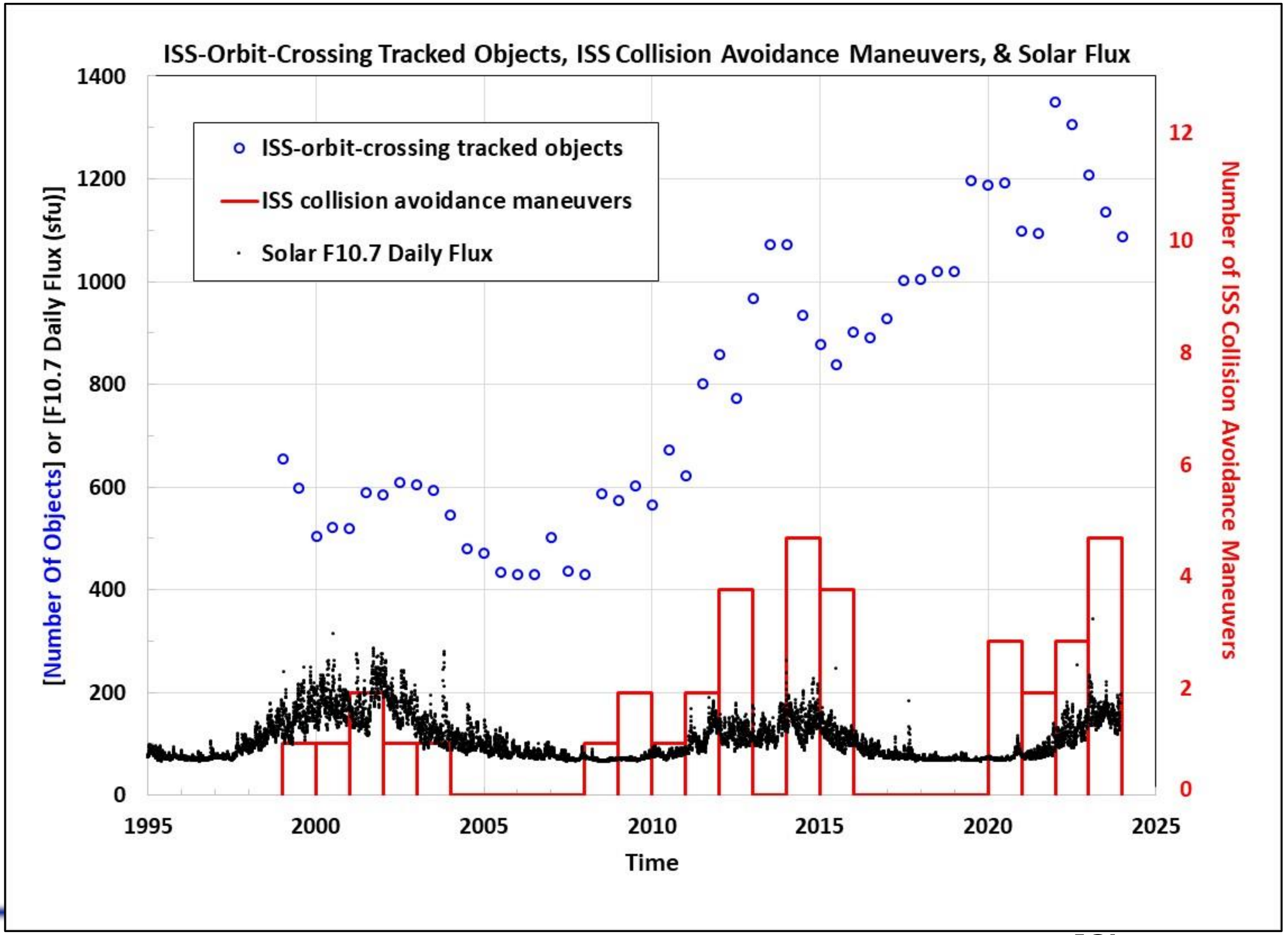


- **The mass in orbit also continues to increase**
- **At the end of 2023, the total mass in orbit exceeded 11,000 metric tons**
  - The mass was dominated by spacecraft (~65% of the total) and rocket bodies (~32% of the total)
  - Approximately half of the mass concentrated in low Earth orbit (LEO)

Protecting Assets From Large/Tracked Objects

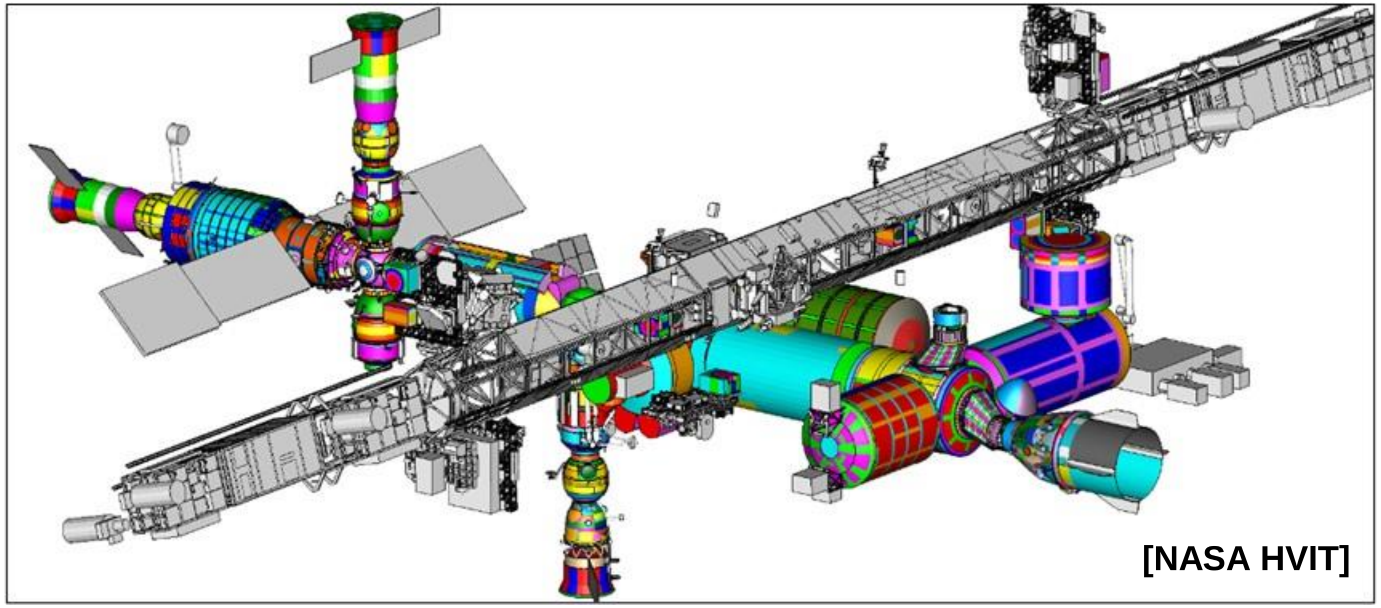
- **NASA has established conjunction assessment processes for missions to avoid accidental collisions with large objects tracked by the SSN**

- **The International Space Station (ISS) has conducted 38 collision avoidance maneuvers since 1999**
  - Including five times in 2023
  - Frequency of the avoidance maneuvers depends on solar activity, number of objects crossing the ISS orbit, the SSN tracking capability, and other factors



Protecting the ISS From Small Orbital Debris

- **The ISS is equipped with various micrometeoroid and orbital debris (MMOD) impact protection shields**
  - U.S. modules: protected against debris smaller than ~8 mm
  - Russian modules: protected against debris smaller than ~3 mm
  - The biggest threat to the ISS comes from debris too small to be tracked but large enough to penetrate the protection shields

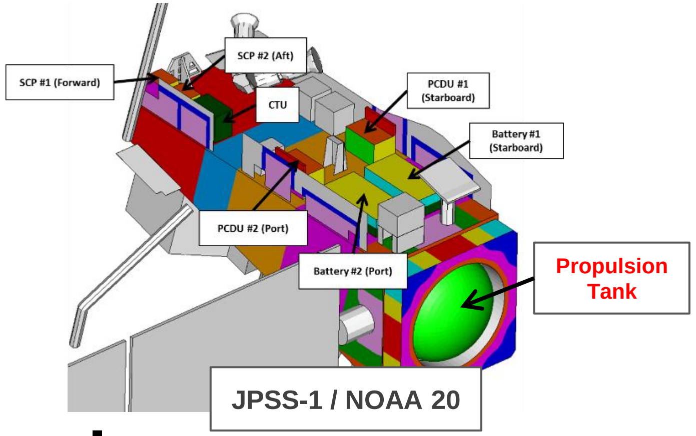

[NASA HVIT]

The ISS MMOD shielding models: each color represents a different MMOD shield configuration

About 500 different shields protect ISS modules and external pressure vessels

Top Orbital Debris Risks to Robotic Missions in LEO

- **Millimeter-sized orbital debris represents the highest penetration risk to most operational spacecraft in LEO**
  - As concluded by, for example, a NASA Engineering and Safety Center panel study (NASA/TM 2015-218780)
- **Currently, more than 400 missions operate at 600–900 km altitudes**
  - Including 18 NASA missions (A-Train@705km, NOAA@825km, IXPE@600km, *etc.*)

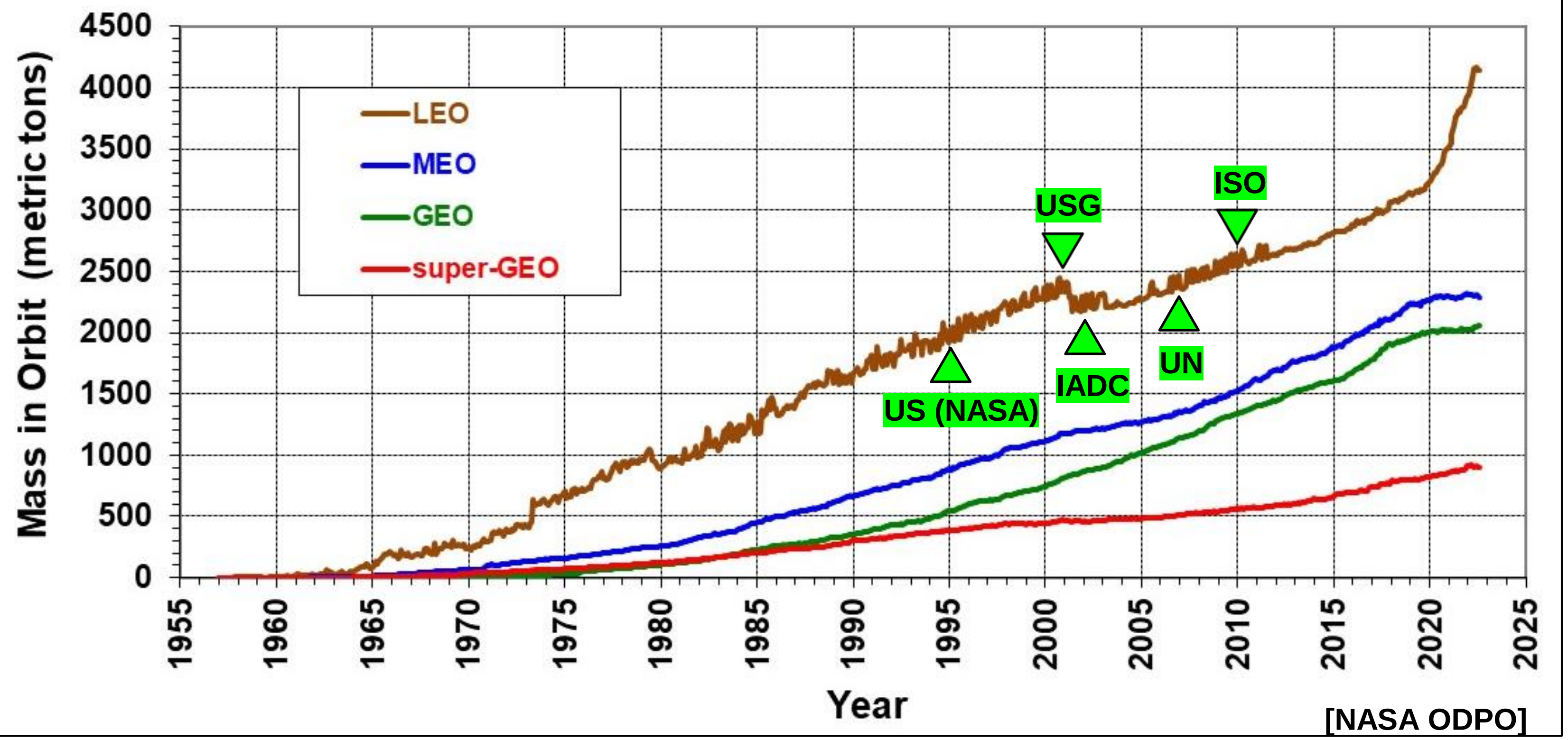


- **There is a lack of measurement data on millimeter-sized orbital debris above 600 km altitude**
  - Direct measurement data on such small debris is needed to support the development and implementation of cost-effective, protective measures for the safe operations of future missions

Orbital Debris Mitigation

- **Four guiding principles to limit the generation of new, long-lived debris**
  - Control the generation of mission-related debris
  - Limit accidental explosions (during and post mission)
  - Limit accidental collisions
  - Conduct post-mission disposal, limit reentry risk

- **OD mitigation guidelines and best practices have been developed by the international community since 1995**



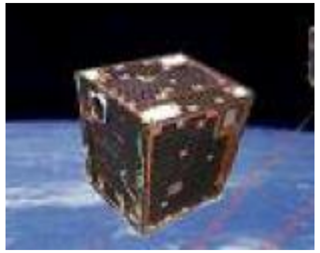
[NASA ODPO]

Managing the Long-term Orbital Debris Problem

- **OD Mitigation = Prevention**
  - Limiting the generation of new debris
- **OD Remediation = Cure**
  - Dealing with objects that already exist in the environment (*i.e.*, active debris removal, ADR)

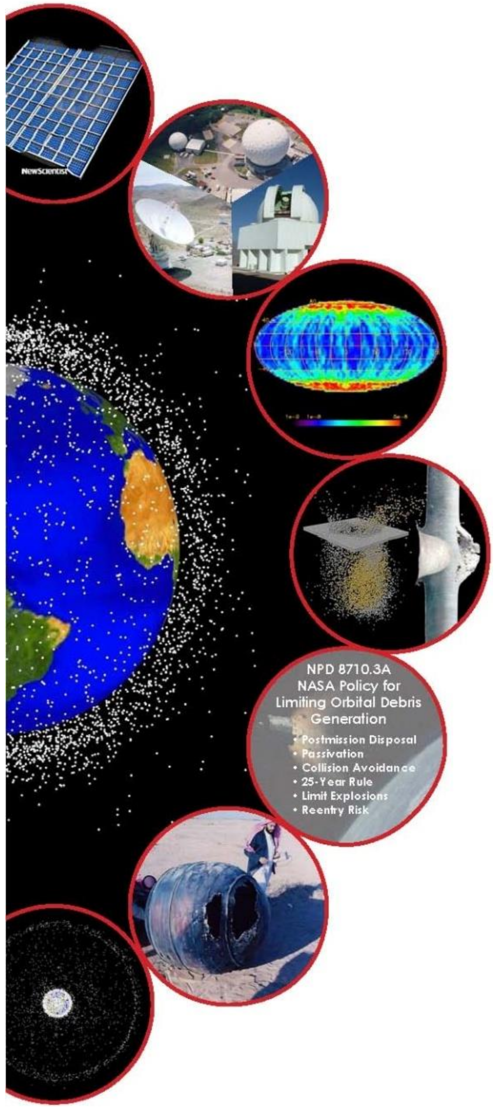
> - **"An ounce of prevention is worth a pound of cure"**
>   - (*Prov.*) It is better/cheaper to stop something bad from happening than it is to deal with it after it has happened

- **Cost of ESA's ClearSpace-1 mission to remove a 94 kg smallsat (Proba-1): €100M**
- **Between 600 and 2000 km altitudes**
  - Number of spent upper stages and retired spacecraft : >2200
  - Total mass of spent upper stages and retired spacecraft: >1,700,000 kg
    - **58% Russia, 20% U.S., 11% China, 11% others**



Probe-1 (60 cm x 60 cm x 60 cm)

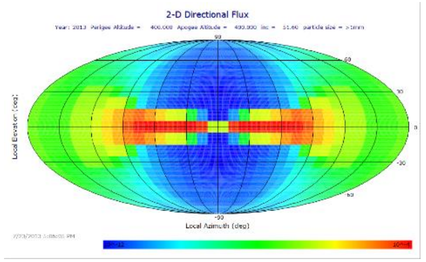
NASA Orbital Debris Program Office (ODPO)

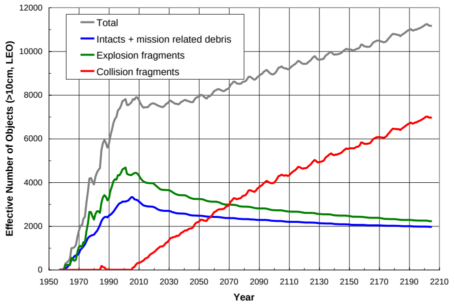


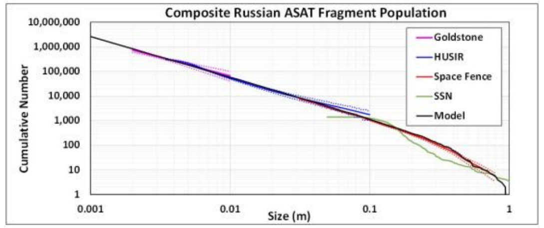
- **ODPO is the only organization in the USG conducting a full range of research on orbital debris**
  - Is a Delegated Program in NASA/HQ OSMA
  - This unique NASA capability was established by pioneers led by Don Kessler, Joe Loftus, and others at NASA JSC in 1979
- **ODPO provides technical and policy support to NASA HQ, NASA missions, USG (Congress, NSpC, OMB, OSTP, *etc*.) and commercial organizations**
- **ODPO represents the USG in international fora (United Nations, IADC*, ISO, *etc.*)**
- **ODPO is recognized as a pioneer and leader on orbital debris environment definition, modeling, and mitigation policy development**

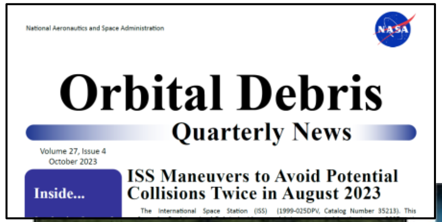
*IADC = Inter-Agency Space Debris Coordination Committee

End-to-End Orbital Debris Activities at ODPO








National Aeronautics and Space Administration

Orbital Debris
Quarterly News

Volume 27, Issue 4
October 2023

Inside...

ISS Maneuvers to Avoid Potential Collisions Twice in August 2023

The International Space Station (ISS) (1999-025DPV, Catalog Number 35213). This

Measurements

Radar
Optical
In-situ
Laboratory

Modeling

Breakup
Engineering
Evolutionary
Reentry

Mission Support

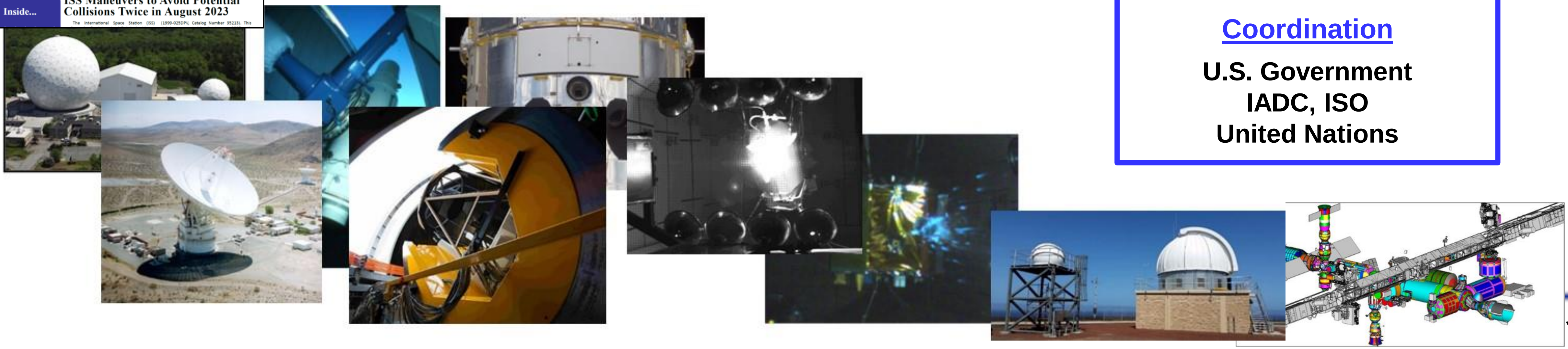
Compliance assessments
Risk assessments
(ISS, Orion, robotic missions, *etc.*)
Reentry assessments

Environment Management

Mitigation
Remediation
Mission Requirements
Policy

Coordination

U.S. Government
IADC, ISO
United Nations



ODPO’s Roles and Responsibilities (1/3)

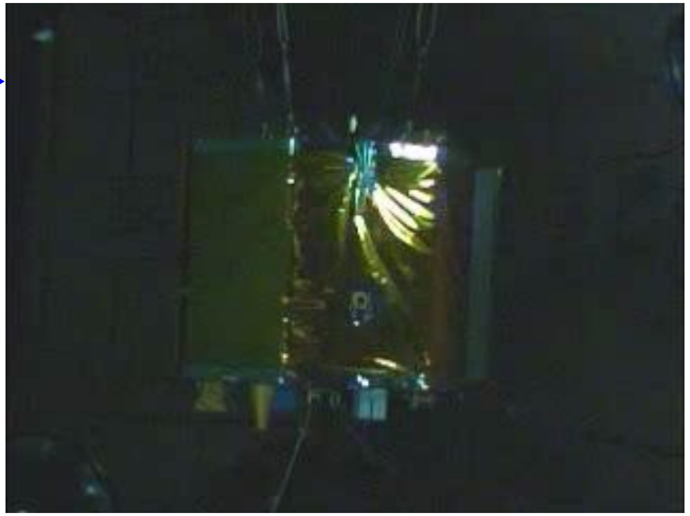
- **Monitor the ever-changing OD environment**
  - ODPO has led the characterization of OD too small to be tracked by the DOD but large enough to threaten human spaceflight and robotic missions for more than 30 years.
    - **Collect/analyze radar measurement data on OD in LEO**
    - **Build/operate telescopes, collect/analyze optical measurement data on OD from LEO to GEO**
    - **Collect/analyze space-based in-situ measurement data on sub-millimeter OD, develop in-situ sensor technologies and pursue mission opportunities to address the millimeter-sized OD data gap**
    - **Design/conduct laboratory experiments and collect/analyze test data for debris characterization and assess risk from OD**

MACS MULTILAYER ACOUSTIC CONDUCTIVE-GRID SENSOR






A 9-cm, 570-g projectile impacted the 56-kg DebriSat at 6.8 km/sec



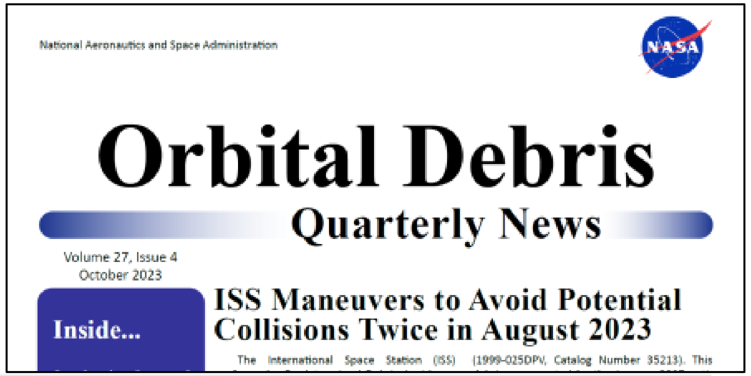
ODPO's Roles and Responsibilities (2/3)

- **Develop/update OD models and mission support tools**
  - ODPO has led the development of OD environment, risk assessment, reentry, and mission compliance models and tools for more than 30 years
  - ODPO's models and mission support tools are used by hundreds of operators (NASA, USG, commercial), academia, and research groups around the world

- **Provide OD mitigation compliance and mission support**
  - ODPO oversees NASA mission compliance with OD mitigation requirements per NS 8719.14, which is NASA's implementation of the USG ODMSP
    - **ODPO reviews NASA mission Orbital Debris Assessment Reports (ODARs) and End of Mission Plans (EOMPs) and maintains NASA mission compliance records**
  - ODPO conducts high-fidelity reentry assessments and supports NASA missions to explore design-for-demise options to mitigate reentry human causality risk
  - ODPO provides real-time risk assessments and mitigation support for the ISS and other critical assets after new on-orbit fragmentation events

ODPO's Roles and Responsibilities (3/3)

- **Provide USG interagency, international, commercial, and outreach support**
  - ODPO has led the development of OD mitigation best practices in the U.S. and has promoted the adoption of the USG ODMSP by the international community since 1995
    - **USG ODMSP (2001, 2019): ODPO led the interagency working group on the efforts.**
    - **IADC Space Debris Mitigation Guidelines (2002, 2007, 2020, 2021): ODPO leads the U.S. delegation to the IADC. ODPO has supported the development of and update to the IADC Guidelines.**
    - **UN COPUOS Space Debris Mitigation Guidelines (2007) and UN COPUOS LTS Guidelines (2019): ODPO supported the U.S. delegation to UN COPUOS on the development efforts.**
    - **ISO Space Debris Mitigation Standard (2010, 2019, 2021, 2023): ODPO has supported the development of and update to the standard.**
    - **Commercial support (via Space Act Agreements)**
    - **NASA Orbital Debris Quarterly News (ODQN): 2000+ subscribers from the global space community**
    - **International Orbital Debris Conference (IOC)**
    - ***Etc.***


National Aeronautics and Space Administration

Orbital Debris
Quarterly News

Volume 27, Issue 4
October 2023

Inside...

ISS Maneuvers to Avoid Potential Collisions Twice in August 2023

The International Space Station (ISS) (1999-025DPV, Catalog Number 35213). This

Backward Planetary Protection Public Safety and Mission Assurance Considerations

Dr. Elaine Seasly

Director, NASA Mission Assurance Standards & Capabilities Division

Dr. J. Nick Benardini

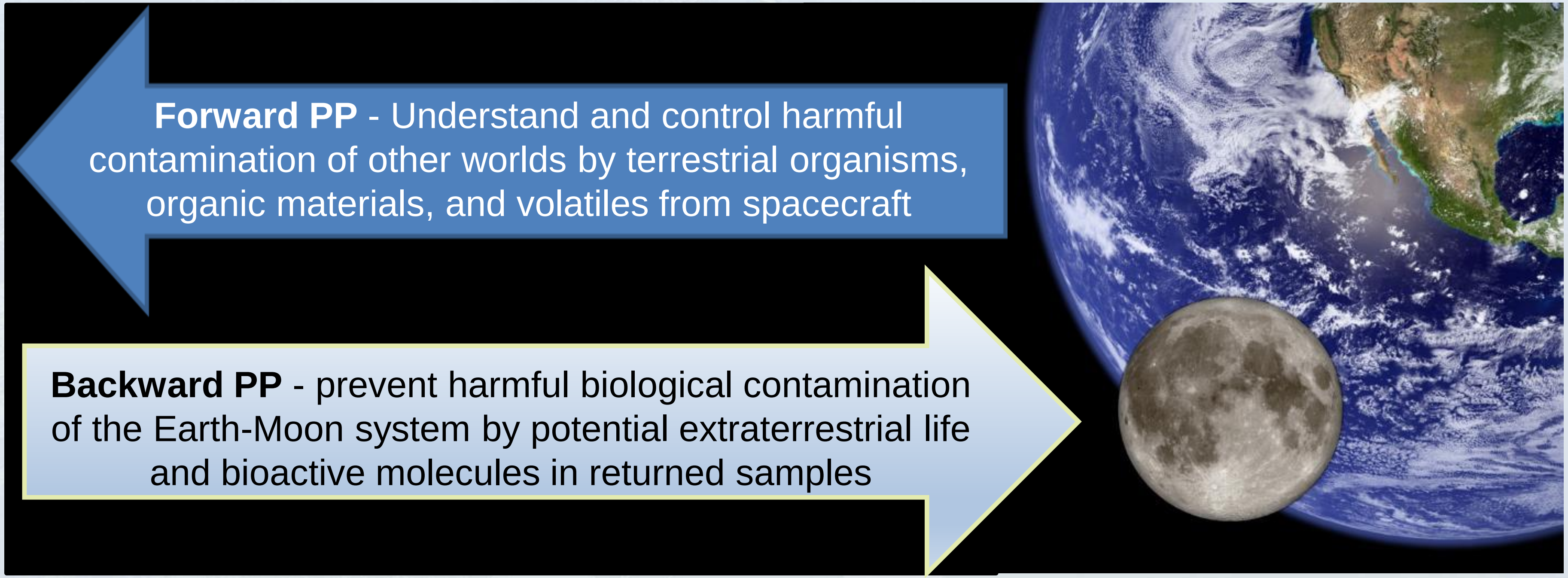
NASA Planetary Protection Officer

TRISMAC 2024

June 25, 2024

Planetary Protection Objective

Protect current and future scientific investigations by limiting biological and relevant molecular contamination of other solar system bodies through exploration activities and protecting the Earth's biosphere by avoiding harmful biological contamination carried on returning spacecraft, as described in the Outer Space Treaty.



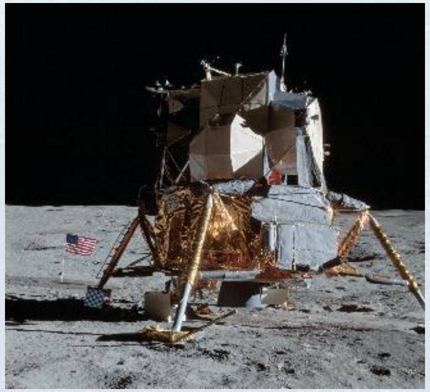
Backward Planetary Protection: Unrestricted vs. Restricted Earth Return

- Backward PP is based on the risk of contamination to the Earth from returning material from the target body.
- **Unrestricted Earth Return Missions**
  – Very low risk of contaminating Earth when returning material from the explored target body
  – No additional PP requirements
  – Examples: Earth's Moon (after Apollo 14), Venus, most asteroids & comets
- **Restricted Earth Return Missions**
  – Possibility for indigenous life
  – Significant sensitivity to contamination of the target body and the science investigation in understanding the process of chemical evolution or origin of life
  – Required to implement high containment controls to ensure that returned material is not released before sterilization or sample safety assessment
  – Examples: Earth's Moon (Apollo 11, 12, 14), Mars, Europa, Enceladus

Apollo 14 Crew Quarantine

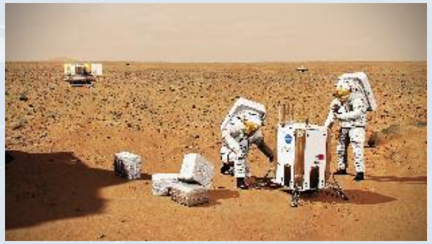
Restricted Earth Return – Then & Now

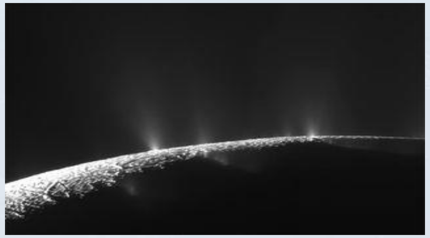
THEN



- Apollo 14 was the last restricted Earth return mission with Backward PP requirement
- Mission elements only targeted Earth's Moon
- Mission was US Government only & run by NASA
- Elements part of a single mission focus

NOW

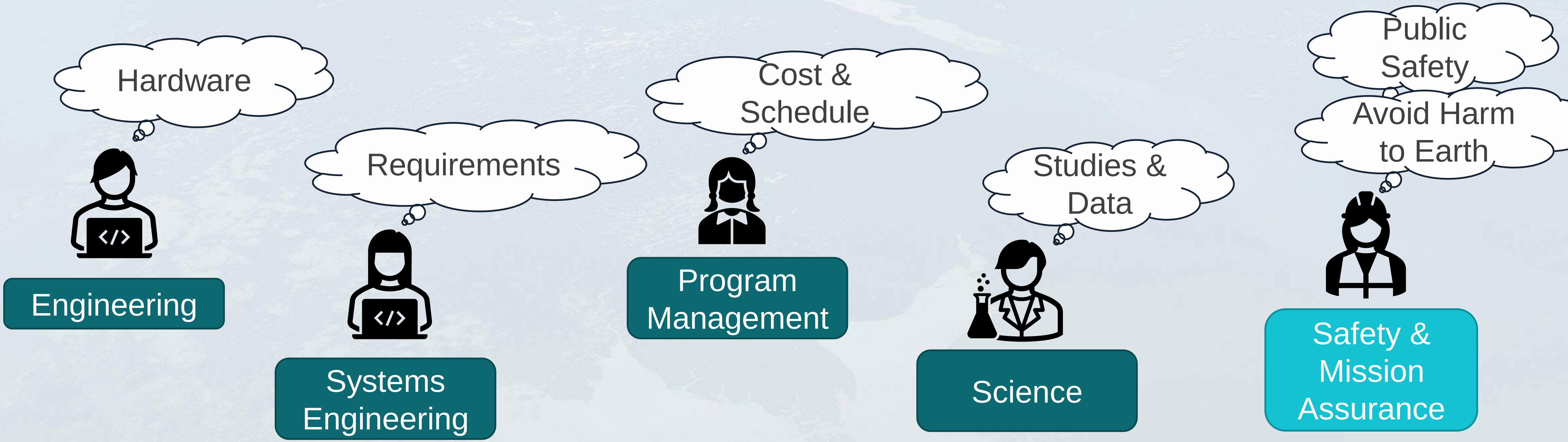




- Mars Sample Return and future crewed mission to Mars on the horizon
- Missions planning for sample return from restricted Earth return targets of Mars, Europa, & Enceladus
- International partnerships including both government and commercial partners
- Missions now consider multiple elements phased over time

Safety & Mission Assurance Plays a Key Role in Backward Planetary Protection

- Focus is on public safety & avoiding harm to Earth's environment
- Consults and coordinates processes to assure the safety and containment of Earth-return samples
- Expertise in management of risks that are low-probability & high-impact
- Provides a unique independent perspective from mission project roles



The Objectives-Driven, Risk Informed, and Case Assured Approach

Objectives-Driven

- Objectives are substantiated, monitored, and independently evaluated throughout the lifecycle based on systematic argumentation, explicit assumptions, and objective evidence.

Risk Informed

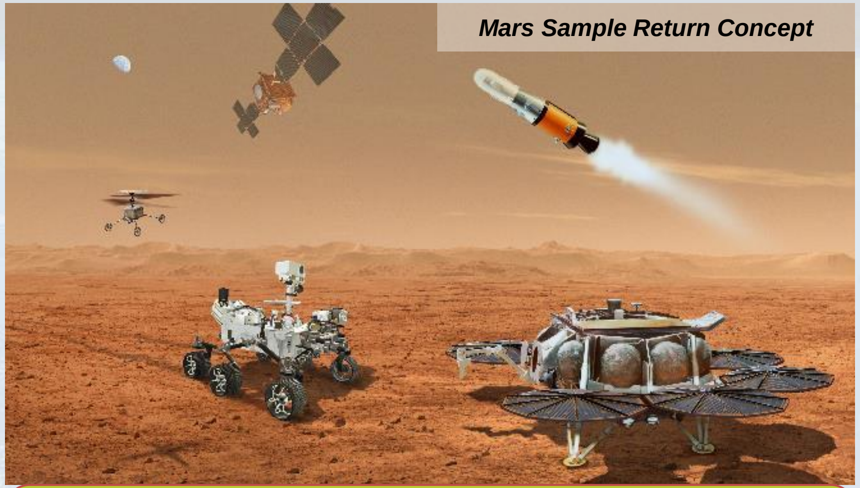
- Risks are understood, documented, and consistent with the established risk posture.
- Consider the potential benefits and strategic importance of the mission(s) and consequences of failure, to inform decisions regarding:
  - Formulation
  - Implementation
  - Assurance of the mission.

Case Assured

- Comprehensive and logical claims made with sufficient argument(s) & objective evidence.

Objectives-Based Performance Requirements

Prescriptive Requirements: Specifying "What to do" and "How to do it"



Performance-based Requirements: Specifying "What to do" but not "How to do it"

- **SMA helps to determine:**
  - *Are the objectives clearly defined?*
  - *Can non-experts understand the objectives?*
  - *Can the objectives be feasibly achieved?*

- Shifting from prescriptive to performance-based requirements:
  - Allows for a better understanding and exploration of the trade space
  - More flexibility to balance trades
  - Ability to realize and implement technical and process innovations for resource, time, and cost savings
  - It is NOT a relaxation of requirements or a "get out of jail free card"

Utilizing Trade Space & Analysis of Alternatives

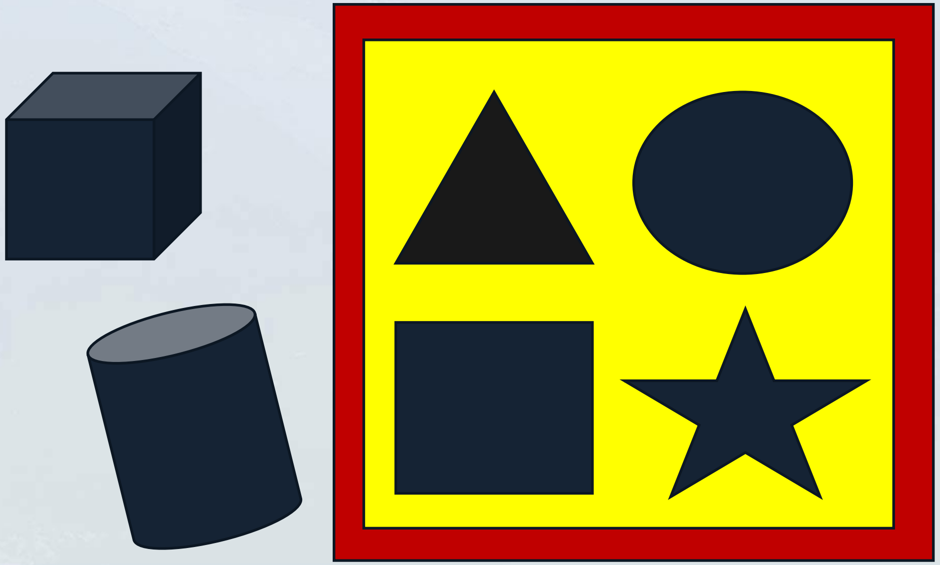
Previous Approach:

- "Design heritage" results from decades of iterations into high fidelity engineering designs and operational concept of a point solution
  - *Example: Mars Sample Return has design elements unchanged from the 1990s*
- PP requirements were then developed in response to these hardware designs and operational concepts resulting in a one-size prescriptive approach
  - *Requirements reactive to hardware designs instead of hardware designed to meet requirements*

- **SMA oversight of design trades and analysis of alternatives:**
  - *Broader identification of risks and consideration of what "could be" for the system*
  - *Independent check for appropriate use of performance-based and prescriptive requirements*

New Approach:

- Taking the Objectives-Driven, Risk Informed, Case Assured approach for PP enables the ability to think creatively about the design and performance of the future state of the system
  - *Allows for use of both performance-based and prescriptive requirements at appropriate levels of the architecture*
  - *Allows for PP requirements to be flexible and adaptive to accommodate and enable engineering trades and analysis of alternatives*



Restricted Earth Return approval requires a formal and well-defined decision-making process.

- Define the approval process, engagement plan, and communication strategy early in the mission lifecycle.
- This risk posture and responsive technical science and engineering decision making approach and implementation should be understood by all stakeholders within the agency.
- SMA community should be in regular communication between partners.
  - *Should track with the project systems engineering schedule and agency level key decision points*
- Broadscale impacts to the Earth's biosphere require high level governmental decision making.
  - *For example, NASA is required to engage the President of the US for approval.*

SMA helps to coordinate and champion the approval process

Agency approval process?

SMA approval?

?

Scientific consensus?

Partner approval?

Regulatory / Intra-gov approval?

Public perception and approval?

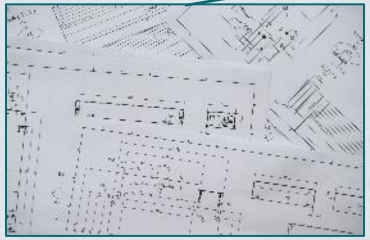
Coordination of the End-to-End Assurance Case Process

Claim
Statement about a property of the system/subsystem

Argument
Links the Evidence to the Claim

- Deterministic
- Quantitative
- Qualitative

Evidence
Information that demonstrates validity of argument



Design review records

Test results

Manufacturing process validation

- **SMA coordinates between multi-mission elements & partners:**
- Establishing the Use Case
  - *Is the approach applicable?*
- Scientific Consensus
  - *Does the use case make technical sense?*
  - *Would most of the international scientific community agree with this approach?*
- Technology Matured to Implement
  - *Other industries or academic uses matured?*
  - *Technology demonstrated in relevant environment?*
- *Is the current policy and standards agile enough to accommodate approach?*
- *Does it align to the safety / risk posture?*

Thank You!

Ensuring public safety and mission assurance for a restricted Earth return mission will require an objectives-driven, risk informed and case assured approach to address backward planetary protection compliance. The safety and mission assurance stakeholders play a key role in this process by consulting and coordinating processes to assure the safety and containment of Earth-return samples and the public.

Abstract

- Apollo 14 was the last restricted Earth return mission that implemented backward planetary protection requirements where preventing harmful contamination of the Earth's biosphere is the highest priority. Over the past 50 years, engineering and science technology advancements have been made to manage, sterilize, contain and assure safety of particles and biological contamination that provide a robust trade space for enabling and implementing a sample return mission. As missions start to plan sample return from restricted Earth return targets (e.g., Mars, Europa or Enceladus) considerations should also be made to understand the complexities of campaign architectures with multi-mission elements, regulatory and external governmental decision makers, and multiple international partners.
- Ensuring public safety and mission assurance for a restricted Earth return mission will require an objective driven, risk-informed and case assured approach to address backward planetary protection compliance. The safety and mission assurance stakeholders play a key role in this process by consulting and coordinating processes to assure the safety and containment of Earth-return samples and the public. Throughout the life cycle of the mission planning consulting and coordination should consider the following: A. how modern advancements play a role in trade space where heritage design and prescriptive approaches can overshadow early formulation, B. establishment of technical roles and responsibilities and interface controls between agencies and partners within established legal frameworks, C. coordination of the end to end assurance case between multi-mission elements and partners, and D. development of objective-base, performance requirements for managing backward planetary protection. Fostering continued awareness and openness of these considerations will continue the dialogue, a critical step on the path, to enable sample return from restricted Earth return targets from a backward planetary protection perspective.

National Aeronautics and
Space Administration

EXPLORE
SCIENCE

Exploration Science Strategy and Integration Office

Commercial Lunar Payload Services

Angela Melito
Program Executive to the Deputy Associate Administrator of Exploration (DAAX)
Science Mission Directorate, NASA

ESSIO Full Organizational Chart

ESSIO

Dr. Joel Kearns
Deputy Associate Administrator for Exploration

Assistant DAAX
Dr. Brad Bailey

Resource Analyst: Marissa Luedtke
Program Support: Mackenzie Howard
Program Support: Kathryn Martin
Comm. Specialist: Chris Calabrese
Admin. Assistant: Amy Treat

Program Executives

Jay Jenkins

Angela Melito

Dr. Zachary Pirtle

Program Scientists

Dr. Debra Needham

Dr. Ryan Watkins

Dr. Kennda Lynch

Dr. Sarah Noble

Dr. Amanda Nahm

Joint with PSD

PSD

- PESTO (NPLP & DALI)
- PMPO (lunar surface payloads)

JSC

- CLPS Office:
  - Chris Culbert

Commercial Lunar Payload Services (CLPS)

ESSIO

- CLPS is an innovative, service-based, competitive acquisition approach that enables rapid, affordable, and frequent access to the Lunar surface via a growing market of American commercial providers
    - To the greatest legal and practical extent CLPS attempts to model common terrestrial deliveries such as FedEx, UPS, etc
- Service task orders are Firm Fixed Price (FFP) for the full scope of payload delivery: from payload hand-over to delivery (and often operation) on the lunar surface or in CIS lunar space
- NASA wants to be one of many customers for CLPS services
    - Ideally, CLPS contractors will eventually deliver manifests that include no NASA payloads
- CLPS deliveries are CLPS Contractor missions (not NASA missions); NASA imposes no NASA policies that would normally apply to a NASA mission
- CLPS providers secure all necessary hardware, systems, facilities and services to perform the delivery; including launch vehicle and comm/nav systems
    - NASA has no oversight and limited insight into CLPS vehicle/mission designs and processes
    - NASA LSP (Launch Services Program) is not engaged in launch vehicle acquisition
- CLPS launches are commercial launches acquired/provided by CLPS provider and approved/licensed by the U.S. Gov't FAA , FCC, and other agencies (not NASA)

CLPS IDIQ Contract and Portfolio

ESSIO

- 14 domestic companies eligible to compete for Lunar surface delivery task orders
- 8 awarded lunar surface deliveries actively in work with initial deliveries as soon as Q1 2023
- NASA expects to continue cadence of ~2 flights per year
- CLPS contractors are encouraged to sell lunar delivery services outside of the CLPS IDIQ to non-NASA and non-USG customers

Initial CLPS companies (Nov 2018):

- *Astrobotic*
- *Deep Space Systems*
- *Draper*
- *Firefly Aerospace*
- *Intuitive Machines*
- *Lockheed Martin Space*
- *Masten Space Systems*
- *Moon Express*
- *Orbit Beyond*

First On-Ramp (Nov 2019):

- *Blue Origin*
- *Ceres Robotics*
- *Sierra Nevada Corporation*
- *SpaceX*
- *Tyvak Nano-Satellite Systems, Inc.*

Awarded Deliveries:

TO2 2024
Astrobotic
Peregrine

TO2/20C 2024
Intuitive Machines
NOVA-C

TO PRIME-1 2024
Intuitive Machines
NOVA-C

CP-11 2025
Intuitive Machines
NOVA-C

TO19D 2024
Firefly Aerospace
Blue Ghost

TO20A 2024
Astrobotic
Griffin

CP-12 2025
Draper
Series-2

TOCS3/CS4 2026
Firefly Aerospace
Blue Ghost

Payload Accommodations

- CLPS Providers are required to “accommodate” the needs of NASA payloads, including:
    - Utilities: power, data, commanding, etc.
    - Mounting: fields of view, alignments, co-locations, etc.
    - Environments: thermal, vibe, EMI/EMC, etc.
    - Operations: conops, mission phases, etc.
- CLPS Task Orders are generally awarded competitively; payloads should therefore not be designed for a specific CLPS provider
- Firm Fixed Price (FFP) Task Orders necessitate stable definition of interfaces and requirements PRIOR to release of the Request for Task Plan (RFTP)
    - If it is not defined in the RFTP then it is defined de facto by the CLPS provider, or else is a “new” requirement at a cost
    - If requirements cannot be finalized, RFTP should specify achievable envelope for both sides to work toward
    - “Requirements” in an FFP procurement environment are what you are going to get, so RFTP requirements should align with what is needed for mission success

CLPS Payload Services

- NASA-owned and sponsored payloads are:
  - Manifested by a CLPS Manifest Selection Board (CMSB) with multi-Directorate representation
  - Assigned Payload Integration Managers and Project Scientists to guide integration and maximize science
  - Designed to advance science, technology, and exploration through investigations
- After payload handover, CLPS providers are responsible for integration, delivery, deployment and/or operation of customer payloads on the lunar surface
- CLPS providers secure all necessary hardware, systems, facilities and services to perform the delivery
  - NASA LSP (Launch Services Program) is not engaged in launch vehicle acquisition
  - DSN (Deep Space Network) (if required by contractor) is acquired by provider via RSAA (Reimbursable Space Act Agreement)
- Payload service tasks may include:
  - Physical operation, release/deployment with or without wireless/tethered services, passive delivery, and/or direct delivery into specified lunar orbit, mobility as a service, augmented insight

Payload Selections for CLPS Deliveries

- NASA Provided Lunar Payloads (NPLPs)
  - NASA Internal Call
  - In 2018, NASA selected 13 instruments that were identified as ready or very nearly ready to fly, and would accomplish a mixture of science, technology, and exploration objectives
- Lunar Surface Instrument and Technology Payloads (LSITPs)
  - External Community Call
  - In 2018, NASA selected 12 LSITPs that will address science goals from a variety of NASA's four divisions
- Payloads and Research Investigations on the Surface of the Moon (PRISM)
  - The PRISM solicitation call results in PI-led suites of instruments
  - Currently the Science Mission Directorates primary way of soliciting science-driven suites of instruments to fly to the surface of the Moon
  - To date, six PRISM selections have been awarded
- STMD, ESDMD, and International Payloads
  - Captured by Memorandum of Agreement (MOA) and manifest via CMSB
  - International Partner payloads are generally represented by a "sponsoring" or "representative" mission directorate
  - International payload vendors can work with NASA or go directly to a CLPS provider to acquire a lunar delivery service for their payload

International Payloads Agreements

ESSIO

Partner	Payload Name	CLPS Delivery
ESA	PITMS Contribution	Task Order 2 - Astrobotic
CSA	Leap LRM (Rover)	Future CLPS Task Order
ESA	Retroreflector	Task Order CP-11 – Intuitive Machines
ESA	PROSPECT	Future CLPS Task Order
ESA	Lunar Pathfinder	Task Order CS-3 – Firefly Aerospace
CNES	LuSEE-Lite Search Coil Mag	Task Order CP-12 - Draper
UNiBE	LIMS	Future CLPS Task Order
KASI	LUSEM	Task Order CP-11 – Intuitive Machines
CNES	FSS Contribution	Task Order CP-12 - Draper
Grapevine Productions	Sanctuary	Future CLPS Task Order

CLPS Task Orders

ESSIO

TO2-AB

PM-1

Peregrine Lander

ASTROBOTIC

TO2-IM

IM-1

Nova-C Lander

INTUITIVE MACHINES

TO19D

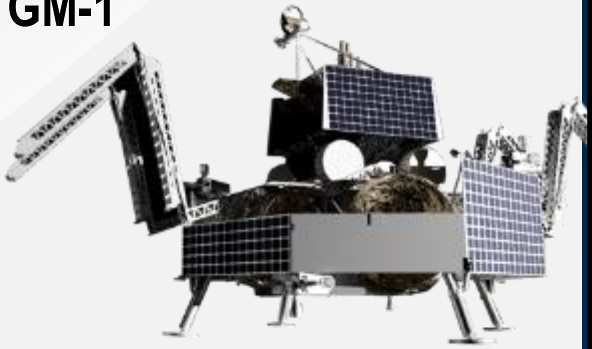
Blue Ghost 1

Blue Ghost lander

FIREFLY AEROSPACE

TO20A – VIPER

GM-1



Griffin Lander

ASTROBOTIC

PRIME-1

IM-2

Nova-C Lander

INTUITIVE MACHINES

CP-11

IM-3

Nova-C Lander

INTUITIVE MACHINES

CP-12

TBA

Series-2 Lander

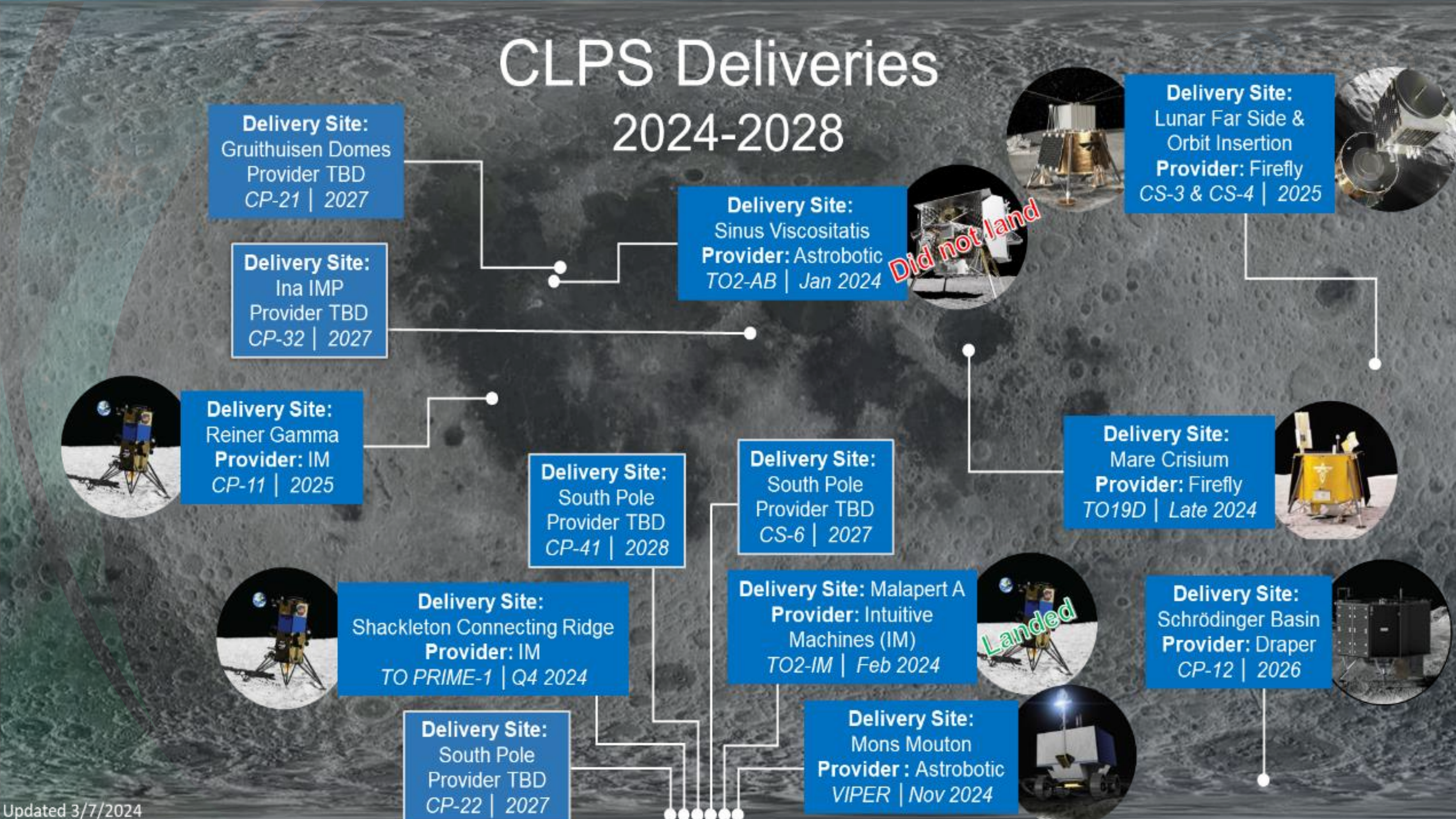
DRAPER

CS-3 & CS-4

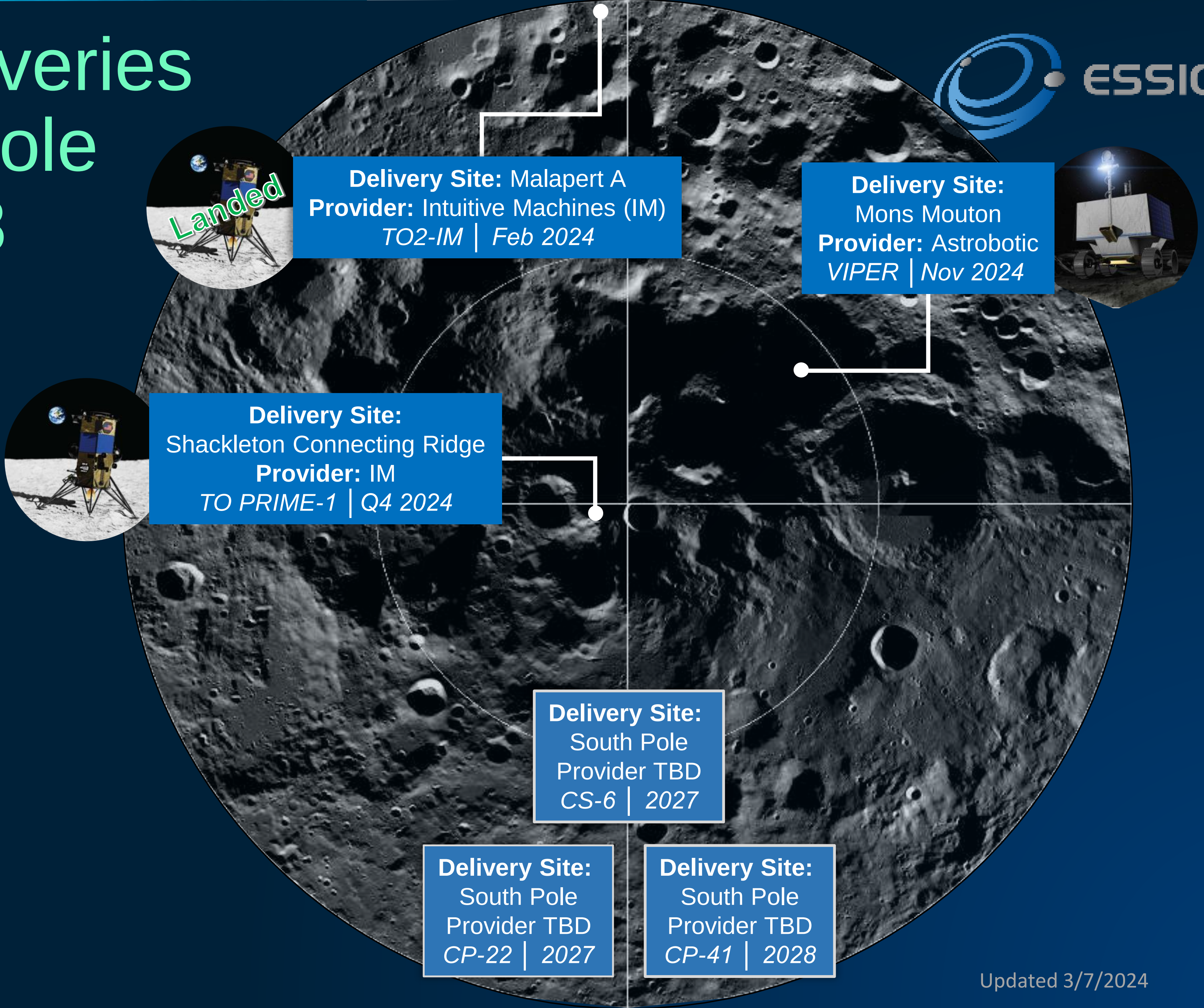
Blue Ghost 2

Blue Ghost Lander

FIREFLY AEROSPACE


CLPS Deliveries
2024-2028
Delivery Site: Gruithuisen Domes
Provider TBD
CP-21 | 2027
Delivery Site: Ina IMP
Provider TBD
CP-32 | 2027
Delivery Site: Sinus Viscositatis
Provider: Astrobotic
TO2-AB | Jan 2024
Did not land
Delivery Site: Lunar Far Side & Orbit Insertion
Provider: Firefly
CS-3 & CS-4 | 2025
Delivery Site: Reiner Gamma
Provider: IM
CP-11 | 2025
Delivery Site: South Pole
Provider TBD
CP-41 | 2028
Delivery Site: South Pole
Provider TBD
CS-6 | 2027
Delivery Site: Mare Crisium
Provider: Firefly
TO19D | Late 2024
Delivery Site: Shackleton Connecting Ridge
Provider: IM
TO PRIME-1 | Q4 2024
Delivery Site: Malapert A
Provider: Intuitive Machines (IM)
TO2-IM | Feb 2024
Landed
Delivery Site: Schrödinger Basin
Provider: Draper
CP-12 | 2026
Delivery Site: South Pole
Provider TBD
CP-22 | 2027
Delivery Site: Mons Mouton
Provider : Astrobotic
VIPER | Nov 2024
Updated 3/7/2024

CLPS Deliveries to South Pole 2024-2028

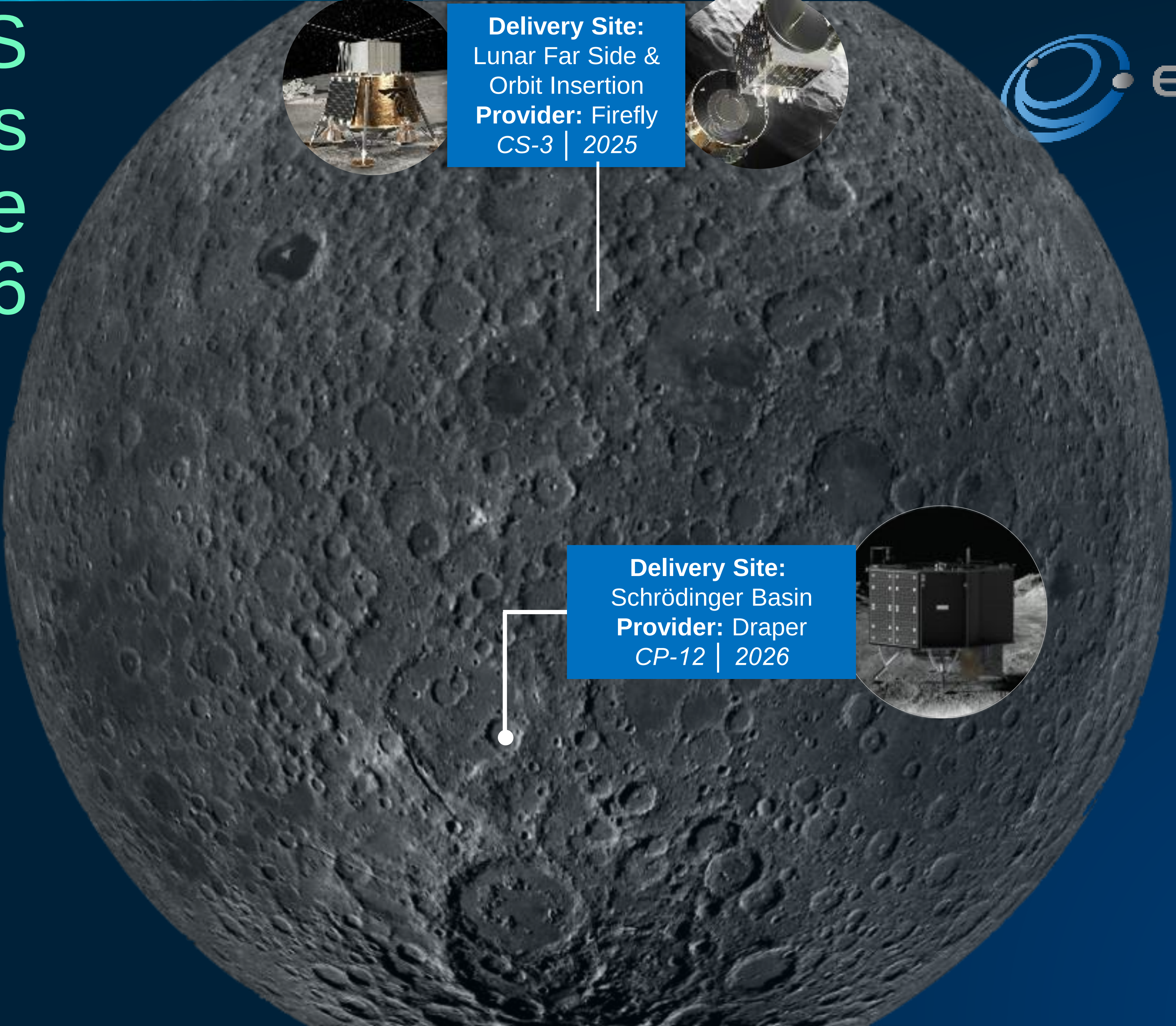


ESSIO

Updated 3/7/2024

CLPS Deliveries to Far Side 2025-2026

ESSIO



Science Highlights of Early Task Orders

TO2 AB

- Characterize volatile composition of regolith and exosphere during and after landing and over the course of the lunar day
- Characterize the local radiation environment

TO2 IM

- Determine the photoelectron sheath density and scale height
- Characterize plume-surface interactions during landing

PRIME-1

- Characterize volatile composition of regolith and exosphere during and after landing and over the course of the lunar day

TO 19D

- Characterize Earth's magnetosphere
- Characterize structure, composition, and thermal properties of the Moon's interior

CP-11

- Study the magnetic and plasma environment within a lunar swirl to address the origin of magnetized crust, origin of swirls, and nature of space weathering on airless bodies

CP-12

- Use geophysical techniques to characterizes the Moon's interior to understand how the Moon differentiated and evolved into its current state

CS 3/4

- Pathfinder to understand the Moon's radio environment and to potentially take a first look at a previously unobserved era in our cosmic history

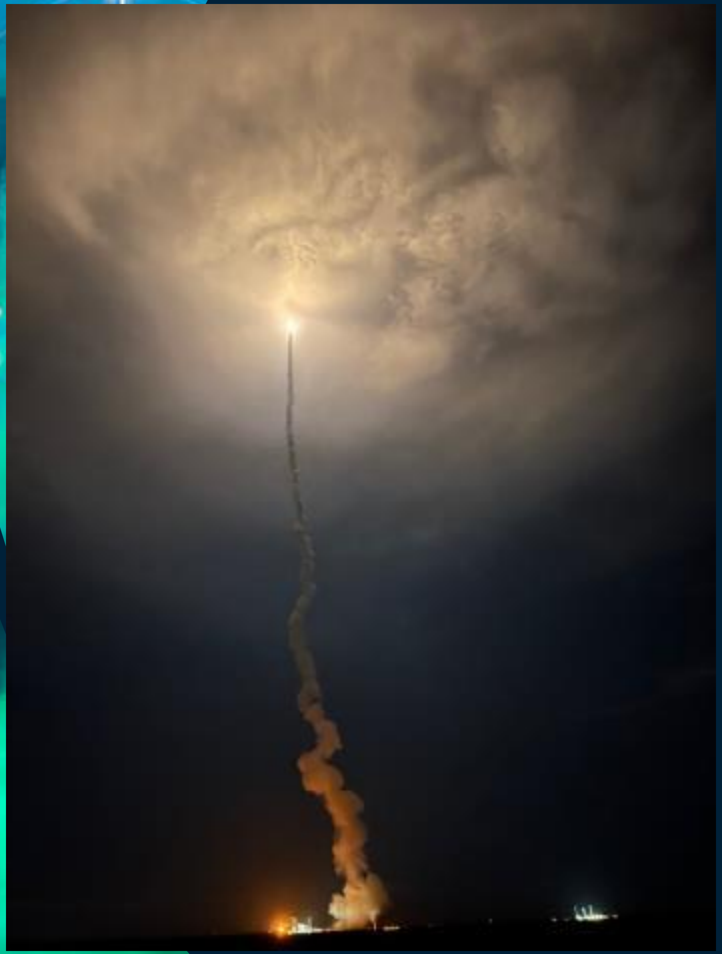
CP-21

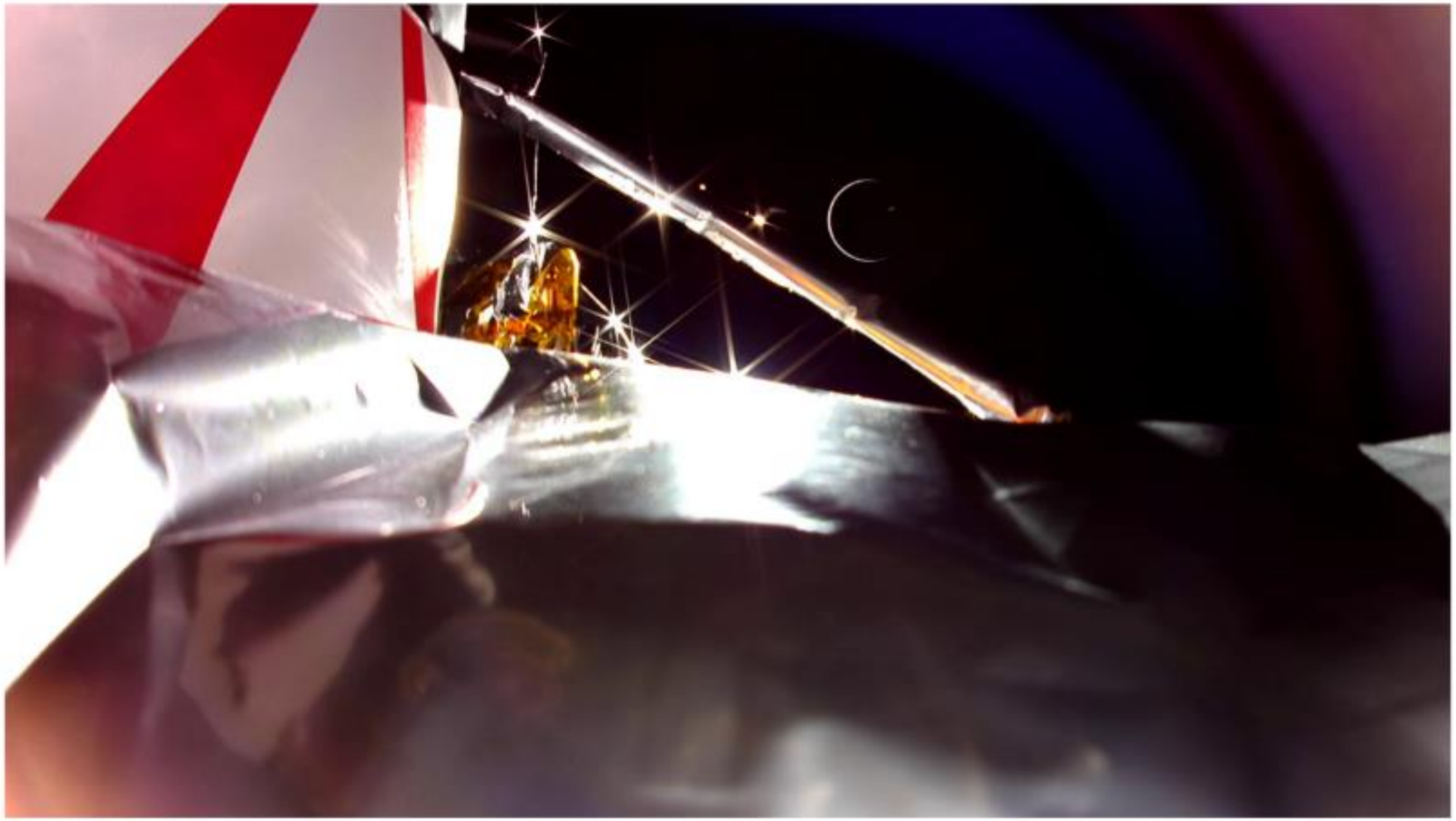
- Study the origin and composition of silicic volcanic constructs at Gruithuisen Domes

CP-22

- Study the biological response of yeast to the lunar environment to determine how partial gravity and deep space radiation influence biological processes
- Characterize the terrain, surface mineralogy, composition, and thermophysical properties of the lunar surface

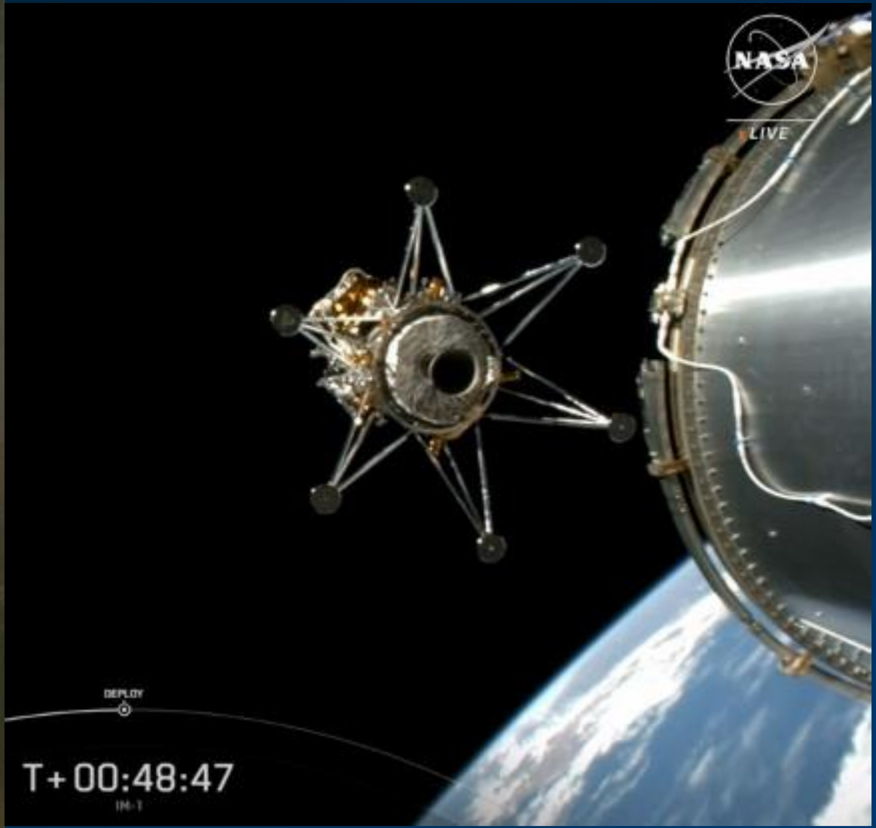
Peregrine Mission 1 – Astrobotic CLPS Task Order 2-AB





By blocking the Sun with one of Peregrine's struts, Astrobotic engineers were able to capture this striking view of the crescent Earth. The company's CEO, John Thornton, identified this photo as his favorite surprise of the mission. Credit: Astrobotic.

Intuitive Machines Mission 1
CLPS Task Order 2-IM



Intuitive Machines Mission 1 Moon Landing

Enlarge / Intuitive Machines' *Odysseus* lander is shown shortly before touching down on the Moon.


National Aeronautics and
Space Administration
NASA
EXPLORE
With Us

Instantiating Safety and Mission Assurance as part of NASA's Evolving Digital Engineering (DE) ecosystem

Tony DiVenti
OSMA – MASCD
(NASA MBMA Program Lead & R&M Technical Fellow)

Tri SMAC 2024
June 2024

Acronyms

- AC = Assurance/Safety Case
- AIM = Assurance Implementation matrix
- APPG = Automated Program Plan Generator
- ASoT = Authoritative Source of Truth
- C&C = NSC Content and Collaboration Project
- CRM = Continuous Risk Management
- DE = Digital Engineering
- DT = Digital Transformation
- DRD = Data Requirements Document
- FAIR = Findable, Assessable, Interoperable and Reusable
- FMEA = Failure Modes Effects Analysis
- FTA = Fault Tree Analysis
- GSN = Goal Structuring Notation
- HQA = Hardware Quality Assurance
- MB = Model-Based
- MBMA = Model-Based Safety and Mission Assurance (Note: inclusive of all Safety and Mission Assurance areas at NASA)
- MOU = Memorandum of Understanding
- NGOs = Needs, Goals, and Objectives
- NPD = NASA Policy Directive
- NPR = NASA Procedural Requirement
- RAAML = Risk Analysis and Assessment Modeling Language
- RIDM = Risk Informed Decision Making
- SMA = Safety and Mission Assurance
- SMAP = SMA Plan
- STD = Standard

Agenda

Background: Importance of a “Digital” SMA and Engineering Partnership

Key OSMA - OCE Focus Areas

- DE / MBMA / Digital SMA Implementation Plan and Strategic Roadmap Integration
- Common Data-Centric Approach to NPRs/NPDs/NASA-Specific STDs
- Digital Engineering Acquisition Best Practices (e.g., Contract DRD Template Language)
- Data flow in support of informing Milestone Review Decisions
  - Engineering V&V Framework
  - Case-Assured Framework

Next Steps

- Potential OCE and OSMA MOU

Background

Why: Engineering and SMA need to ***TRANSFORM*** to manage the growing complexity of systems, both development and operations, by integrating information sources, analysis processes, and tools that were largely Stove-Piped in the past to enable the seamless flow of information in support of NASA Missions

Engineering Role & Responsibilities

(Pull from NASA 1000.B, 7123.1, 7120.5)

Provides leadership, policy direction, functional oversight, assessment, and coordination for Engineering and related Technical Disciplines, including Systems Engineering.

Digital Engineering (DE): "An integrated digital approach that uses authoritative sources of systems data and models as a continuum across disciplines to support lifecycle activities from concept through disposal". [1]

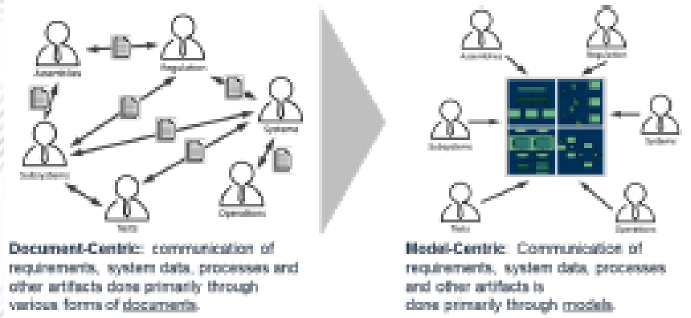
A ***digital engineering ecosystem*** includes Enterprise interconnected digital environments, stakeholder-networks, and semantic and ontological reasoning that allows the exchange of digital artifacts from an authoritative source of truth to serve the stakeholder communities' interests [1].

[1] U.S. Department of Defense (DoD) Digital Engineering (DE) Strategy, https://man.fas.org/eprint/digeng-2018.pdf

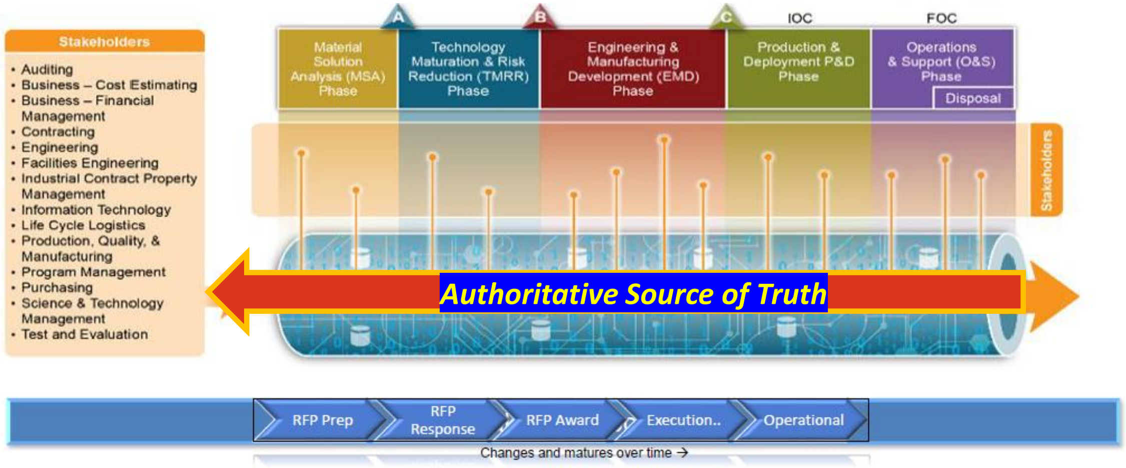
Safety & Mission Assurance Role & Responsibilities

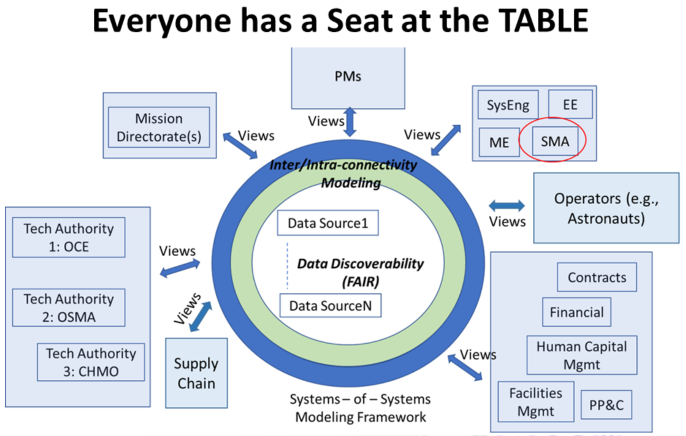
(Pull from NASA NPD 8700)

1. Acceptable Risk Levels for Crew Safety and Mission Success
2. Protect Public, Workforce, Property, and environment
3. Cultivate a Robust Safety Culture. Pursue Organizational/Technical Excellence to understand/reduce risks



Document to Data and/or Model Centric Modeling





Agenda

Background: Importance of a "Digital" SMA and Engineering Partnership

Key OSMA - OCE Focus Areas

- DE / MBMA / Digital SMA Implementation Plan and Strategic Roadmap Integration
- Common Data-Centric Approach to NPRs/NPDs/NASA-Specific STDs
- Digital Engineering Acquisition Best Practices (e.g., Contract DRD Template Language)
- Data flow in support of informing Milestone Review Decisions
  - Engineering V&V Framework
  - Case-Assured Framework

Next Steps

- Potential OCE and OSMA MOU

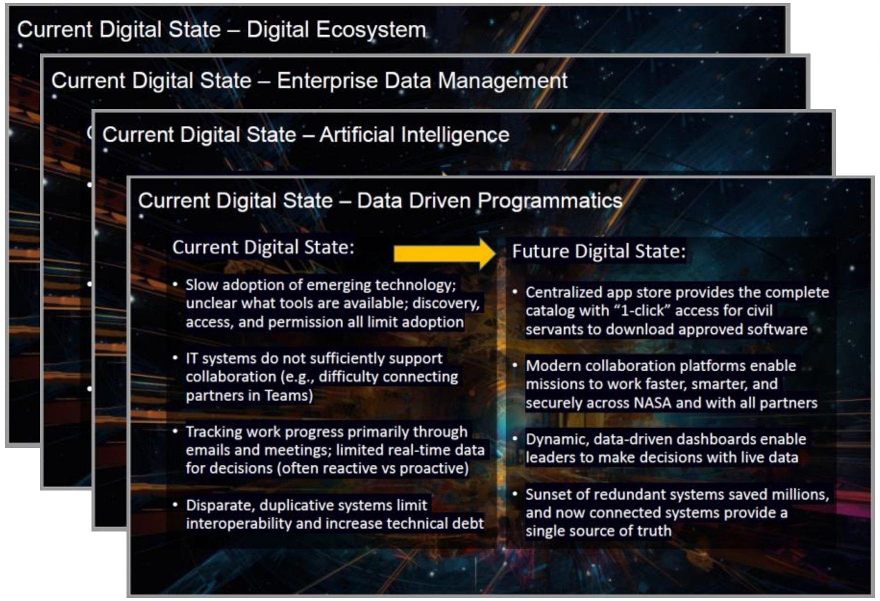
DE / MBMA / Digital SMA Implementation Plan and Strategic Roadmap Integration

Enterprise Gains → **Future Digital States (e.g., NASA 2040 Vision)**

Incremental short-term Gains
(Address Org Goals / Data Flow / Pain Points)

2023 | 2024 | 2025 | 20xx

- Digital Engineering (MBE/MBSE) Implementation Plan
- Digital SMA (MBMA) Implementation Plan
- Centers
- Govt/ Industry Partners



Integrated Digital Engineering (DE) / MBMA / Digital SMA Implementation and Strategic Plan(s) — **leverages** → Agency Roadmap Manager (ARM)

NASA's DT Initiative

DE / MBMA/ Digital SMA Implementation Plan and Strategic Roadmap Integration

Tactical (Incremental Gains): DE / Digital SMA Implementation Plan

OSMA / SMA Strategic Objectives

- Help Customer Products & Reviews
- Enable Risk Leadership
- Effective Policy
- Efficient Resources
- Applicable Processes
- Communication & Coordination
- Organizational Excellence
- Digital Capabilities

Digital SMA Strategic Objectives

- Robust, Evidence Based, Closed Loop Feedback Solicitation
- Digital Enablement of Risk Indicators
- Digital SMA Policy Implementation
- Maximize MBMA/Technology Solution Office (TSO) transformation efficiency
- Digital SMA Command Media, Tools, & Guidance
- Increase Internal / External Communication, Coordination, and Collaboration
- Cultivate Technical / Organizational Excellence part of the evolving Digital SMA / Engineering environments
- Provide overall Digital SMA Leadership, Cross Activity Alignment and Coordination

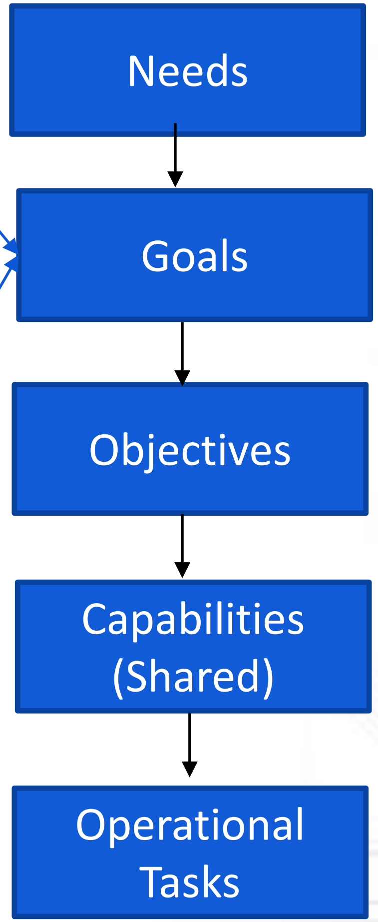
Engineering Needs

Improve how the Agency Engineering Domain operates over the entire NASA lifecycle by effectively managing complexity, reducing cost and schedule, and improving product integrity via the integration of processes, digital tools, and techniques along with seamless flow of information throughout the engineering system development life-cycle (concept development, design, testing and validation, manufacturing and operations).

DE Goals

- **G1 Lifecycle:** Establish a Digital Engineering (DE) strategy that can be integrated throughout the entire Engineering Life Cycle, aligning with NASA's mission objectives.
- **G2 Deployment:** Develop an interoperable, tailorable, and scalable deployment strategy for the Digital Engineering Ecosystem across the Centers including implementation options and methods.
- **G3 Guidance:** Establish the guidance for model development, tool integration and deployment, and formulation of data threads while ensuring alignment with the industry standards advocated by DE.
- **G4 ASoT:** Establish an approach providing stewardship, governance, security, traceability, and management of the engineering Authoritative Sources of Truth (ASoT), while ensuring the data within the ASoT are curated.
- **G5 Configuration/Change Management:** Evolve existing CM approaches for data-centric management of engineering baselines which enable teams to manage and track changes made throughout the entire product lifecycle.
- **G6 Digital Threads:** Develop strategies for Digital Threads/Ecosystem that improve collaboration, data exchange, design formulation, data-centric processes and workflows, operations, and insight, and data-informed decision making.
- **G7 Culture and Workforce:** Evolve NASA Culture and the Workforce by creating a demand for adoption of DE techniques, providing training, and cultivating a digital engineering community.

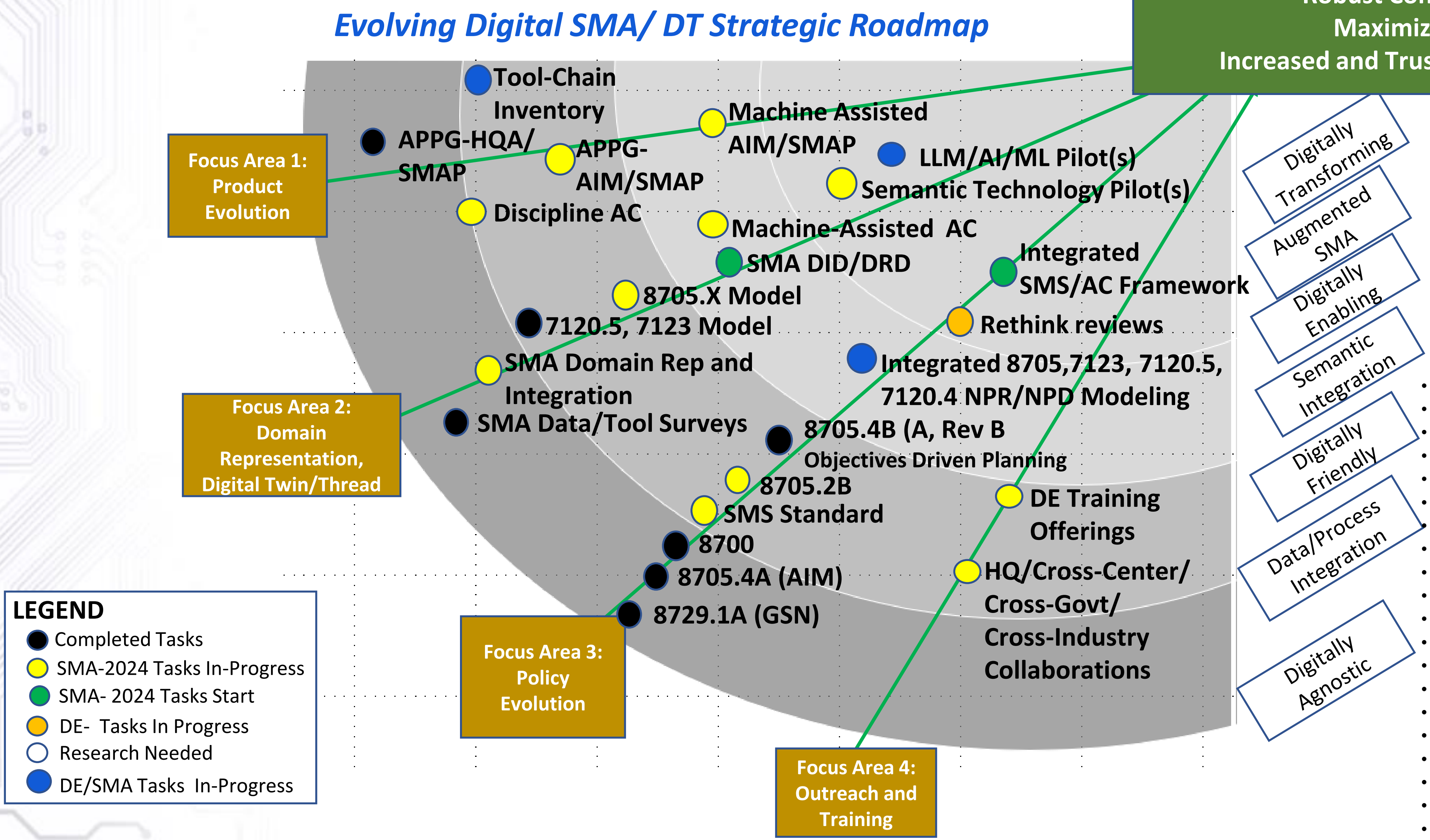
Simplified United Architectural Framework (UAF) illustration



MBMA / Digital SMA Implementation Plan and Strategic Roadmap Integration

Strategic Focus: Transformation Gains towards a Future Digital State

Findable, Accessible, Interoperable, Reusable (FAIR)
Robust Contextualization
Maximize Efficiency
Increased and Trusted Decision Velocity



Acronyms

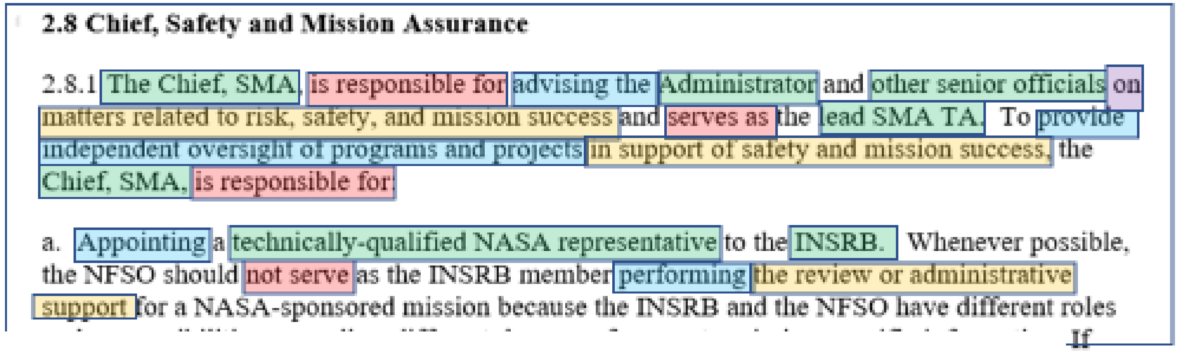
- AC = Assurance/Safety Case
- AIM = Assurance Implementation matrix
- ANASWA=R&M Logic Fragment Engine
- APPG = Automated Program Plan Generator
- C&C = NSC Content and Collaboration Project
- CRM = Continuous Risk Management
- DT = Digital Transformation
- EDP – Enterprise Data Platform
- FAIR = Findable, Assessable, Interoperable and Reusable
- FMEA=Failure Modes Effects Analysis
- FTA=Fault Tree Analysis
- GSN = Goal Structuring Notation
- HQA = Hardware Quality Assurance
- MB = Model-Based
- MBMA+ = Model-Based Safety and Mission Assurance
- RAAML = Risk Assessment and Modeling Language
- RIDM = Risk Informed Decision Making
- SMA = Safety and Mission Assurance
- SMAP = SMA Plan
- SPARTA=Smart Project and Reviews with Transformative Analytics (SPARTA)

Common Data-Centric Approach to NPDs/ NPRs/ NASA Specific STDs

Objectives-Driven Development ***provides an*** ***<u>On-Ramp for Digital Objectives-Driven Planning and Assurance Case Framework</u>***

"Parsing" the NPRs: an Example

From **NPR 8715.26, Sec 2.8:**


2.8 Chief, Safety and Mission Assurance

2.8.1 The Chief, SMA, is responsible for advising the Administrator and other senior officials on matters related to risk, safety, and mission success and serves as the lead SMA TA. To provide independent oversight of programs and projects in support of safety and mission success, the Chief, SMA, is responsible for:

a. Appointing a technically-qualified NASA representative to the INSRB. Whenever possible, the NFSO should not serve as the INSRB member performing the review or administrative support for a NASA-sponsored mission because the INSRB and the NFSO have different roles

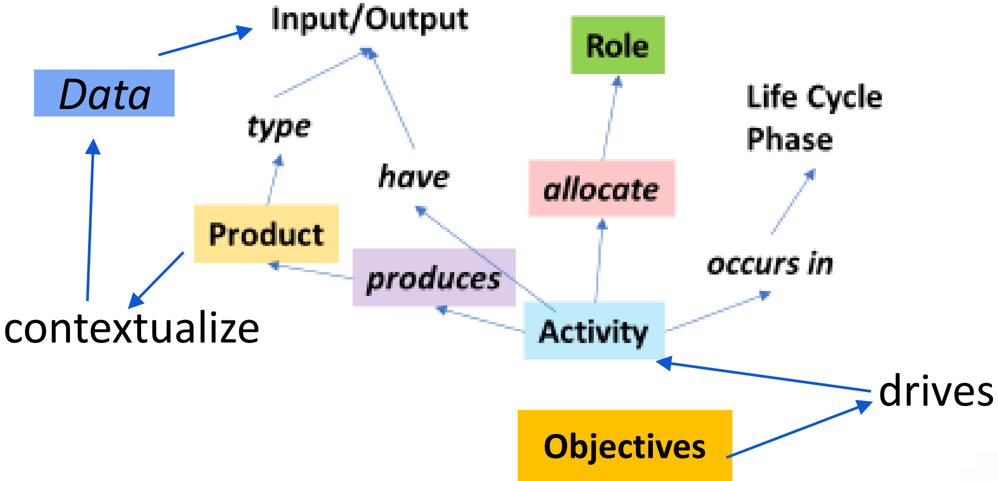
LEGEND

Role	An Actor/actor's part
Activity	Things being done
Product	Things produced
allocation	Assigned
produces	Creates/Results In

Argument*	**Structured Assertion**
Case*	**Assurance Case**
Objectives*	**Intended results**
Data*	**Actual Data itself**
Evidence*	**Pieces of "proof"**

- ***Note1:*** *Only part of the MetaModel is explicitly highlighted in the above "snippet"*
- ***Note 2:*** *Products / Data are further elaborated (decomposed) in various Standards. Structure still in discussions.*
- ***Note3:*** *This explicit traceability will enable broader use of Assurance Cases*

Simplified "Ontology"

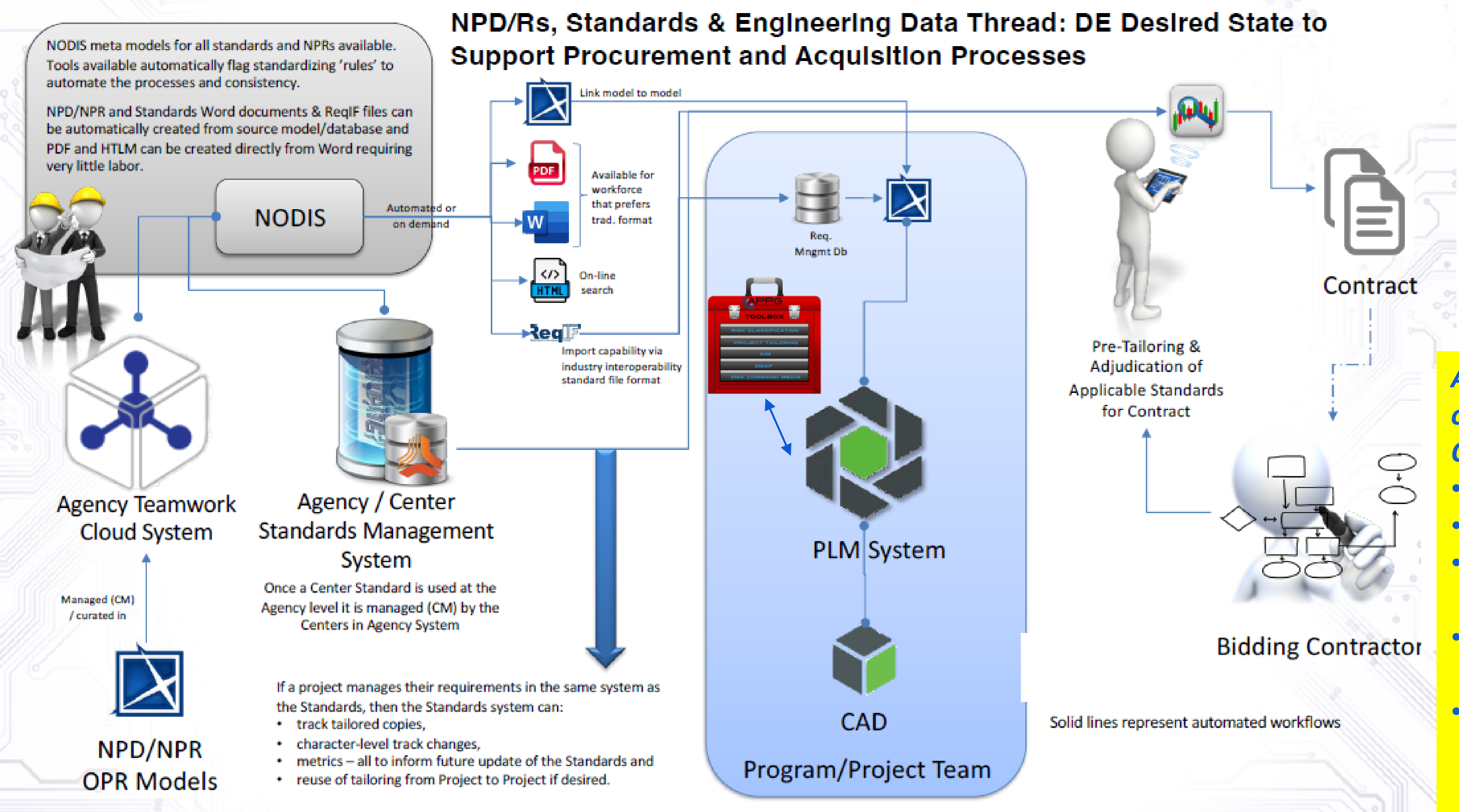


**Information not shown in the NPR 8715.26 illustration*

Digital Engineering Approach to Planning across the Lifecycle

Project Formulation → Project Design/Development → Operations

(Reference NASA-HDBK-1004)



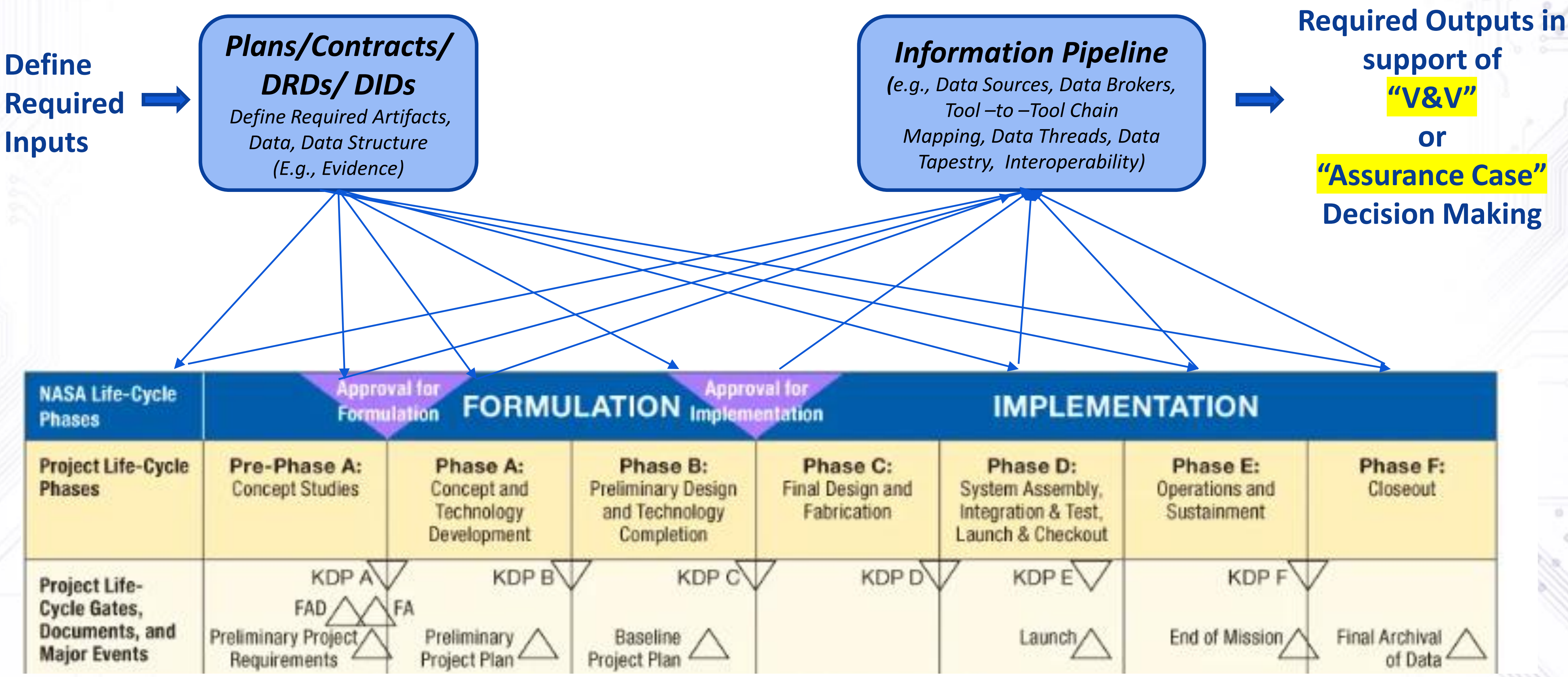
DRDs/ DIDs

Define Required Artifacts, Data, Data Structure (e.g., Evidence)

Approach enables definition of SMA and Engineering Objectives-Driven:

- ***Products***
- ***Data***
- ***Human Readable Interfaces***
- ***Machine Readable Interfaces***
- ***Machine-Assisted Planning and Contract development***

Data flow in support of informing Milestone Reviews Decisions



(Reference NASA-HDBK-1004 as a starting point)

Agenda

Background: Importance of a “Digital” SMA and Engineering Partnership

Key OSMA - OCE Focus Areas

- DE / MBMA / Digital SMA Implementation Plan and Strategic Roadmap Integration
- Common Data-Centric Approach to NPRs/NPDs/NASA-Specific STDs
- Digital Engineering Acquisition Best Practices (e.g., Contract DRD Template Language)
- Data flow in support of informing Milestone Review Decisions
  - Engineering V&V Framework
  - Case-Assured Framework

Next Steps

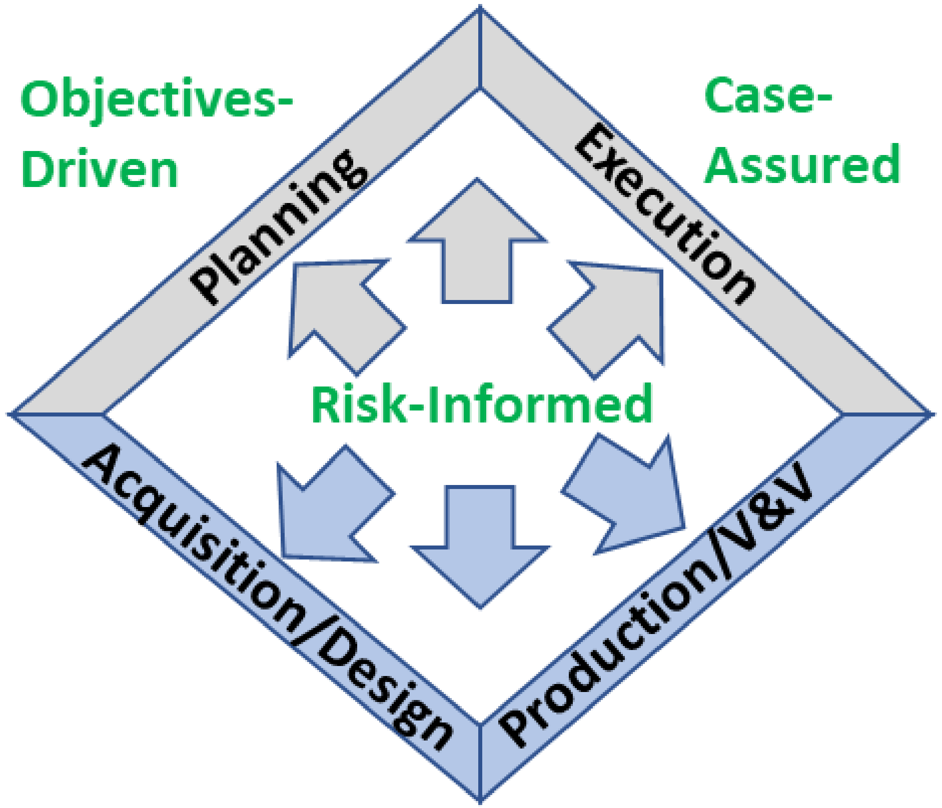
- Exploration of a formal ***OCE and OSMA MOU***

OCE and OSMA MOU

OCE and OSMA beginning to explore an MOU around the following:

- NGOs to MBMA / Digital SMA Objectives Roadmap and Implementation Plan integration
- Common Data-Centric Approach to NPRs/NPDs/NASA-Specific STDs
- Digital Engineering Acquisition Best Practices (e.g., Contract DRD Template Language)
- Data flow in support of informing Milestone Review Decisions
  - Engineering V&V Framework
  - Case-Assured Framework

Any Questions



NASA Project Life Cycle

BACK-UP

OSMA Strategic Objectives

#1 – **Help Customer Products & Review** - Increase Responsiveness to Mission, Institutional, & National Needs

(e.g., Customer focused, Data-Driven, Closed-Loop)

#2 – **Enable Risk Leadership** – Catalyze Culture of Technical & Organizational Risk Leadership & Management

(e.g., Technical Guidance, Risk-Informed Enablers / Tools)

#3 - **Enable Effective Policy** – Enable Missions and Institutions to Effectively & Efficiently Implement SMA

(e.g., Tool Enabled Objectives-Driven Policy Planning and Implementation)

#4 – **Efficient Resources** - Maximize Effectiveness of Resources for Internal Initiatives and Operations

(e.g., OSMA Objective-Funded Activity Alignment; Cross-Domain alignment around common needs/capabilities)

#5 - **Enable Processes** – Make SMA Processes / Services More Objectives-driven and Risk Informed

(e.g., Objectives-Driven Process controls, Risk Informed Planning)

#6 – **Increase Communications and Coordination** – Increase Internal and External Communication, Coordination, and Collaboration

(e.g., Forums, Cross Domain Forums, Communication Vehicles)

#7 – **Enable Organizational Excellence** – Cultivate Technical and Organizational Excellence

(e.g., Resource Development, Training, Best Practices)

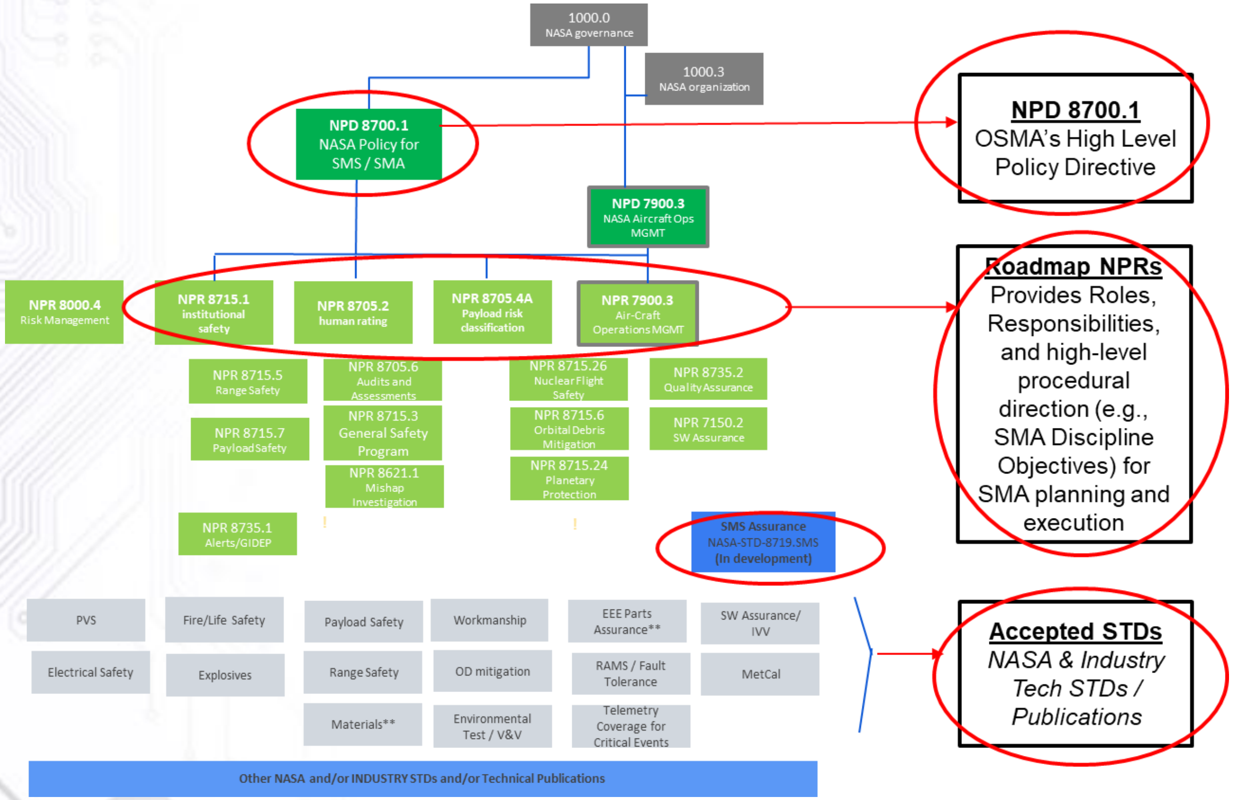
#8 – **Build Capabilities** – Adjust Capabilities & Tools to Support Emerging Needs

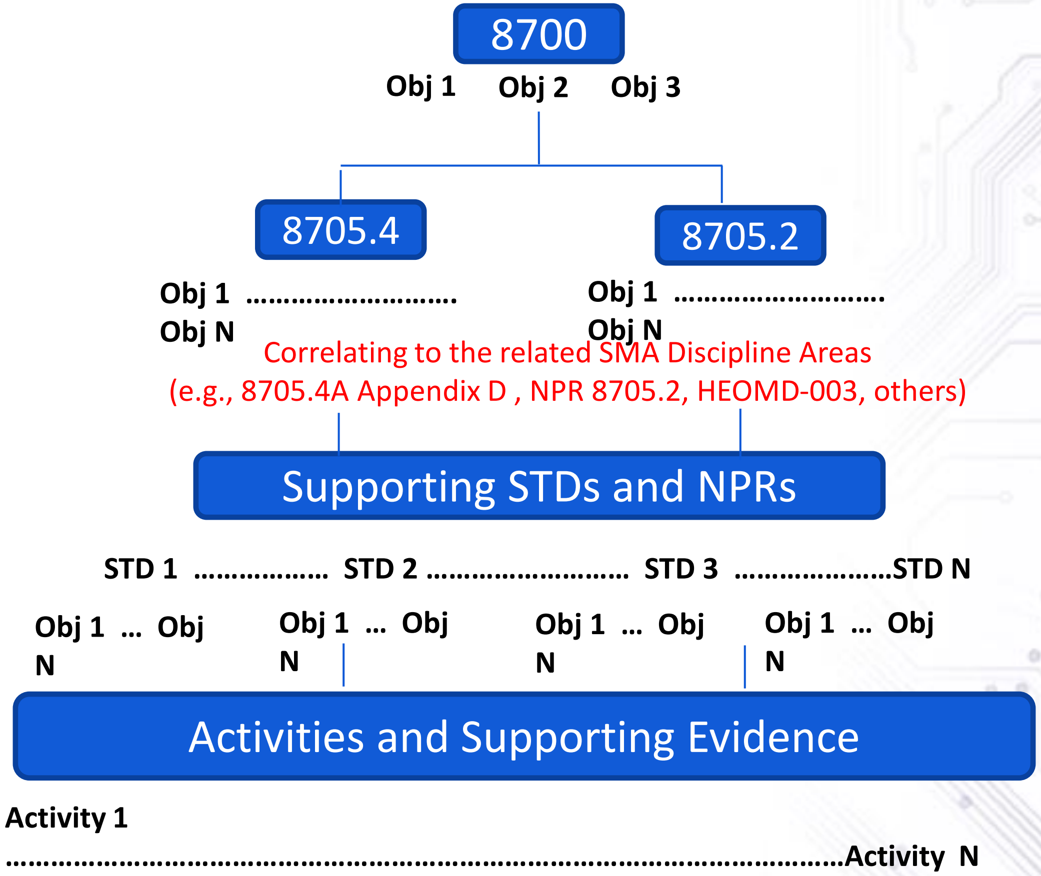
(e.g., Digital SMA Strategy, Digitally enable Workforce / Capabilities , Data Access for Decision Making)

Objectives-Driven Reqts and Use of Accepted STDs

OSMA's Policy Enabled <u>Objectives Hierarchical Structure</u> *provides an <u>On-Ramp for Digital Objectives-Driven Planning and Assurance Case Framework</u>*

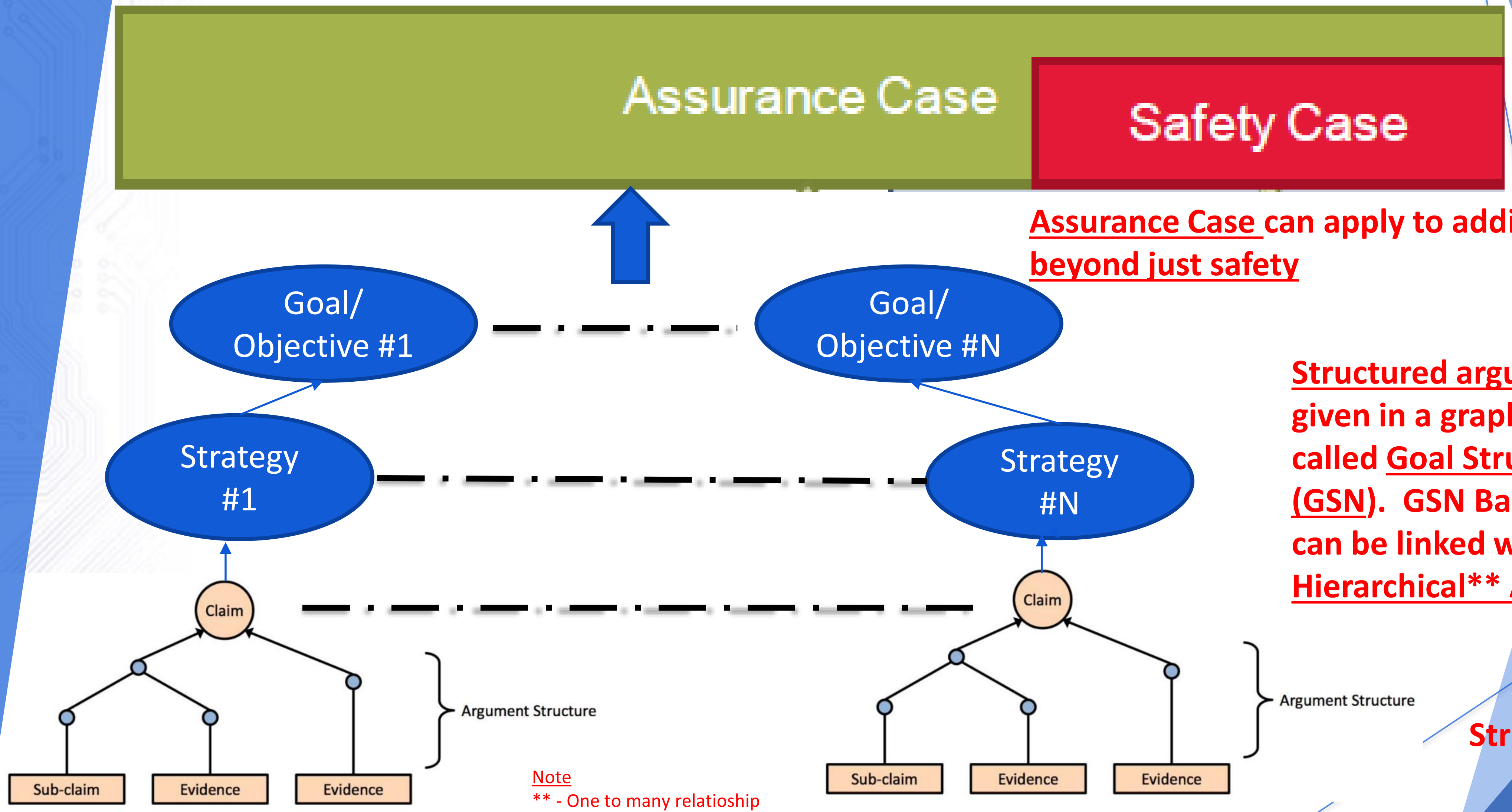
- Top-Level SMA and Mission Objectives
- SMA Discipline Area Objectives
- Risk Posture/Risk Class Objectives Driven
- Accepted (including Alternatives) Standards





Ties-in with (complements) NPR 7120.5 Activities
(i.e., NPR 7120.5F Chapter 2, Appendix C, Appendix G , Appendix H, & Appendix I)

Conceptual Illustration



Assurance Case can apply to additional system attributes beyond just safety

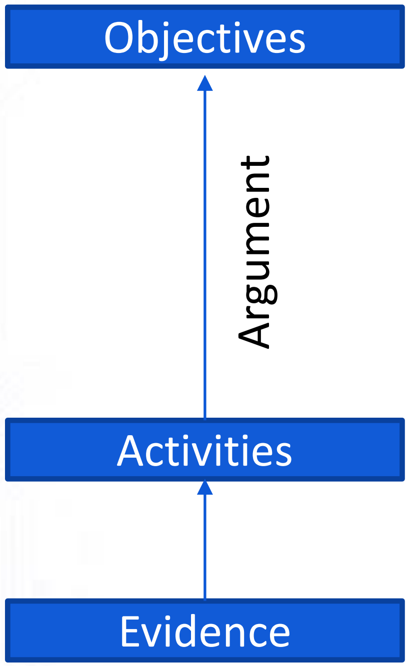
Structured arguments can be given in a graphical notation called Goal Structure Notation (GSN). GSN Based Arguments can be linked with an Objectives Hierarchical Approach.**

Structured argument

Note
** - One to many relatioship

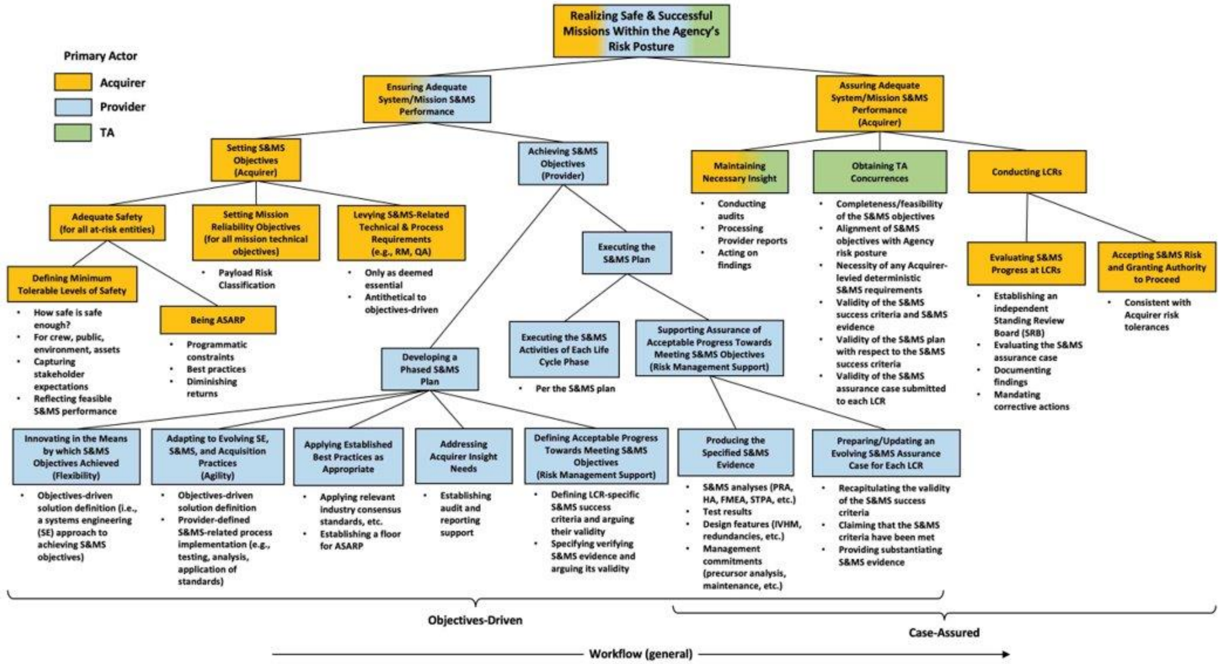
Objectives-Driven Hierarchy

They contrast with "prescriptive" requirements (must do X, Y, Z)



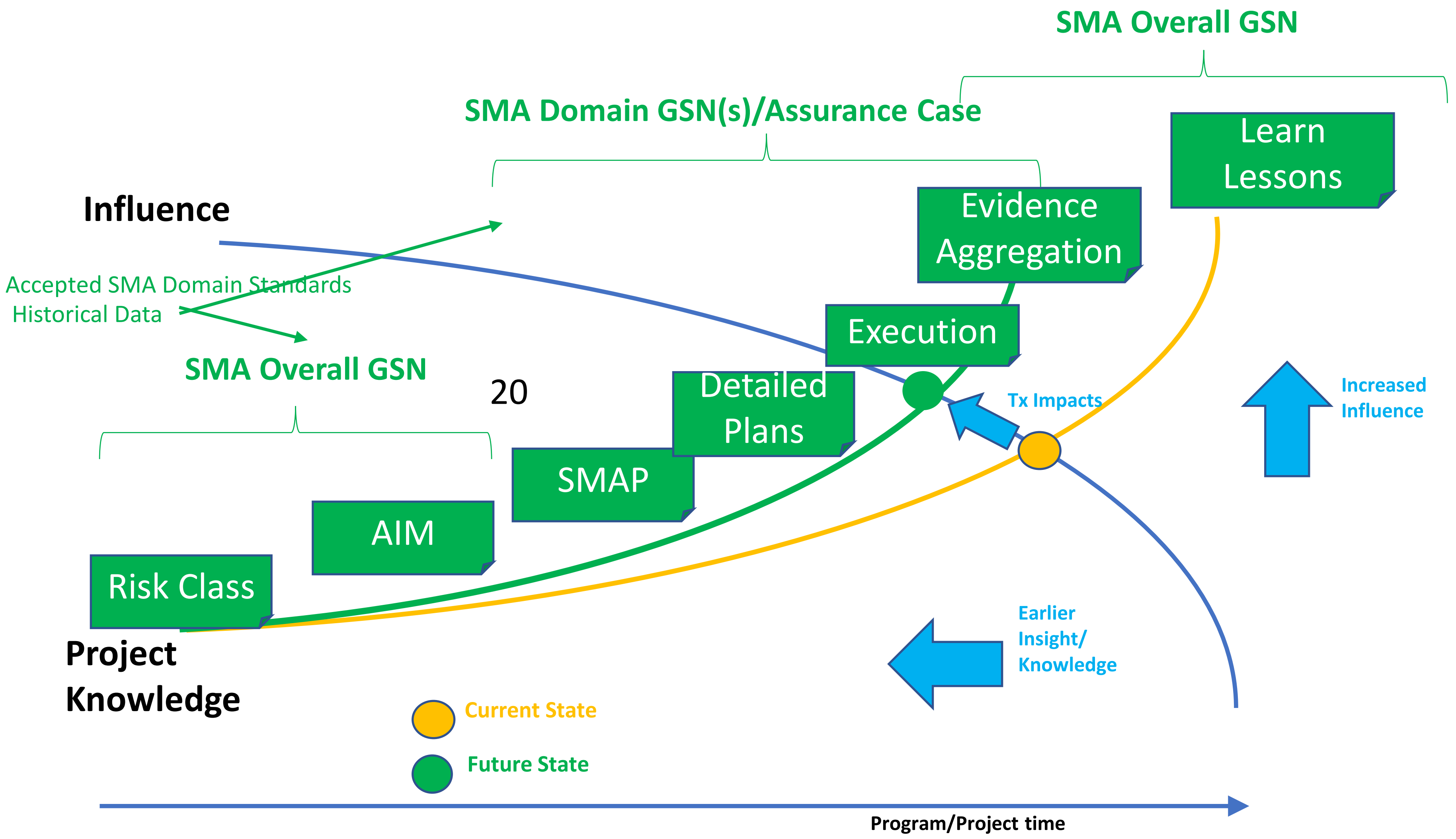
An **Assurance Case** is an organized argument that a system is acceptable for its intended use with respect to specified concerns

"The Nimrod Safety Case represented the best opportunity to capture the serious design flaws …which had lain dormant for years. ***If the Nimrod Safety Case had been drawn up with proper skill, care, and attention,*** *the catastrophic fire risks …, would have been identified and dealt with, and the loss of XV230 in September 2006 would have been avoided"*[2]



Assurance Cases, starting from Objective Hierarchies, enable our "transformed" SMA Framework

Optimal SMA Planning – In Synch with on-going Knowledge and Influence Transformations and Impacts



Key SMA Tranformational Impacts

- Faster (Decision Velocity)
- More efficient
- More robust information
- More Trusted
- Re-Usable
- etc

Agency DT Engine

NASA's Strategic Framework & Implementation Plan outlines the following activities on an annual basis to unify and drive transformational activities

Remember, Digital Transformation is not a goal, it's a lever. A big one……To achieve Organization & NASA Goals

OSMA/ SMA

1 Ignite Transformation

Facilitate Tx Target Community-owned Roadmaps & near-term priority actions to align DT intent & goals across NASA

2 Connect Plans

Coordinate like Organizational DT Plans that respond to the DT Strategic Framework to synchronize DT intents

3 Integrate Solutions

Analyze Integrated DT Solutions Portfolio vs. Roadmaps / priorities for redundancies & gaps to identify leveraging opportunities & inform investment decisions by OCIO, DT & other organizations

4 Facilitate Adoption

Measure DT Progress on funded Org DT Plans vs. Roadmaps/Priorities; elevate & address cross-cutting barriers via DT Catalyst Projects; celebrate & share DT Successes & Exemplars

Refine "Tx Engineering's" Roadmap by integrating Digital SMA Plan with Digital Engineering's (DE) Needs, Goals, and Objectives (NGO) plan

Update & connect OSMA's Digital SMA Plan using the Agency Roadmap Manager (ARM)

Support ITSB, ITMB, DE Leadership Team, NEW DT Working Group, and NEW SMA MB to influence Investment Decisions

Lead / support DT related projects and share progress (both Agency DT and SMA funded activities)

Origins of Digital SMA

MBMA Program
- Trilateral WG
- MIAMI support
- RAMS papers
- RAAML

KSAO Program
- NASA-wide STAR
- NMIS
- QCARD

Agency DT ReOrg (Agency DT Strategic Framework/ARM)
4 Transformation Target Areas (Discovery, Operations, Engineering, Decision-Making)*

OSMA/OCE partnership around DE / DE Eco System

Development of OSMA's Strategic Objectives (1-8) and **Obj#8 Digital SMA Team**

NASA's Digital Transformation Initiative

Agency DT (i.e., Jill Marlowe) moves into OCIO

Pre 2022	2022	2023	2024+

Extension of MBMA into DT **(MASCD + KSAO)**
Extend beyond Reliability/ Modeling to other Disciplines/ Areas, Automated Program Plan Generator (APPG)

SMA grouped under the Digital Eng (DE) Workstream
Also includes links with Decision-Making & Ops

MBMA/ KSAO Partnership
Initial Digital SMA Planning around 8 OSMA strategies

Realignment/ Reorganization of Digital SMA-related Activities
OSMA Leadership/ SMA MB Forums

Digital SMA Partners and Activities

Summary and Notable Examples

Key Players and Activities

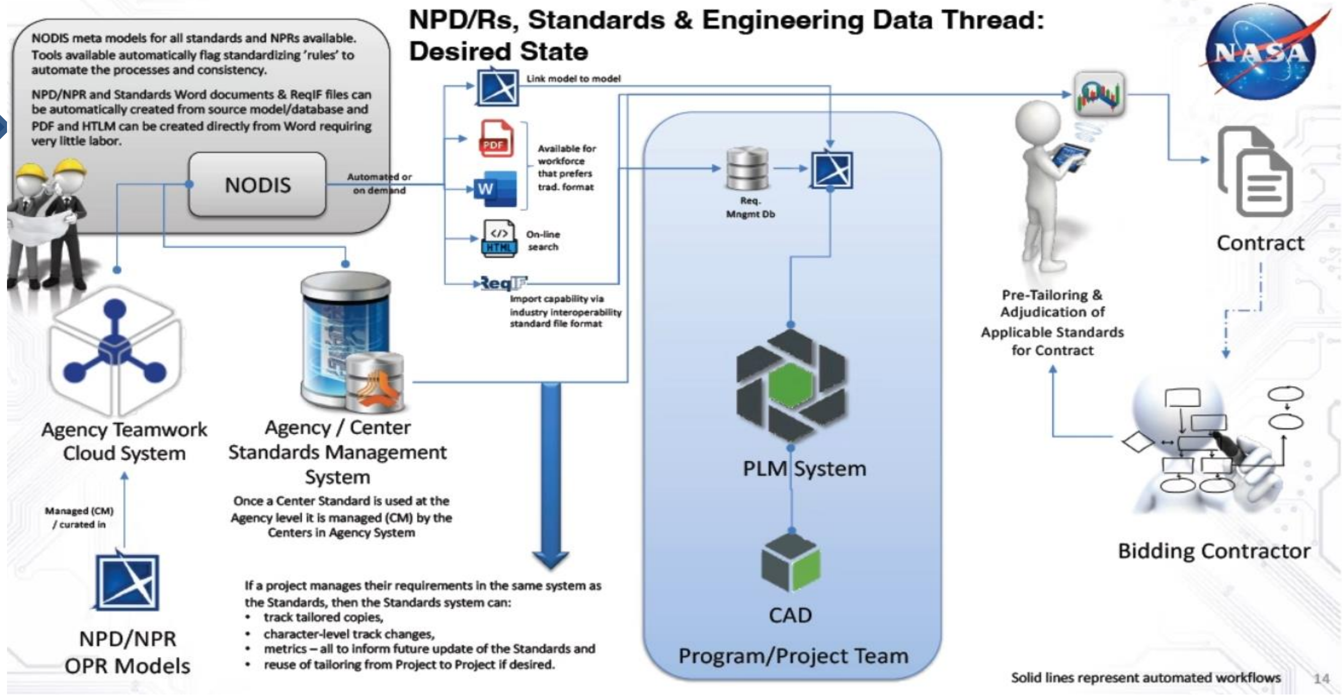
- SMA In-Kind: SMA Disciplines, SMA Policy Mgmt (~25 tasks)
- NASA Partner: OCE, OCIO, OCE, NODIS (~6 tasks)
- External Partner (~4 tasks): OUSD/DoD – Army DevCommand, etc.; SDOs – SAE, OMG, etc.,; Govt-Industry Consortiums – RAMS, FEDEF – INL, etc., Trilateral – ESA, JAXA, Universities – FL Institute of Technology, etc.: Aerospace Companies – LM, NGST, etc.
- OSMA KSAO (~6 tasks):
- OSMA MBMA (~5 tasks)

30+ tasks!

All focused on Digital SMA's Strategic Objectives

Cross-TA NPR Meta-Model Development and Machine Assisted Planning

(with OCE, OCIO, OES, NODIS, SMA Policy Management)



LEGEND

ARM *= Agency Roadmap Model*
DSO *= Digital SMA Objective*
DE *= Digital Engineering,*
DoD *= Department of Defense*
DT*= Digital Transformation*
ESA *= European Space Agency*
JAXA = *Japanese Aerospace Exploration Agency*
KSAO *= Knowledge Sharing and Analysis Office*
MBMA *= Model Based Mission Assurance*
OES *= Office Executive Secretary*
OMG *= Object Management Group*
OUSD – *Office Undersecretary of Defense*
RAMS *= Reliability and Maintainability Symposium*
SAE *= Society of Automotive Engineers*
SDO's *= Standards Development Organization*

MBMA Program Background

MBMA Overview:
It is important that SMA data, activities and products are integrated as part of the evolving MBSE and broader Digital Engineering environment, This includes integration of concepts and language, as well as integration of data, products, and processes.
Model-Based Systems Engineering (MBSE) focuses on creating and exploiting domain models as the primary means of information exchange between engineers, rather than on document-based information exchange. Domain models include both data and behavior.
Moving forward, the concepts and processes of S&MA must be accurately represented in the evolving Digital Engineering Eco System, while remaining broadly accessible by the S&MA community. Thus, the SMA activities must also address the following primary objectives:
1. Representing S&MA concepts and **information** in SysML, and
2. Providing Interfaces to MBSE tools and data therein ("lowering the barrier to entry").

Corresponding products and deliverables of this Program shall include:
- Ontologies, Shared Capabilities, and Guidance (e.g., Profiles and Model Elements)
- Views and Viewpoints, and approaches for interacting with the models as part of the broader Digital Eco System/MBSE environment.
- Papers, Pilots/Pilot effort documentation, presentations and other outreach activities
- The organization and implementation of the annual MBMA Workshop.

Qualification Challenges for Additive Manufacturing Processes and Parts

Andrew L. Glendening

NASA Goddard Space Flight Center

Code 541 – Sr. Metallurgist / Code 373 – Material and Process Assurance Engineer

Goddard SPACE FLIGHT CENTER

Outline

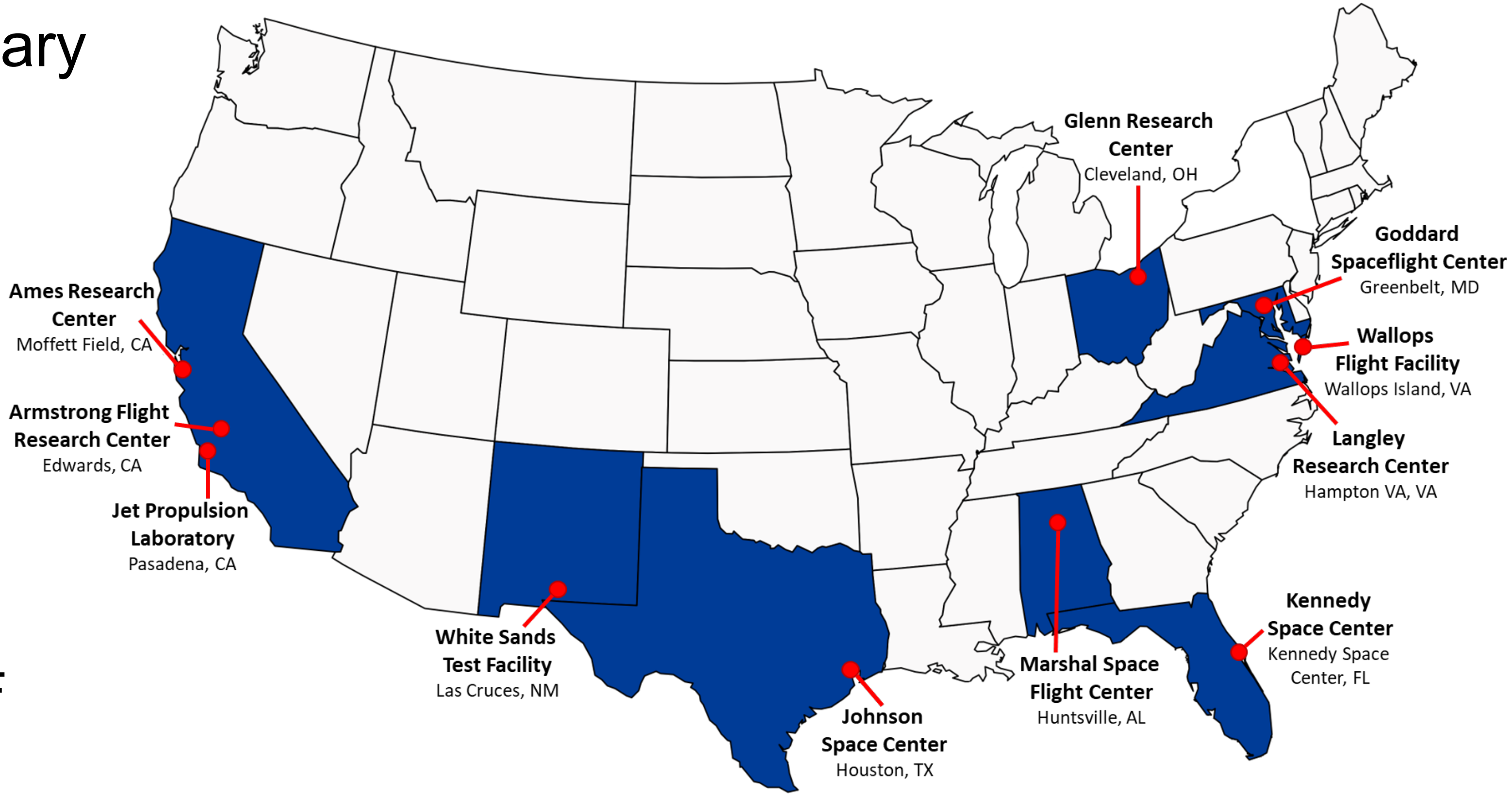
- Where NASA uses Additive Manufacturing
- The Basic Principles of NASA-STD-6030
- The Biggest Qualification Challenges for Additive Manufacturing Processes and Parts

Additive Manufacturing at NASA

Where does NASA use AM?

NASA is not homogeneous

- Technical and risk cultures vary by facility and mission, as shaped by its history
- Human-rated spaceflight
  - JSC, KSC, MSFC
- Space Science
  - GSFC, JPL
- Aeronautics
  - ARC, AFRC, GRC, LaRC, WFF



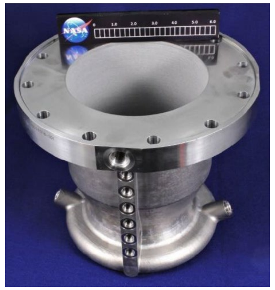
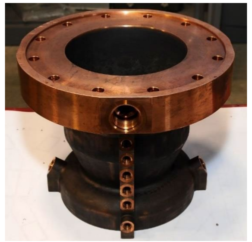
Goddard SPACE FLIGHT CENTER

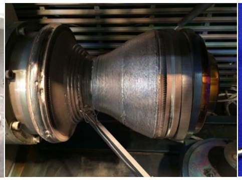
Approved for Public Release, Distribution Unlimited

Engines (MSFC)

NASA MSFC has also built channel-cooled combustion chambers using L-PBF, but that use bi-metallic additive and hybrid techniques.

- The materials used vary from Inconel® 625 and 718, Monel® K-500, GRCop-84, and C18150 metal alloys.
- Designs tested ranged from 200 to 1,400 psia in a variety of propellants and mixture ratios, producing 1,000 to 35,000 lbf thrust.



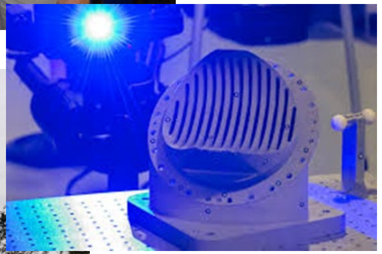
https://arc.aiaa.org/doi/abs/10.2514/6.2018-4625

NASA MSFC rocket injectors made by AM resulting in a 70% reduction in cost.

- Using traditional manufacturing methods: 1 Year, 163 parts
- With AM, 4 months. only 2 parts


28-element Inconel® 625 fuel injector built using a laser powder bed fusion (L-PBF) process

https://www.nasa.gov/press/2014/august/sparks-fly-as-nasa-pushes-the-limits-of-3-d-printing-technology/
https://arc.aiaa.org/doi/abs/10.2514/6.2018-4625


RS25 Prime Contractor, Aerojet Rocketdyne, technician exhibits the RS-25 pogo accumulator (top and middle), which was subsequently hot-fire tested (bottom)

- Over 100 Weld Eliminated
- Nearly 35% Cost Reduction

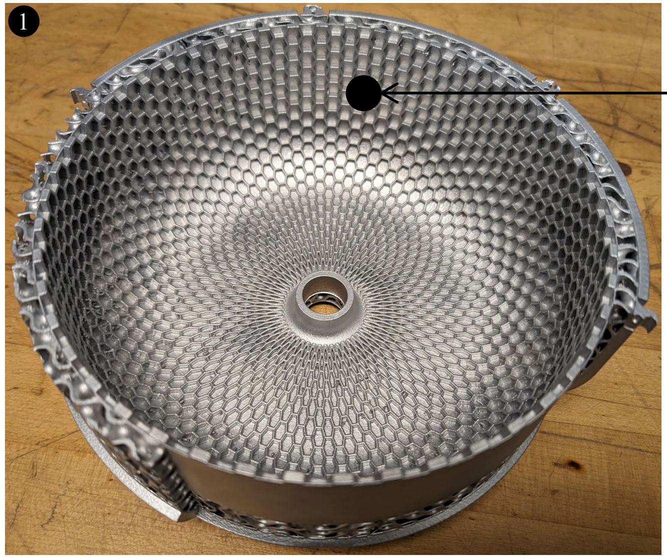
https://www.nasa.gov/exploration/systems/sls/nasa-tests-3-d-printed-rocket-part-to-reduce-future-sls-engine-costs

Goddard SPACE FLIGHT CENTER

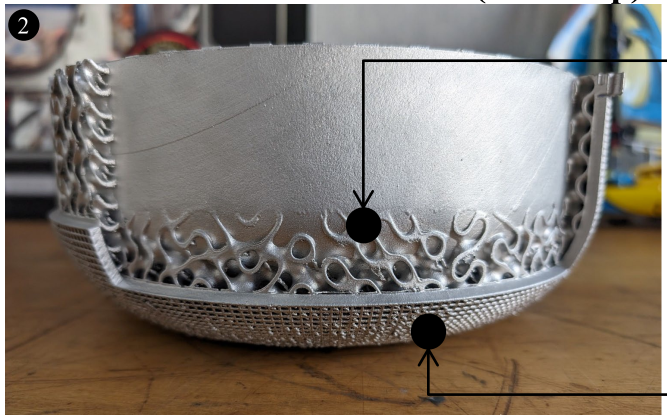
Generative Design & Lattices (GSFC)

https://www.nasa.gov/science-research/nasa-turns-to-ai-to-design-mission-hardware/

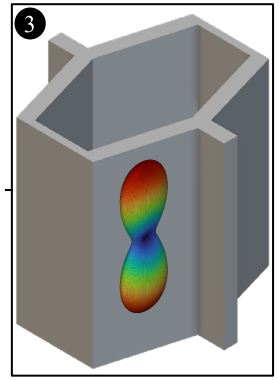
Lattice Structure (Variable Lattice Network)
Metal Additively Manufactured Component



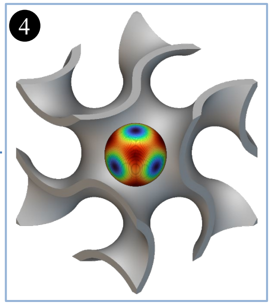
Lattice Structure Network (Close-Up)



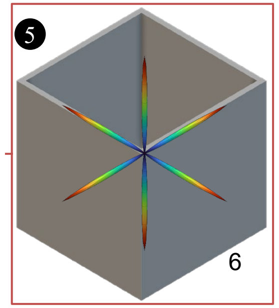
Hexagonal Honeycomb (Internal Stiffness)



TPMS Gyroid (Thermal Efficiency)

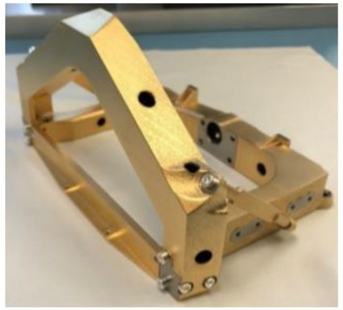


Square Honeycomb (Shock Absorption)



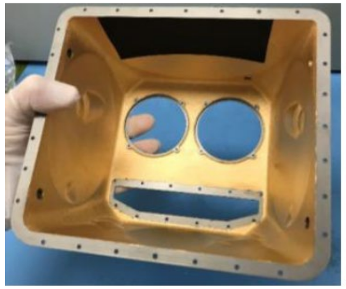
Goddard SPACE FLIGHT CENTER

Approved for Public Release, Distribution Unlimited

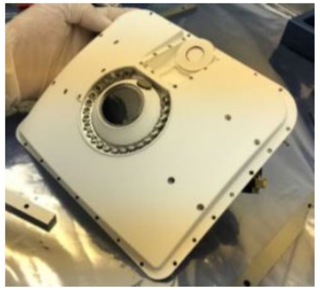


X-ray bench and support

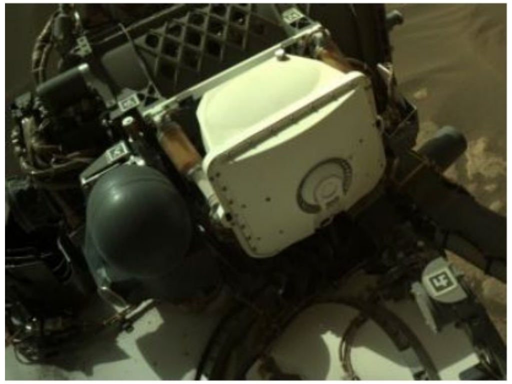
Mounting frame

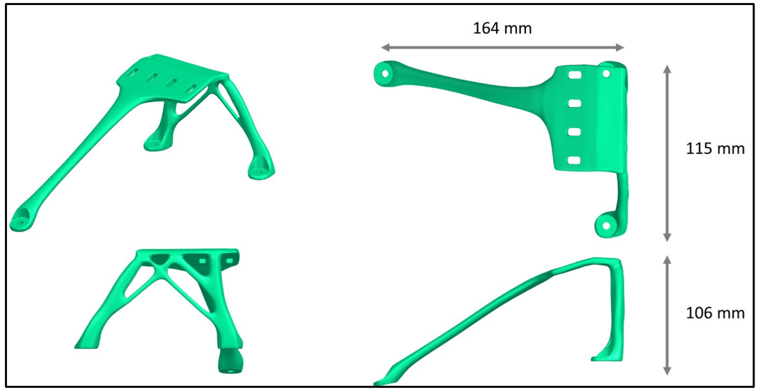


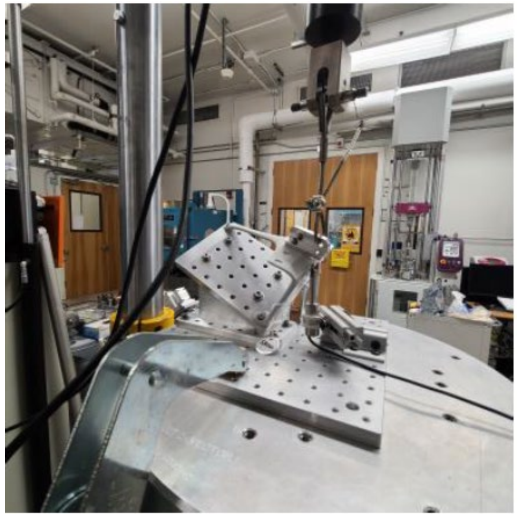
Back cover

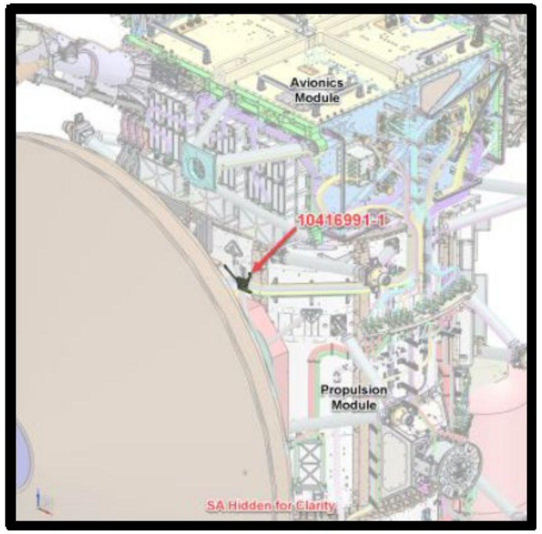


Front cover



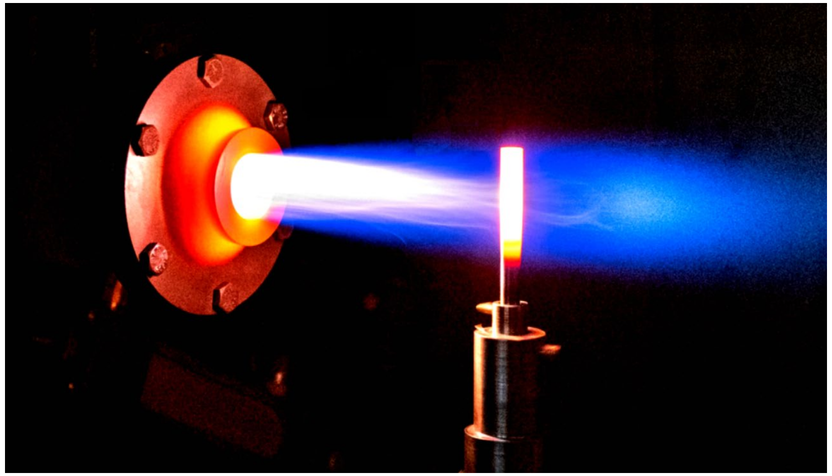


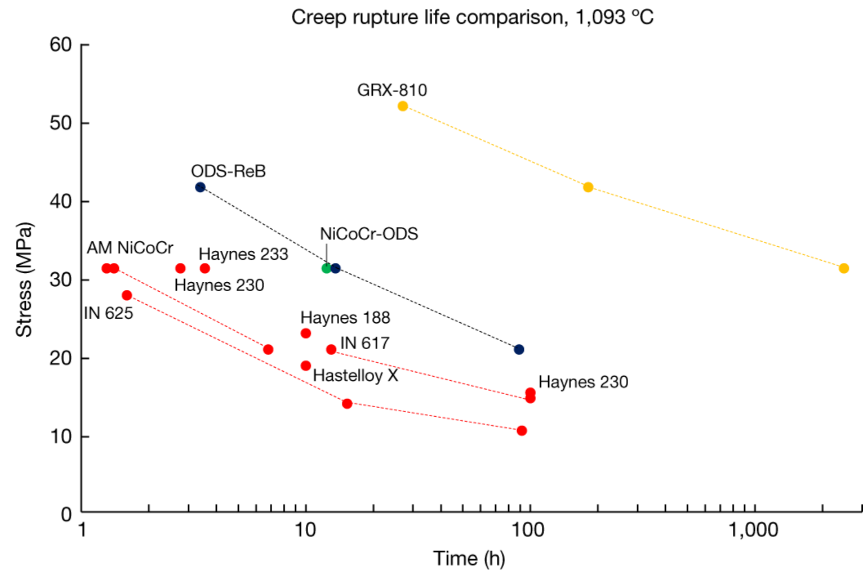


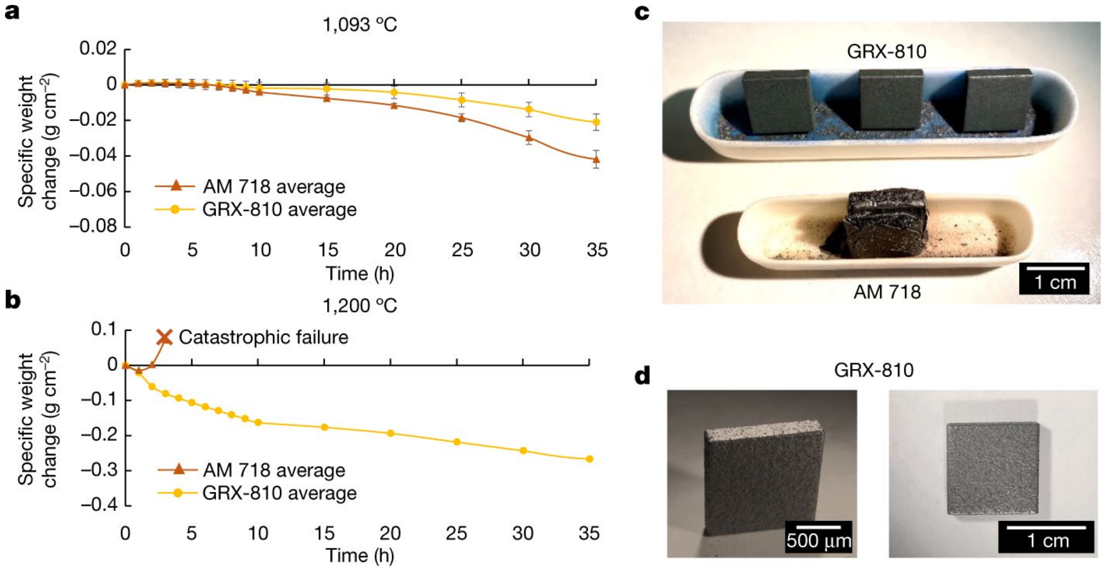


Images courtesy NASA/JPL-Caltech

Research and Development (GRC)







Approved for Public Release, Distribution Unlimited

The Basic Principles of NASA-STD-6030

The "NASA Way"

Disclaimer: “Certification” and “Qualification”

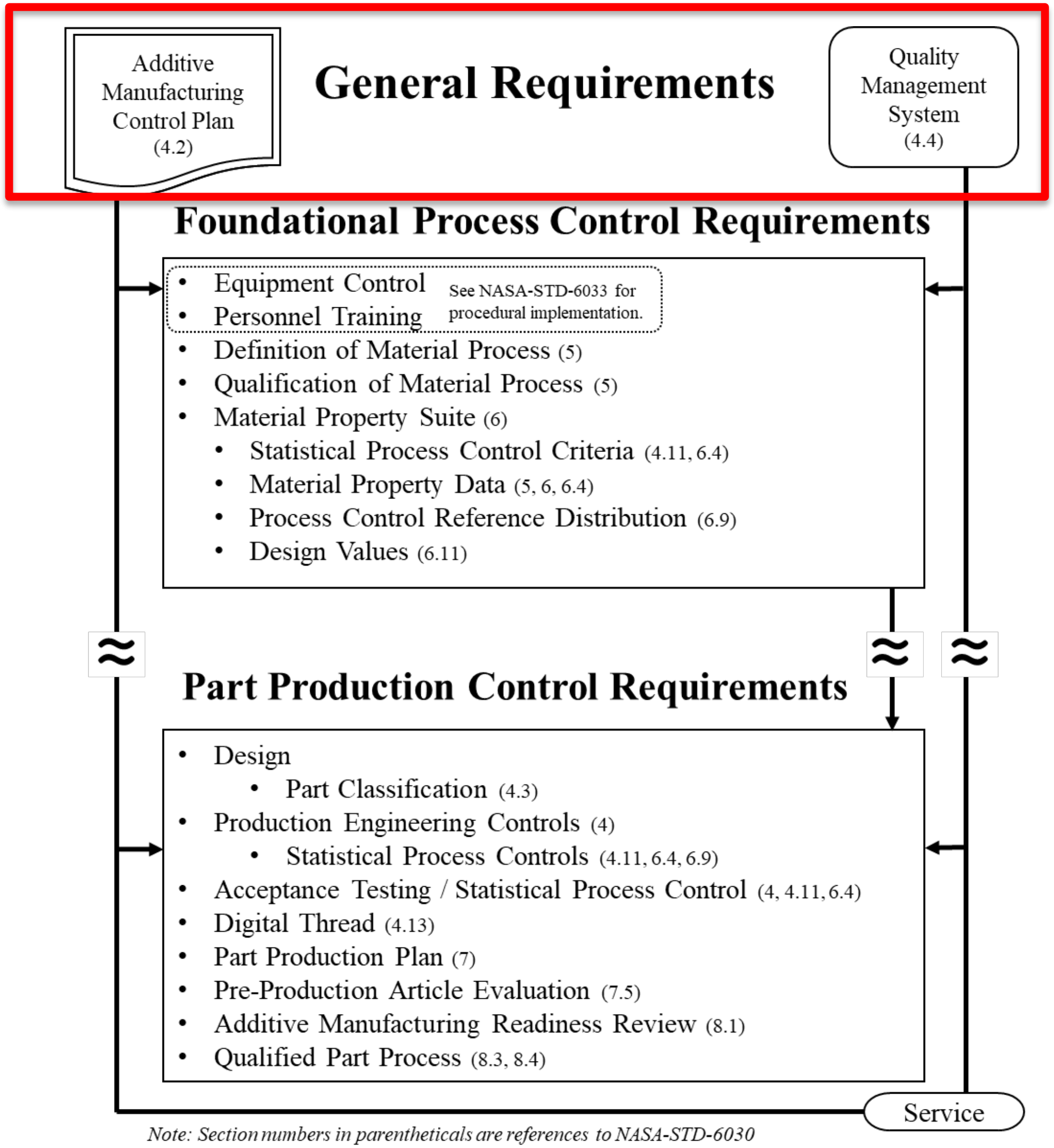
- There is NO centralized Certification or Qualification body at NASA.
- Each individual Program/Project is responsible for “Qualifying*” AM Processes and “Certifying” AM Flight Hardware.
  - *or accepting another projects “qualification”
- There is an informal group of Materials Engineers across the agency who routinely communicate to help ensure that AM requirements are being implemented across the agency as consistently as possible.
- The hope is that by maintaining a single “NASA AM Ecosystem”, the non-recurring engineering costs associated with each new using program or project will be dramatically reduced.

What are the Basic Principles of NASA-STD-6030?

- **Document what you do & follow the documentation**

  4.4.1 Quality Management Systems *– A QMS compliant to SAE AS9100, Quality Management Systems – Requirements for Aviation, Space, and Defense Organizations, or an alternate QMS approved by the CEO and NASA, documented or referenced in the AMCP,* ***shall*** *be in place for all entities involved in the design, production, and post-processing of AM hardware*

- Quality Management System/QMS is mentioned ~100 times in NASA-STD-6030
- Having a well defined and executed QMS is *critical* for the production of high reliability spaceflight hardware.
- Almost every work product mentioned in NASA-STD-6030 must be maintained under configuration/revision control

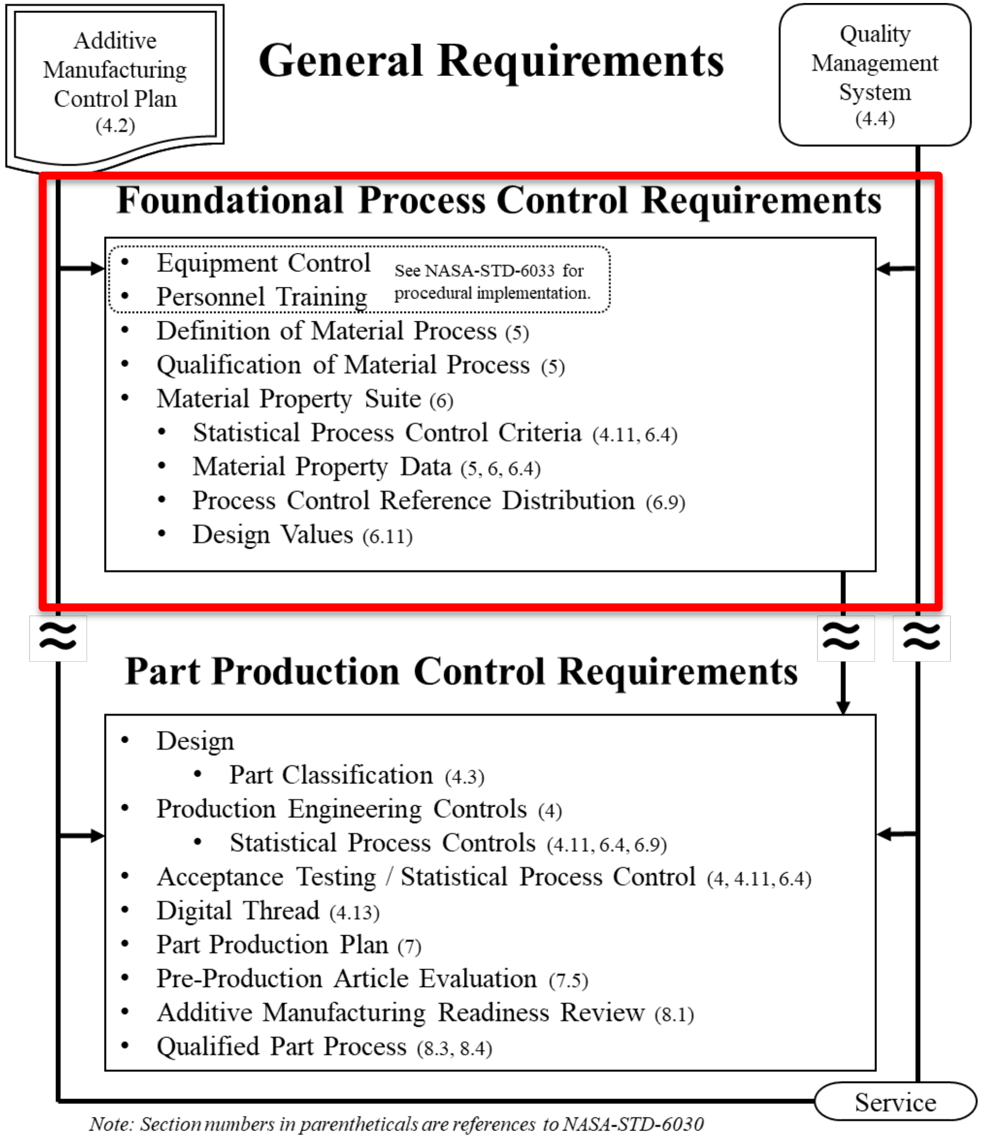


Note: Section numbers in parentheticals are references to NASA-STD-6030 section numbers, unless stated otherwise

What are the Basic Principles of NASA-STD-6030?

- **Document what you do & follow the Documentation**

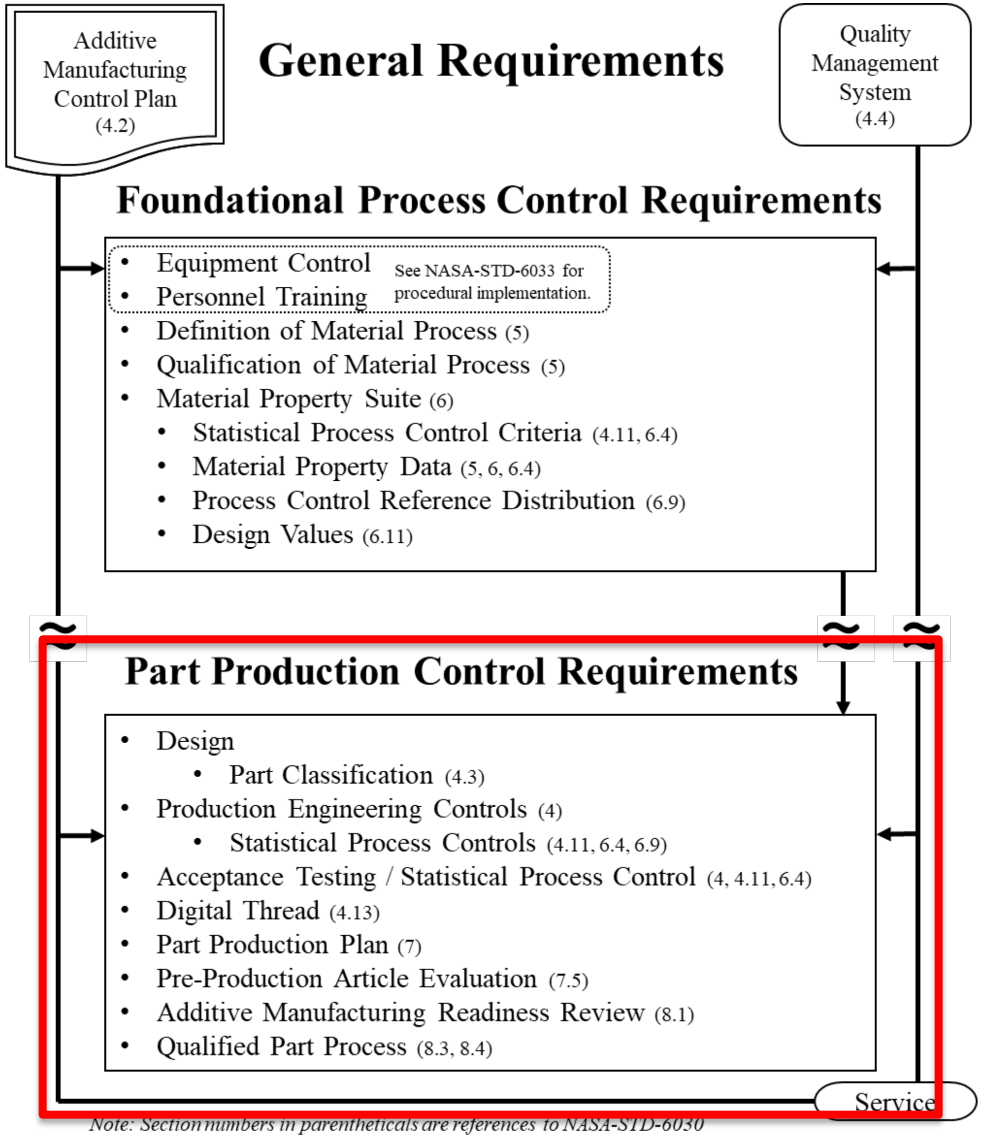
- **Foundational Process Controls**
  - How to define your process
  - How to characterize your process
  - How to monitor your process
  - How to use your process in a design



Note: Section numbers in parentheticals are references to NASA-STD-6030 section numbers, unless stated otherwise

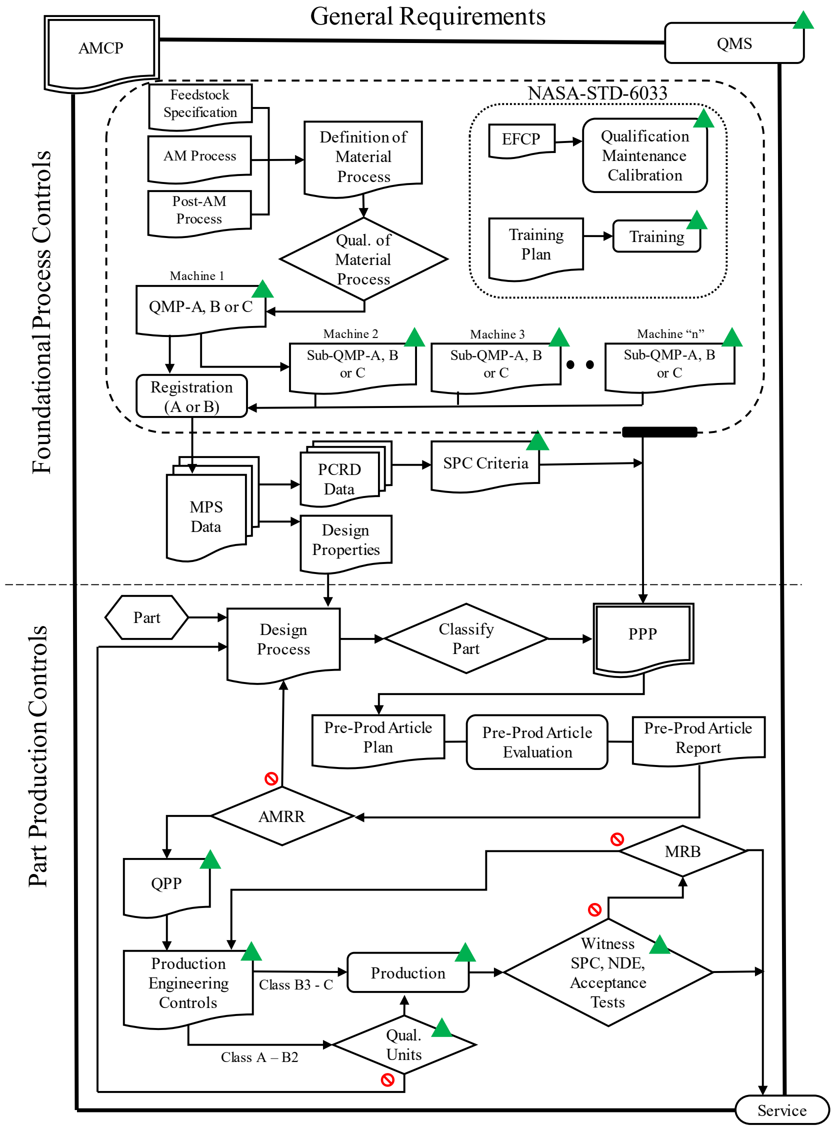
What are the Basic Principles of NASA-STD-6030?

- **Document what you do & follow the Documentation**
- **Foundational Process Controls**
  - How to define your process
  - How to characterize your process
  - How to monitor your process
  - How to use your process in a design
- **Part Production Controls**
  - How to document *why* AM works for your part
  - How to plan to make your part
  - How to qualify your part
  - How to make your part successful



Note: Section numbers in parentheticals are references to NASA-STD-6030 section numbers, unless stated otherwise

Where is the Quality in (AM) Qualification?

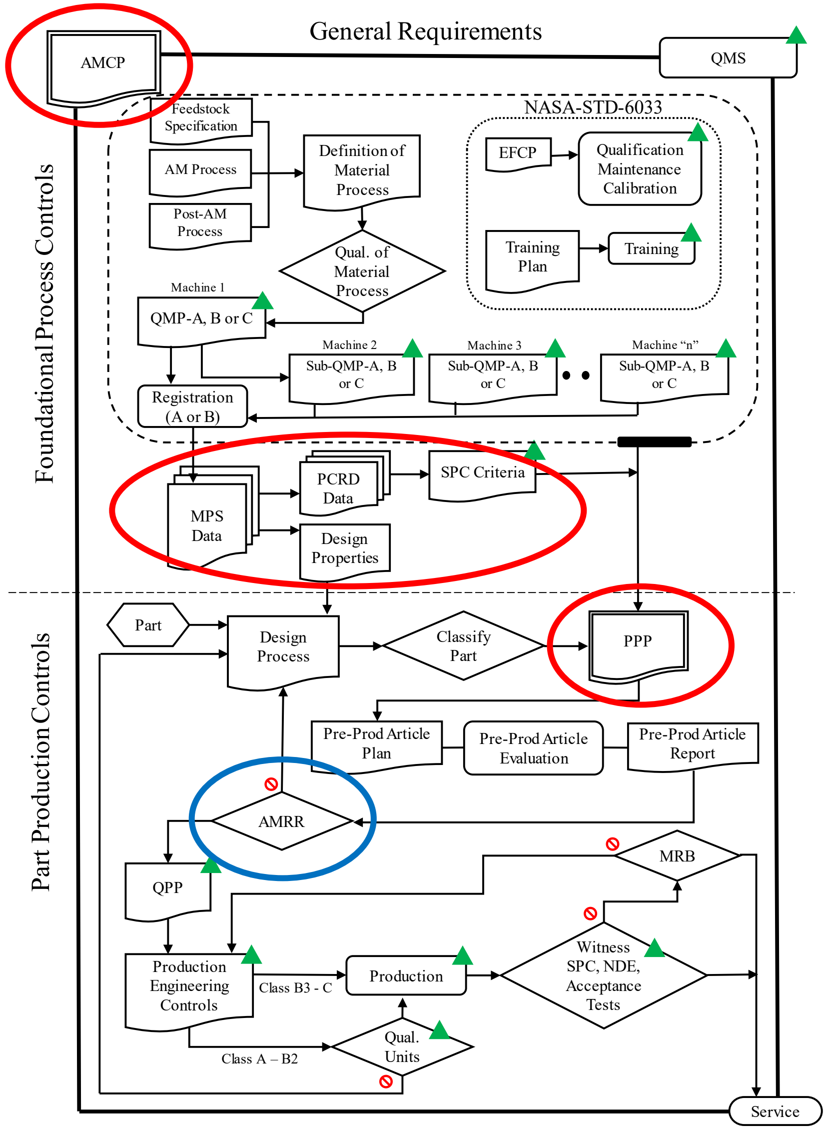


Approved for Public Release, Distribution Unlimited

Where is the Quality in Qualification?

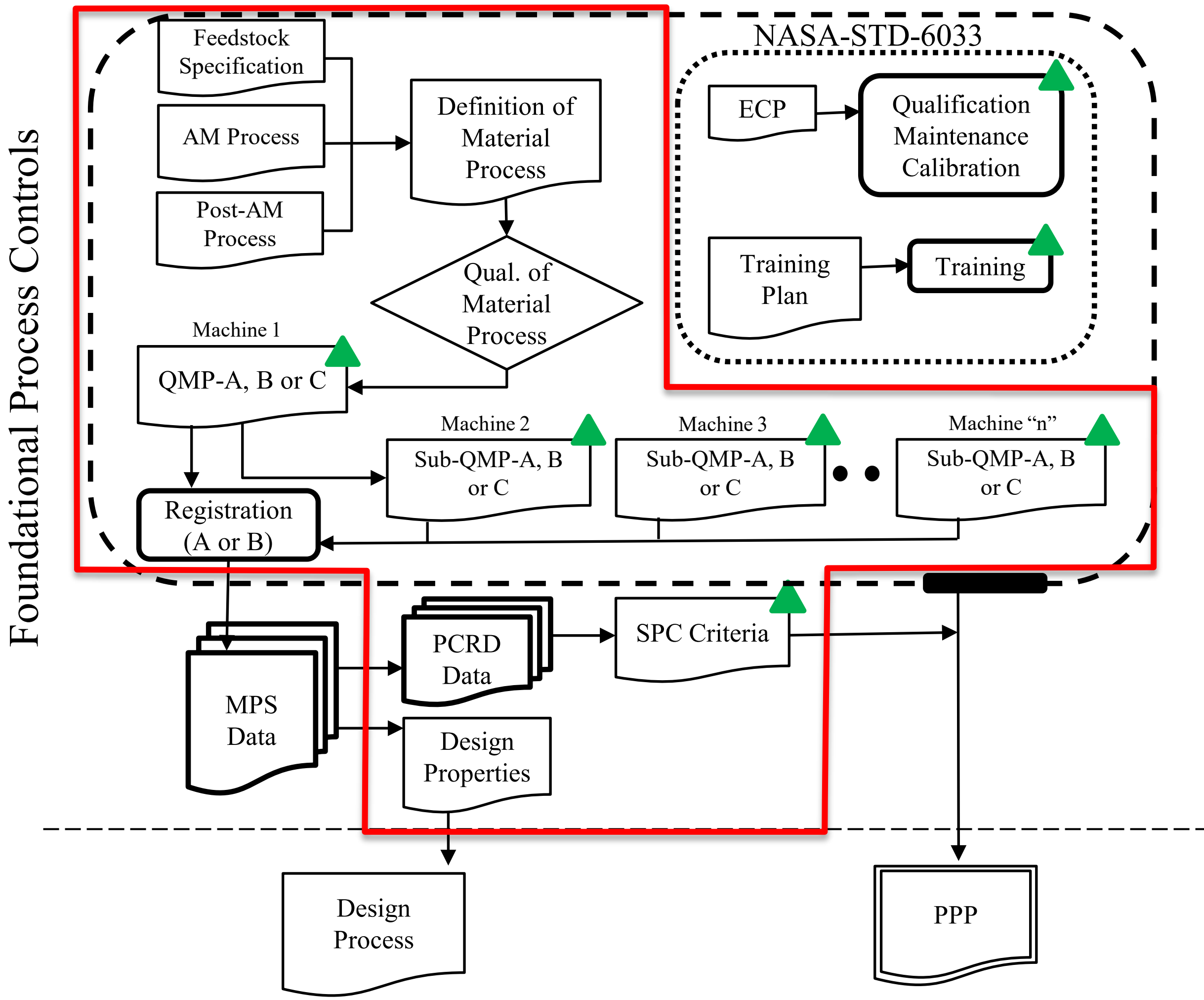
- There are only three deliverables:
  1. Additive Manufacturing Control Plan (AMCP)
  2. Material Property Suite (MPS) via an MUA
  3. Part Production Plan (PPP)

- In many/most cases NASA is expected to be invited to the Additive Manufacturing Readiness Review (AMRR)
  – NASA's attendance is only required for Class some Class A Parts
  – NASA Approval is NOT required



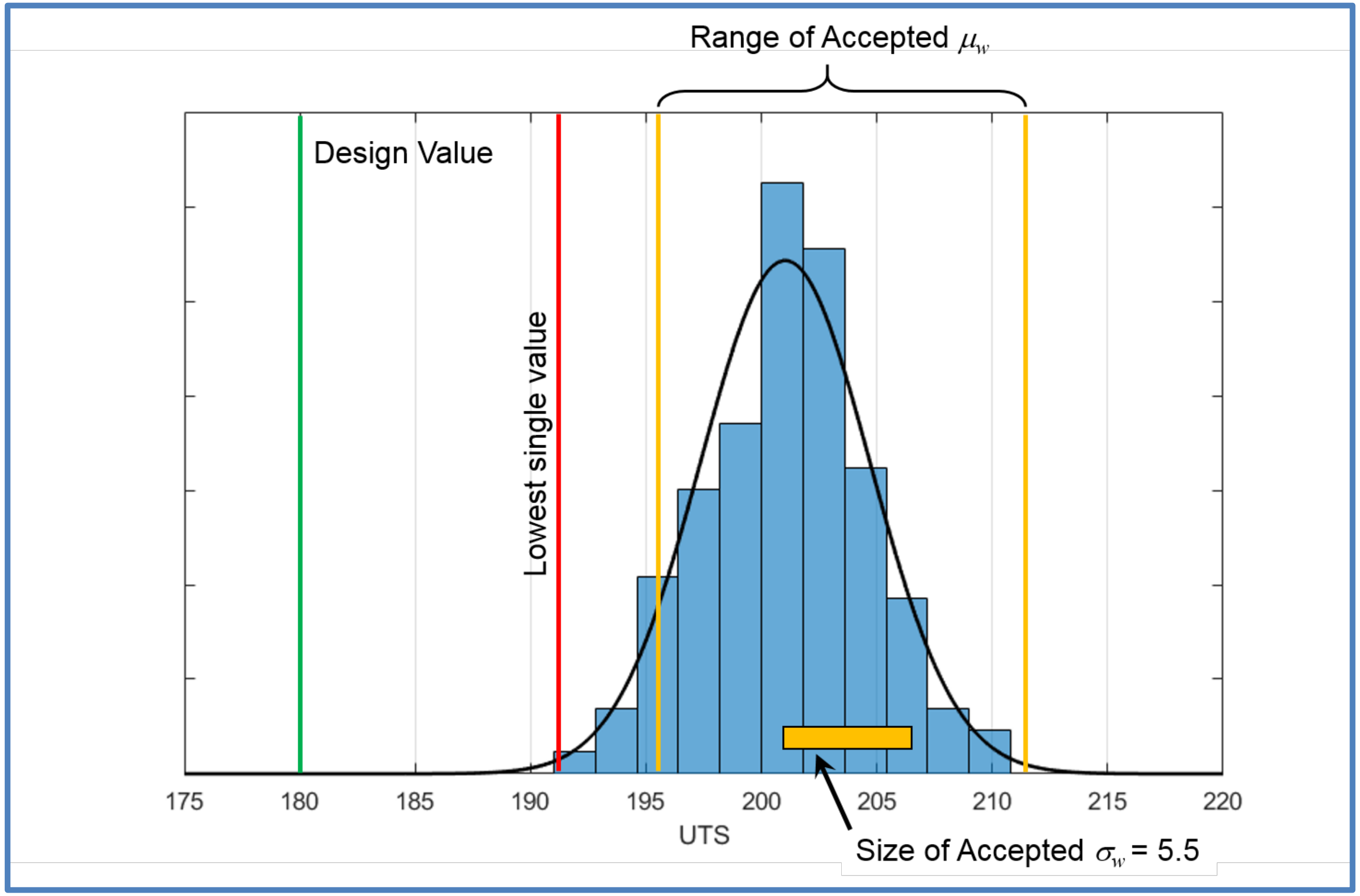
Where is the Quality in Qualification?

- A Qualified AM Process begins as a Candidate QMP
- Defines aspects of the basic, *part agnostic*, fixed AM process:
  - Feedstock
  - Fusion Process
  - Thermal Process
- Enabling Concept
  - Machine qualification and re-qualification, monitored by…
  - Process control metrics, SPC, all feeding into…
  - Design values
- Quality Engineering plays a vital part
  - Needs to ensure everything is documented and followed
  - However, NASA doesn't have direct oversight of this facet of an AM program in the vendor base



Where is the Quality in Qualification?

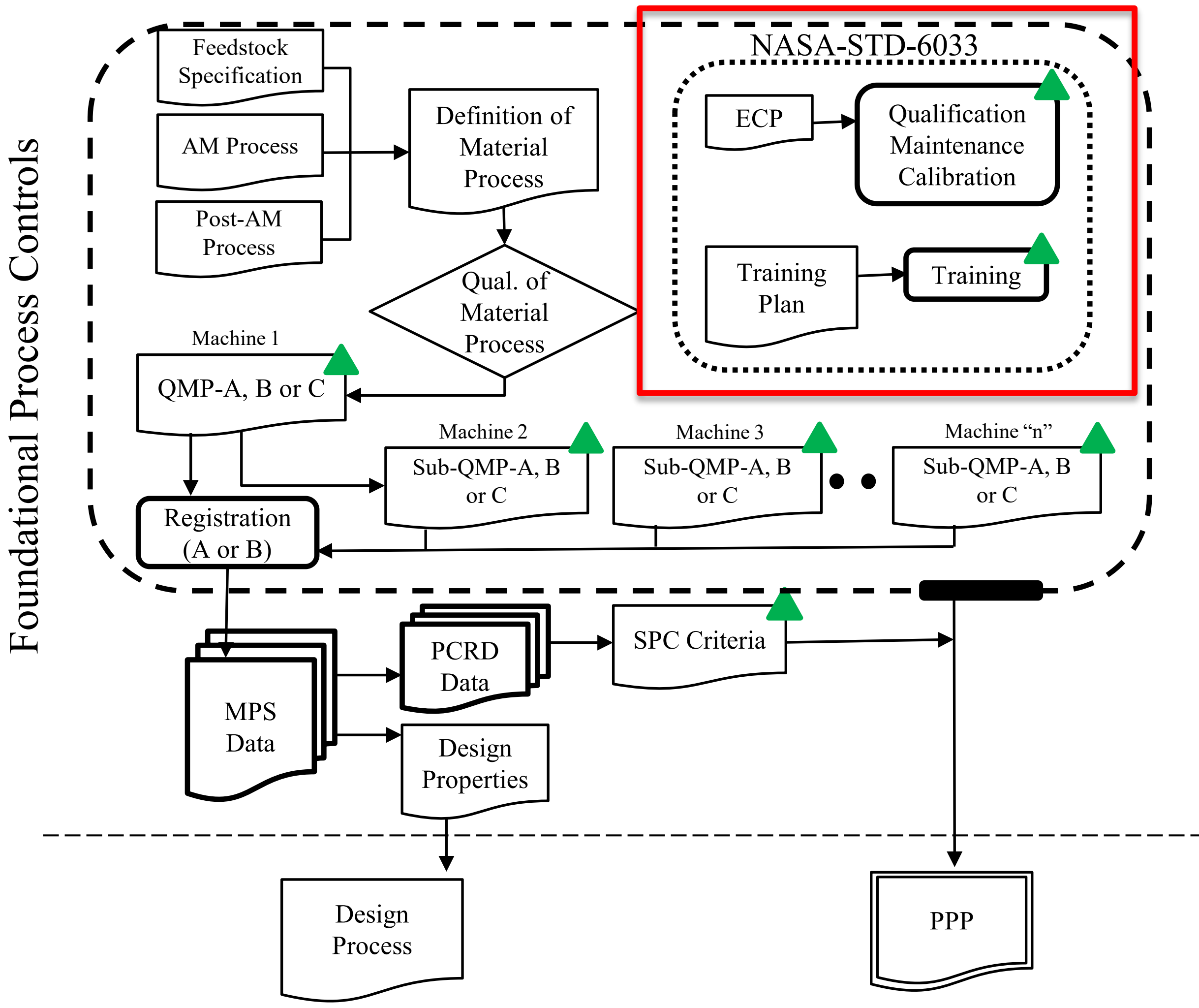
- Witness test acceptance is not intended to be based upon design values or "specification minimums"
- Acceptance is based on witness tests reflecting properties in the MPS used to develop design values
- Suggested approach
  - Acceptance range on mean value
  - Acceptance range on variability (e.g., standard deviation)
  - Limit on lowest single value



Goddard SPACE FLIGHT CENTER

Where is the Quality in Qualification?

- NASA-STD-603<u>3</u> deals with everything that has to do with the Additive Manufacturing *Facility.*
- Fundamentally, the requirements on an AM Factory are no different than any other
- Third-party AS9100 certification will get you 99% of the way there.



Goddard Space Flight Center

Qualification Challenges for Additive Manufacturing Processes and Parts

Goddard
SPACE FLIGHT CENTER

What are the major stumbling blocks?

- Using additive manufacturing where it makes sense
- NASA-STD-6030 is *Looooooooong*
- Lack of an integrated design, procurement, & manufacturing team
- Intellectual property & prior contracts

Additive Manufacturing is Not Here to Save You

- You have a fully designed part
- You need it to be good
- You need it to be cheap
- You need it quickly

Additive Manufacturing is Not Here to Save You

- ~~You have a fully designed part~~
- ~~You need it to be good~~
- ~~You need it to be cheap~~
- ~~You need it quickly~~

Recipe for Disappointment

Additive Manufacturing is Not Here to Save You

- ~~You have a fully designed part~~
- ~~You need it to be good~~
- ~~You need it to be cheap~~
- ~~You need it quickly~~
- You need to prototype and/or iterate a *lot*
- You need an *extremely* optimized part (i.e., topology optimization)
- You can't easily make the part using legacy "subtractive manufacturing"
- You need a part with a high "buy to fly" ratio

Additive Manufacturing is Not Here to Save You

- ~~You have a fully designed part~~
- ~~You need it to be good~~
- ~~You need it to be cheap~~
- ~~You need it quickly~~
- You need to prototype and/or iterate a *lot*
- You need an *extremely* optimized part (i.e., topology optimization)
- You can't easily make the part using legacy "subtractive manufacturing"
- You need a part with a high "buy to fly" ratio
- **You literally *can't* make it any other way**
- **You want to decrease part count**

One Requirement at a Time

- NASA-STD-6030
  - 138 pages
  - 115 unique "shall statements"
  - Additive Manufacturing Control Plan

- NASA-STD-6033
  - 31 pages
  - 31 unique "shall statements"
  - Equipment and Facility Control Plan

Additive Manufacturing Control Plan

- NASA is NOT trying to tell fabricators exactly *how* to utilize AM (mostly)

- NASA *is* telling you all the things you have to:
  - **Think about** Sometimes the Stupid Questions are the most important
  - **Define** If you haven't defined something, you can't do it again
  - **Control** Without controls, how do you know you're doing it
  - **Monitor** Controlling something doesn't mean it can't go *wrong*

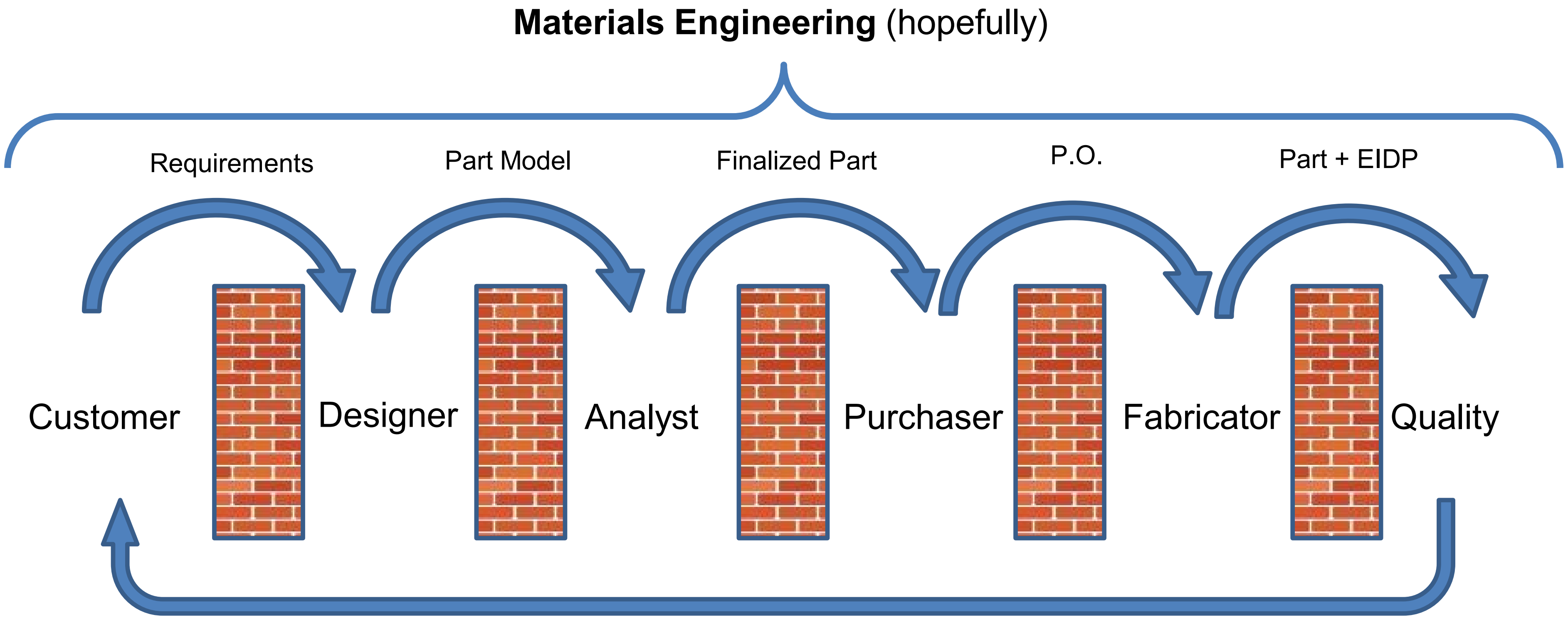
- An Additive Manufacturing Control Plan is how you document how you do AM *for yourself* and *communicates it to your customers*.

"Remember kids, the only difference between screwing around and science is writing it down"

-Adam Savage (Mythbusters)

An Integrated Multidisciplinary TEAM

- You can not throw an AM design "over the wall" (yet)



An Integrated Multidisciplinary TEAM

- You can not throw an AM design “over the wall” (yet)
- All stakeholders need a seat at the table *concurrently*

Approved for Public Release, Distribution Unlimited

Intellectual Property & Prior Contracts

A lot of people have spent a lot of money figuring out AM…

1. Customer
   - e.g., NASA
2. Cognoscente Engineering Organization (CEO)
   - i.e., might be the same as the Customer
3. Fabricator
   - i.e., might be the *same* as the CEO…might be separate company

Hoarding Knowledge Helps No One

- Hoarding knowledge isn't really an issue for vertically integrated organizations

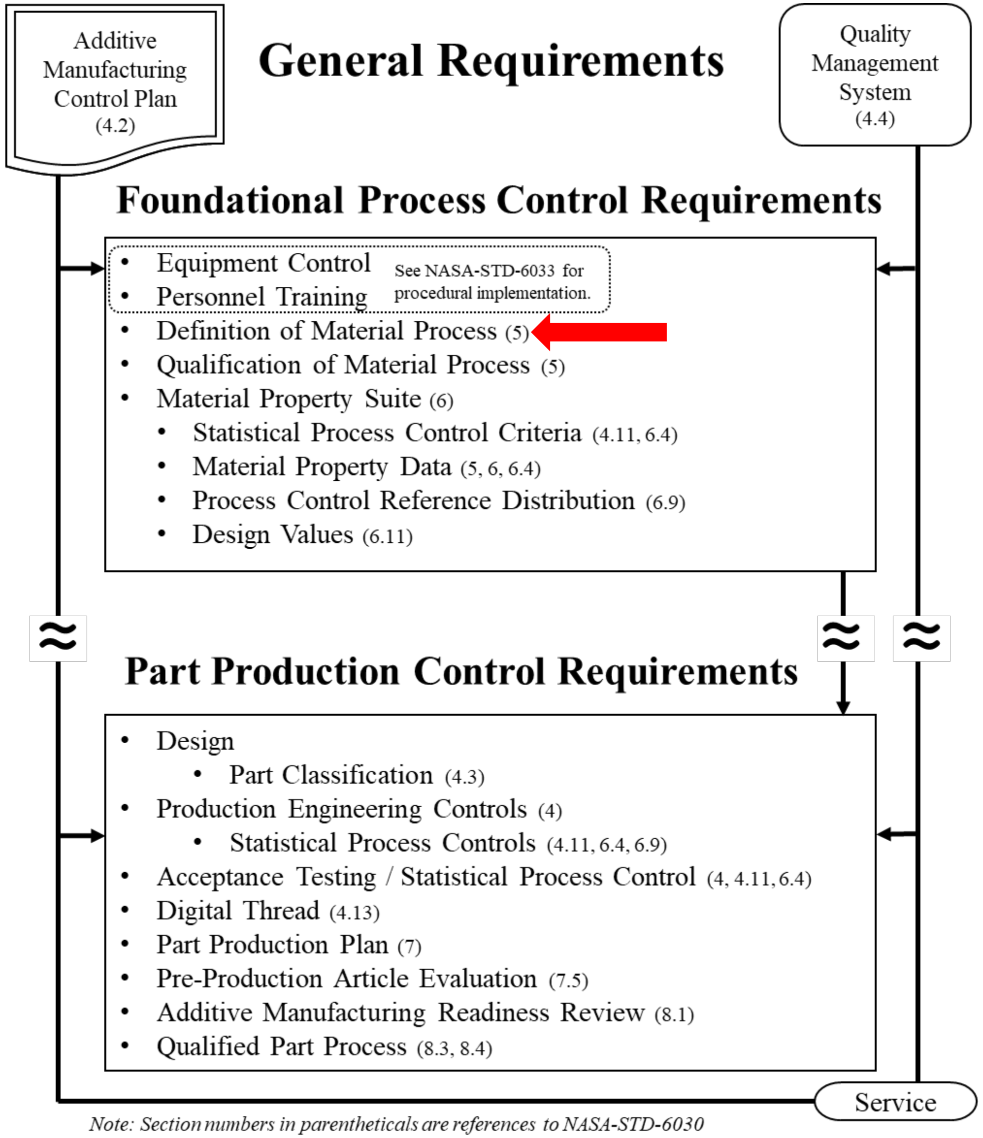
- If the Designer *is* the Fabricator, the inability to share information (usually) isn't a problem.

- Please Remember: For most Aerospace/Advanced Manufacturing applications, you still need to make most things "available upon request" to your customers
  - In most situations, you can require the customer to come to *you* to do it

But when the CEO *is NOT* the Fabricator

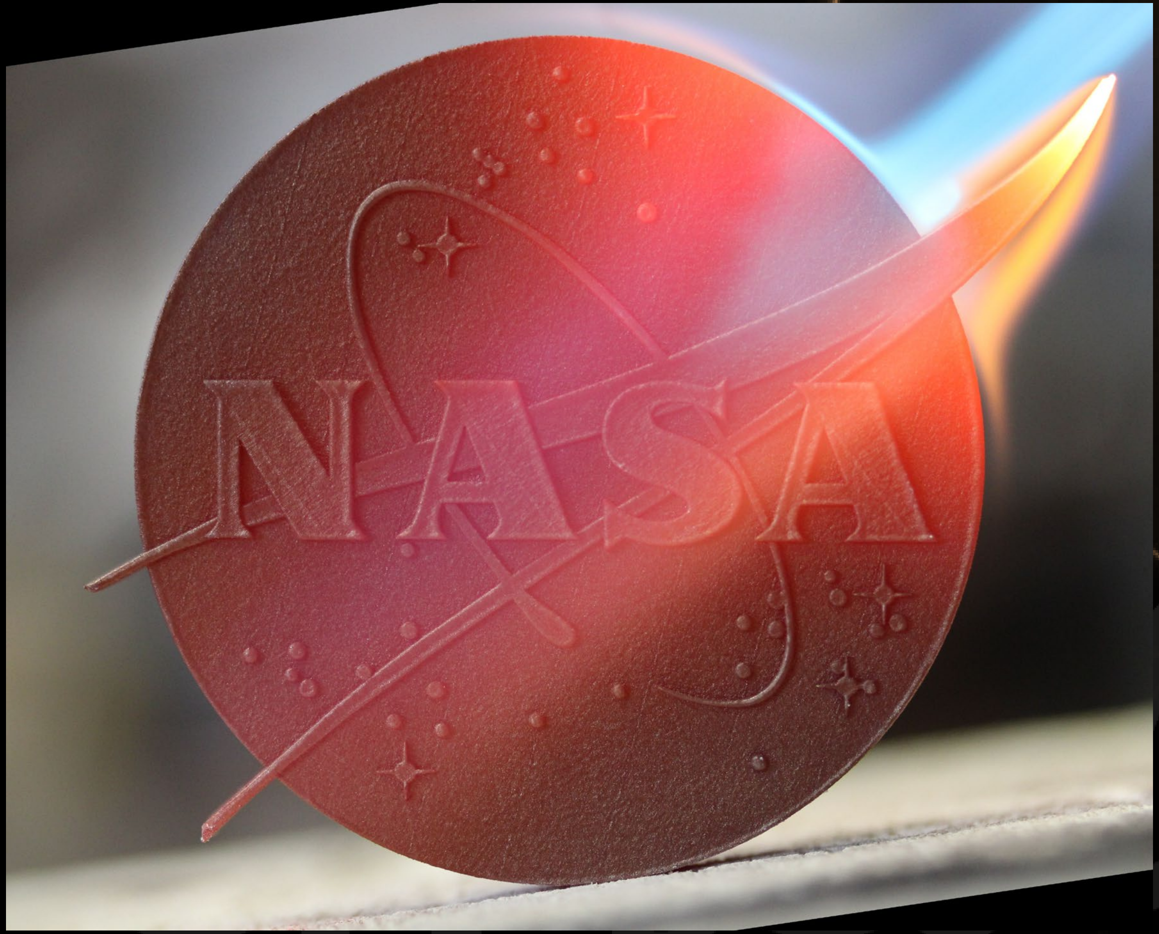
Hoarding Knowledge Helps No One

- By *far* the biggest roadblock for the author’s organization are prior contracts in our potential vendor base
- Many if not most fabricators have entered into agreements where they don’t actually own the Intellectual Property associated with the processes they use in their own facility. (or at least they’ve convinced themselves that’s the case)
- Tensile Data alone, does not a competitive advantage make
- AM Process Parameters and Post Processing Specifications are a more understandable problem, but still make things difficult.
- Shackling your vendors will NOT help you or your partner fabricators in the long run
- The widespread utilization of successful AM processes is in EVERYONE’S best interest, even if its at a competitor
- **The more AM is used *generally*, the more *your* customers will be comfortable using *your* technologies**



Note: Section numbers in parentheticals are references to NASA-STD-6030 section numbers, unless stated otherwise

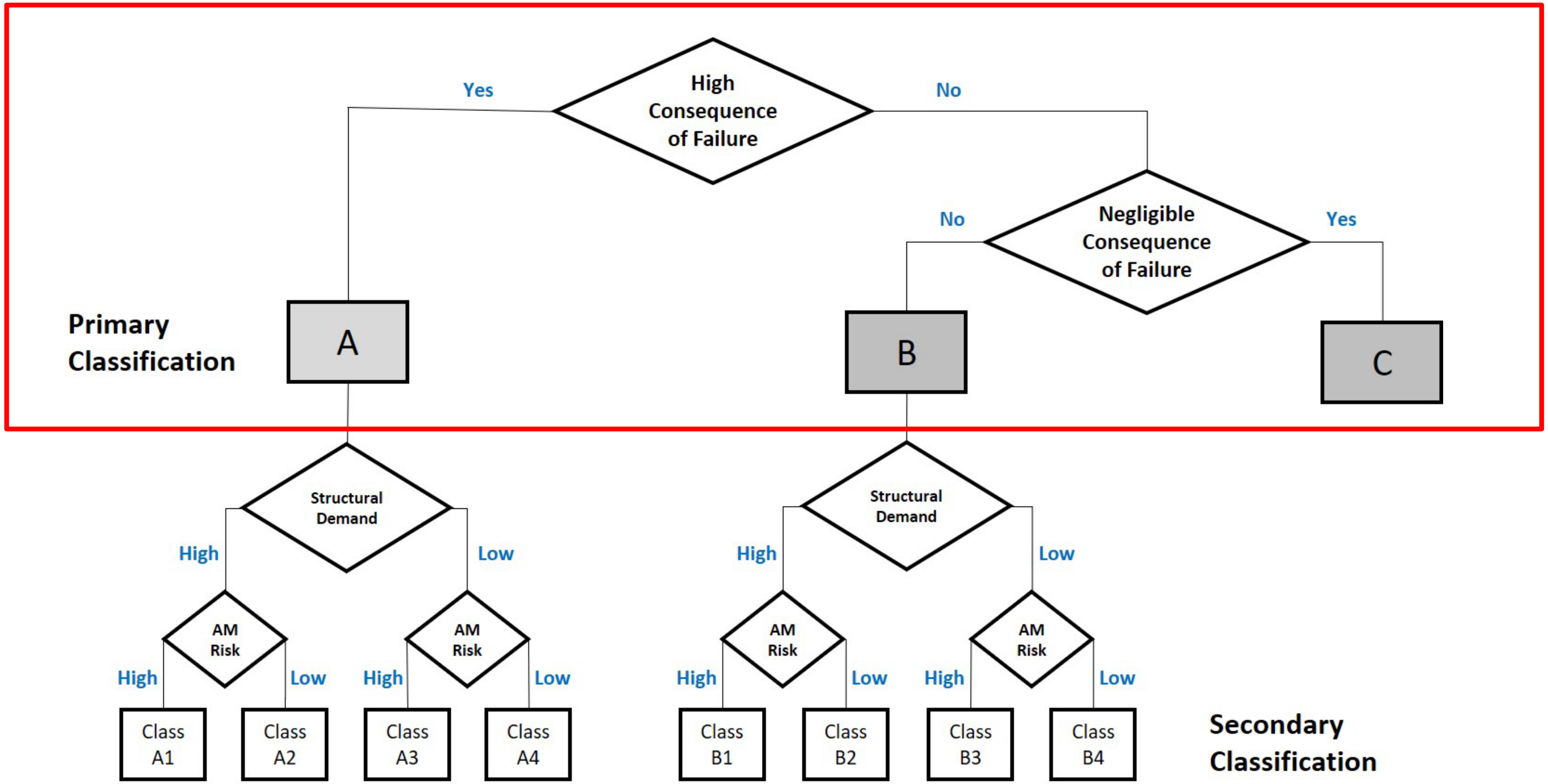
Thank you for your time!



Goddard
SPACE FLIGHT CENTER

Backup

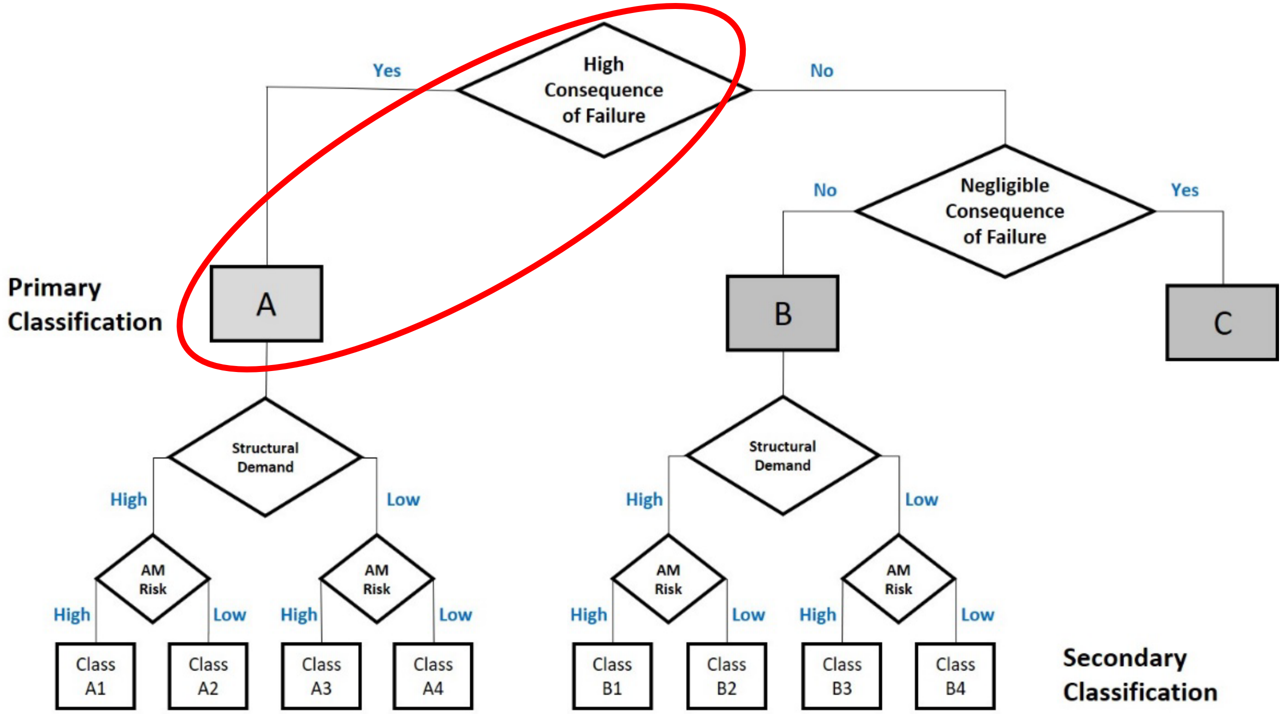
Classification



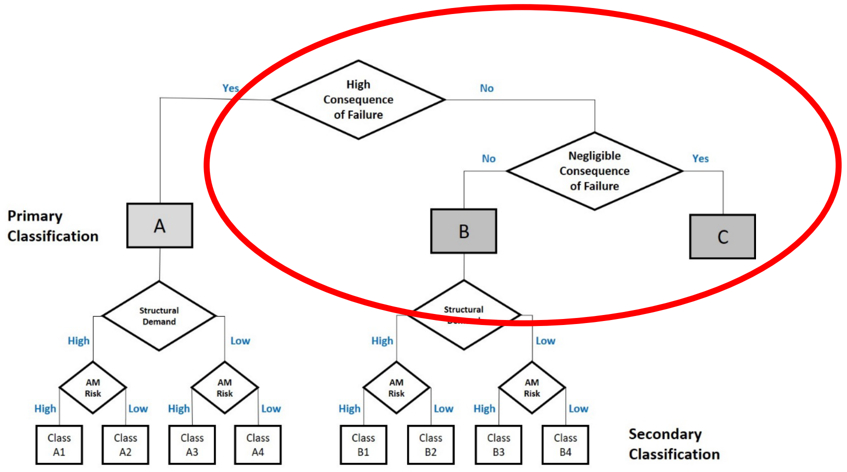
High Consequence of Failure

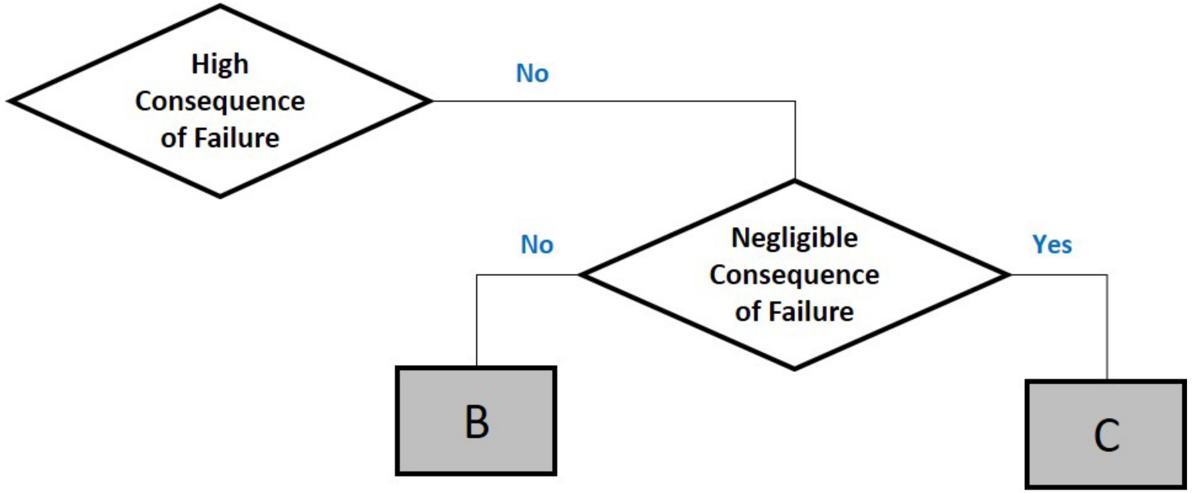
- A part **shall** be designated as Class A, High Consequence of Failure, if failure of the part leads to a **catastrophic**, **critical**, **or** **safety hazard** and/or the part is **defined as mission critical by the program or project**.

- Class A parts **shall not**:
  - Be made from polymeric materials
  - Be fasteners
  - Contain printed threads.



Negligible Consequence of Failure





- Parts not designated Class A or Class C **shall** be designated as Class B.
- Class B parts **shall** not:
  - Be fasteners
  - Contain printed threads.

Negligible Consequence of Failure

- A part **shall** be designated as Class C, Negligible Consequence of Failure, provided that ALL of the following criteria are satisfied:
  - Failure of part does not lead to any form of hazardous condition.
  - Failure of part does not eliminate a critical redundancy.
  - Part does not serve as primary or secondary containment.
  - Part does not serve as redundant structures for fail-safe criteria per NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware.
  - Part is not designated "Non-Hazardous Leak Before Burst" per NASA-STD-5019.
  - Failure of part does not cause debris or contamination concerns, as defined by the Non-Fracture Critical Low-Release Mass classification per NASA-STD-5019, NASA-STD-6016, and/or other project/program requirements.
  - Failure of part causes only minor inconvenience to crew or operations.
  - Failure of part does not alter structural margins or related evaluations on other hardware.
  - Failure of part does not adversely affect other systems or operations.
  - Failure of part does not affect minimum mission operations.

NASA Space Nuclear System Safety and Authorization Activities for Lunar Missions

Don Helton & Matt Forsbacka,
NASA/OSMA

TRISMAC

Trilateral Safety and Mission Assurance Conference 2024

24–26 June 2024
ESA-ESRIN | Frascati (RM), Italy

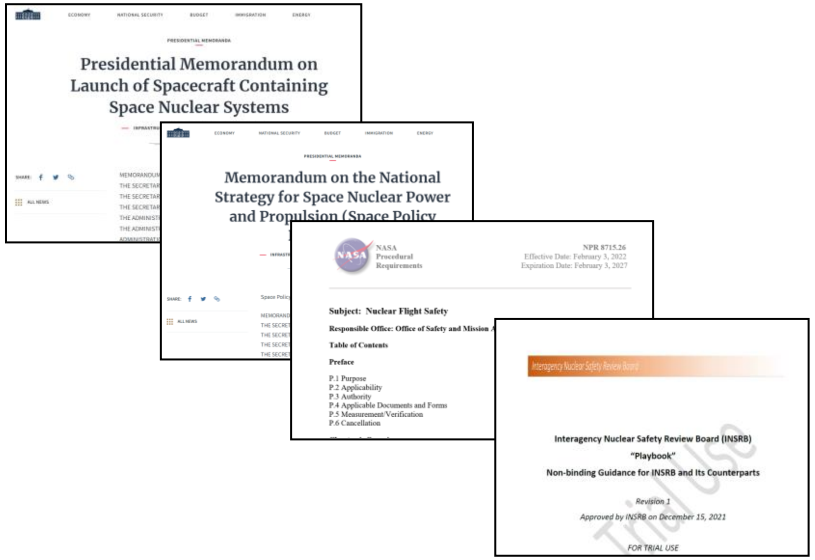
Types of devices

- Incidental (small) sources (e.g., calibration sources)
- Industrial-use sources (e.g., radiography)
- Equipment that generates ionizing radiation (e.g., irradiators)
- Radioisotope power systems (for heat and electricity)
- Fission systems (a.k.a., reactors)
- Fusion devices

The focus of this presentation

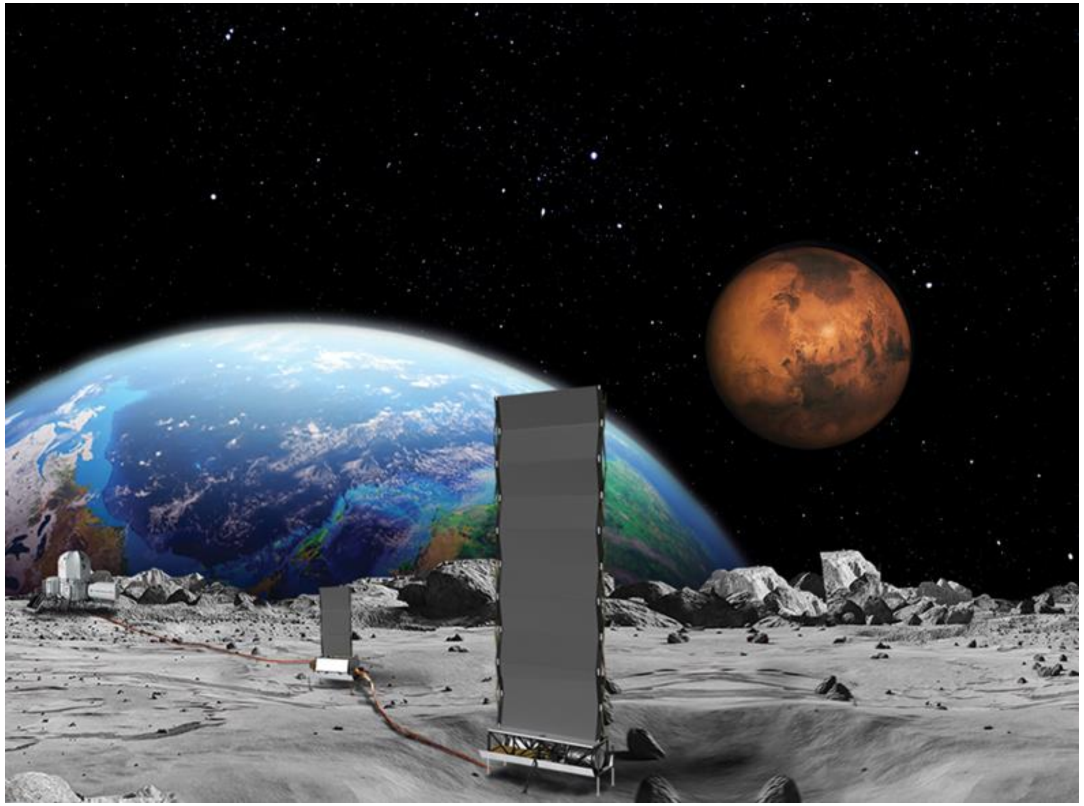
Applicable U.S. and NASA Safety Policy

- National Security Policy Memorandum No. 20
- Space Policy Directives No. 1 and No. 6
- NASA NPR 8715.26
  - supported by NASA-HDBK-8715.26
- Interagency Nuclear Safety Review Board



Technology Demonstration – Fission Surface Power

- NASA, Department of Energy, industry
- 40-kilowatt class fission system to operate on the Moon by the early 2030s
- High-assay low-enriched uranium



A concept image of NASA’s Fission Surface Power Project, as of January 2024.
Credit: NASA

Technology Development - Survive-the-Lunar-Night

- Tipping Point Award - Harmonia Radioisotope Power Supply for Artemis
  - Zeno Power and partners - Am-241 isotope with Stirling dynamic power conversion
- Recent Small Business Award Examples:
  - Ultra Safe Nuclear Corporation – Technologies Affordable In-Space Demonstration of Dynamic Radioisotope Power Conversion
  - Advanced Cooling Technologies, Inc. - Additively Manufactured Ceramic Heat Pipes for Space Nuclear Reactors
  - Direct Kinetic Solutions - Modular Radioisotopic Power Sources
- Lunar Surface Innovation Consortium – Surface Power Focus Group

System Deployment

- Earth launch:
  - Use of conventional chemical-based lift and heavy-lift vehicles
  - Government-sponsored or commercial services
- Lunar landing (potential options):
  - Commercial Lunar Payload Services Program
  - Human Landing System Program
  - Others

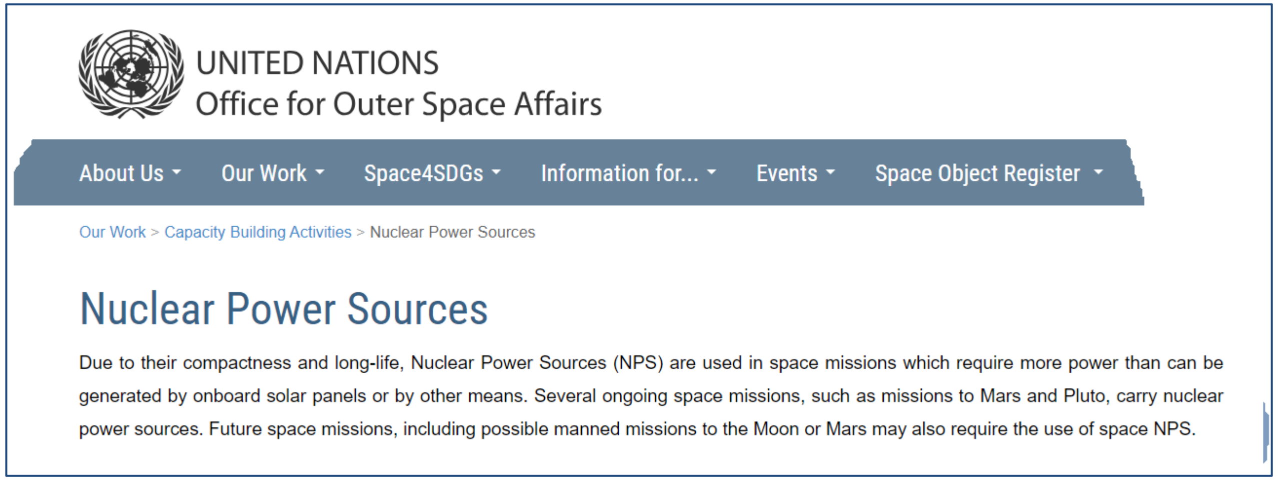
Mars 2020 launch
July 2020

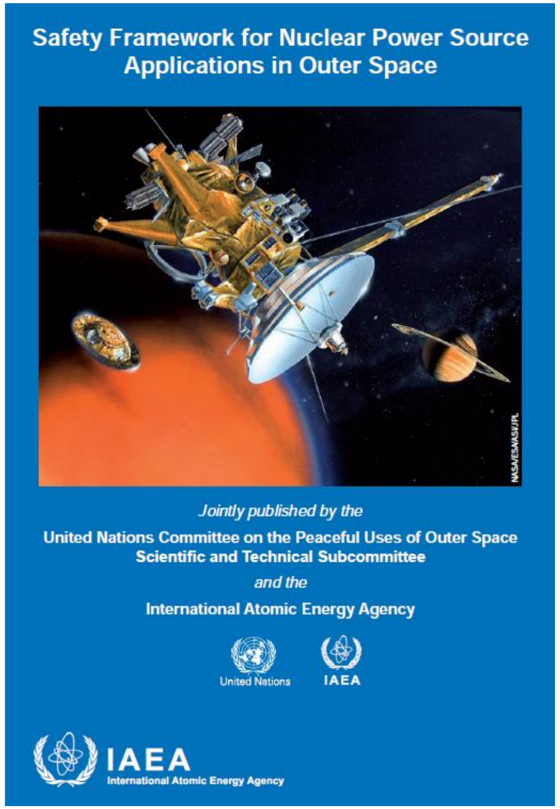
NASA's Involvement in U.S. Harmonization Activities

- Range and flight safety
  - NASA, Department of Defense, Federal Aviation Administration
  - Common Standards Working Group
  - Better align NASA, Space Force, and commercial licensing process for launch
- Whole-of-government ("Regulatory Harmonization Pathfinder") –
  - Forum for 12 affected agencies to discuss the integrated government roles and responsibilities in novel contexts

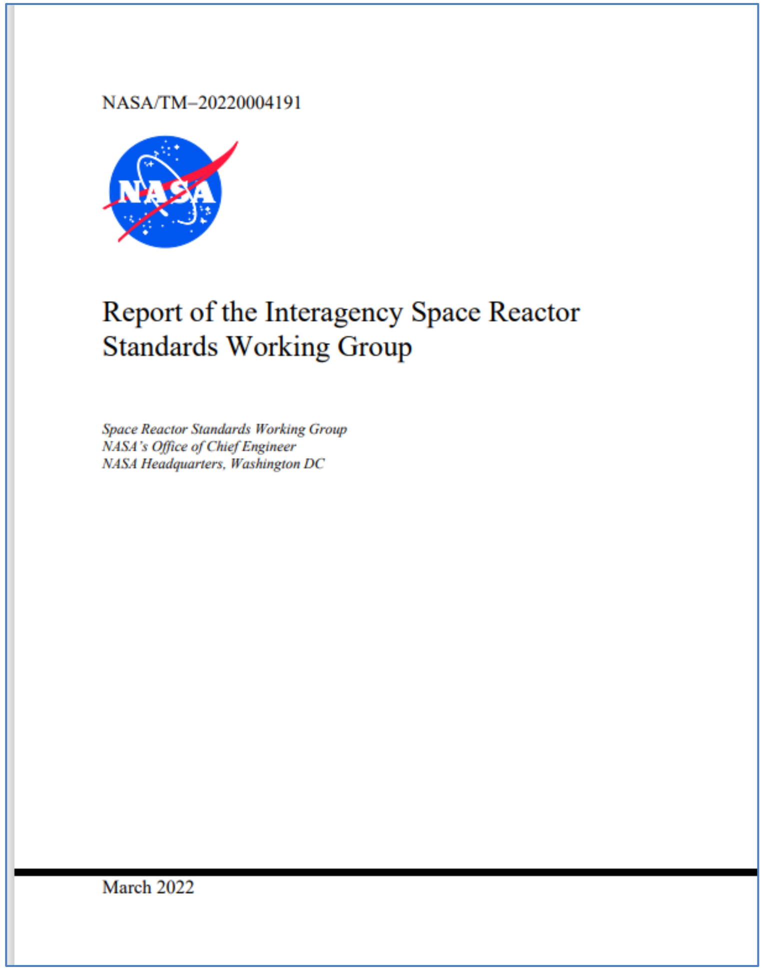
NASA's Involvement in International Harmonization Activities

- UN COPUOS Scientific and Technical Subcommittee on Nuclear Power Sources
- International Space Exploration Coordination Group
- Bilateral agreements
- Etc.





NASA's Involvement in Voluntary Consensus Standards



NASA/TM–20220004191

Report of the Interagency Space Reactor Standards Working Group

Space Reactor Standards Working Group
NASA's Office of Chief Engineer
NASA Headquarters, Washington DC

March 2022

NASA/TM−20220004191, March 2022, publicly available

- ASTM International Task Group
  - Safe Operating Practices In-Space for Space Reactors
- American Nuclear Society
  - Testing and Facility Practices for Terrestrial Testing of Space Reactors

Opportunities for NASA/JAXA/ESA Cooperation

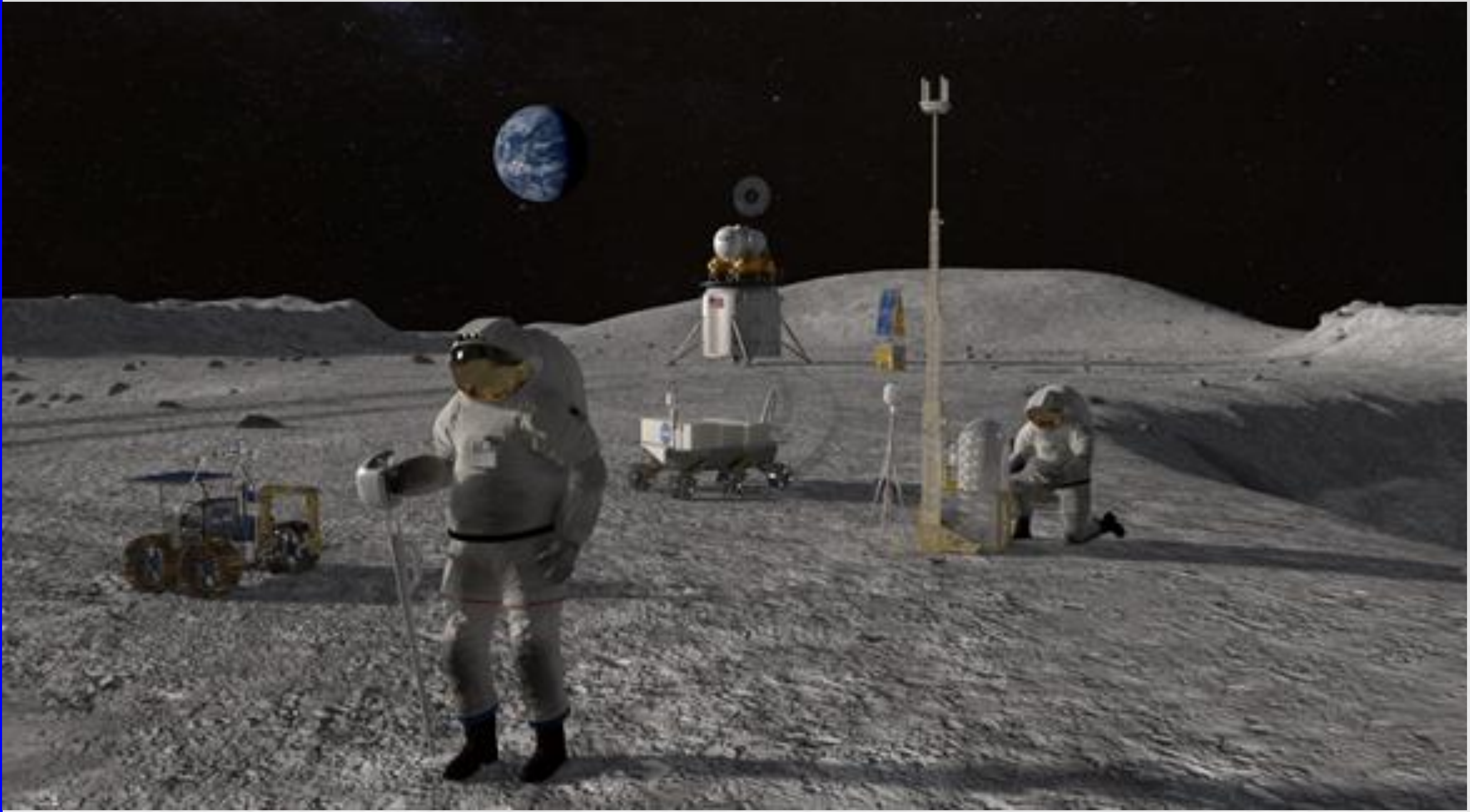
- Aligning agency policies and practices
- Continued collaboration on specific missions
- International forums
- International Standards

Moon to Mars:
Exploration Atmosphere

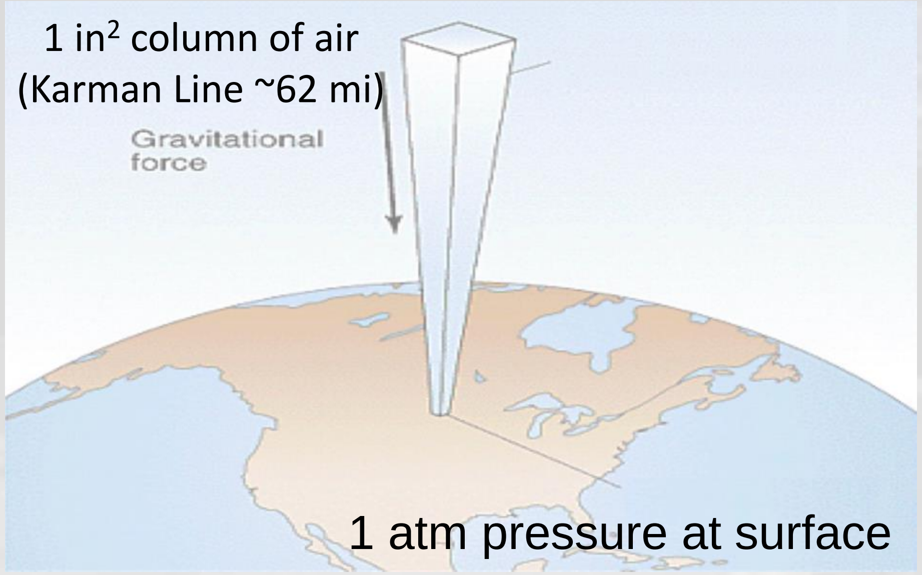
Trilateral Safety and Mission Assurance Conference
June 22, 2024

Marlei Walton, PhD, MSE
marlei.walton@nasa.gov
Jason Norcross, MS

Moon to Mars: Exploration Atmosphere



Atmospheric Composition



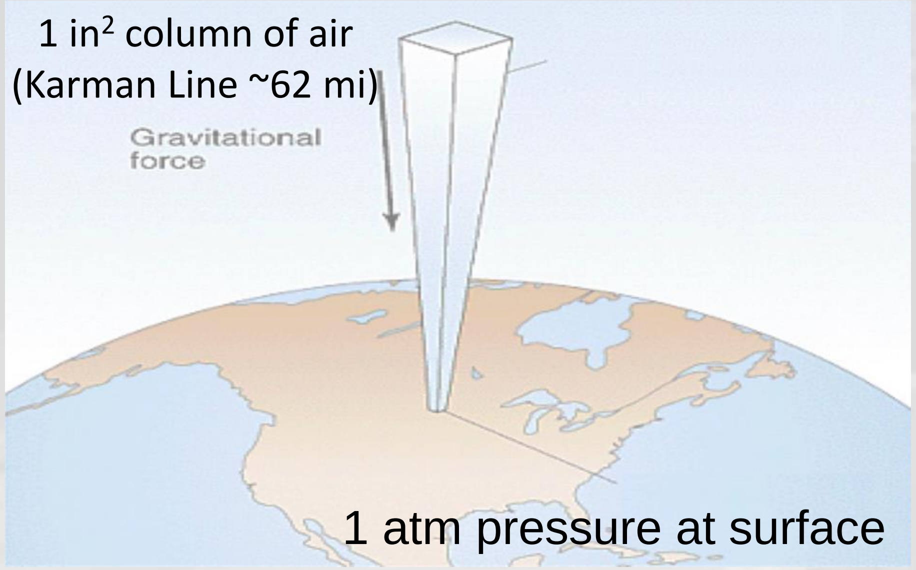
Atmospheric pressure (1 atm) is:

- 14.7 psi
- 101.3 kPa

Atmospheric Composition

- 21% O_2, 78% N_2, 1% Ar & trace

Atmospheric Composition

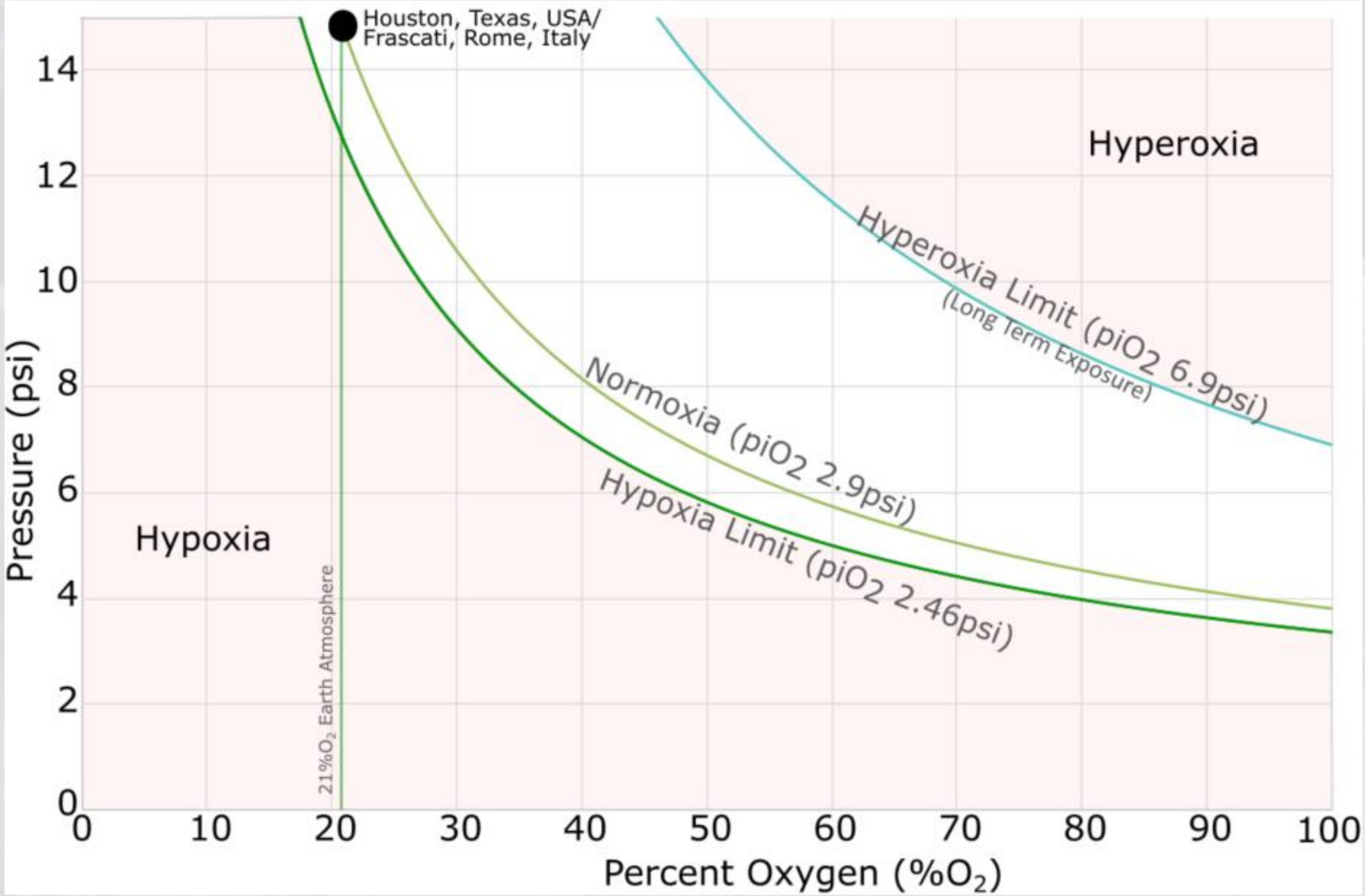


Atmospheric pressure (1 atm) is:

- 14.7 psi
- 101.3 kPa

Atmospheric Composition

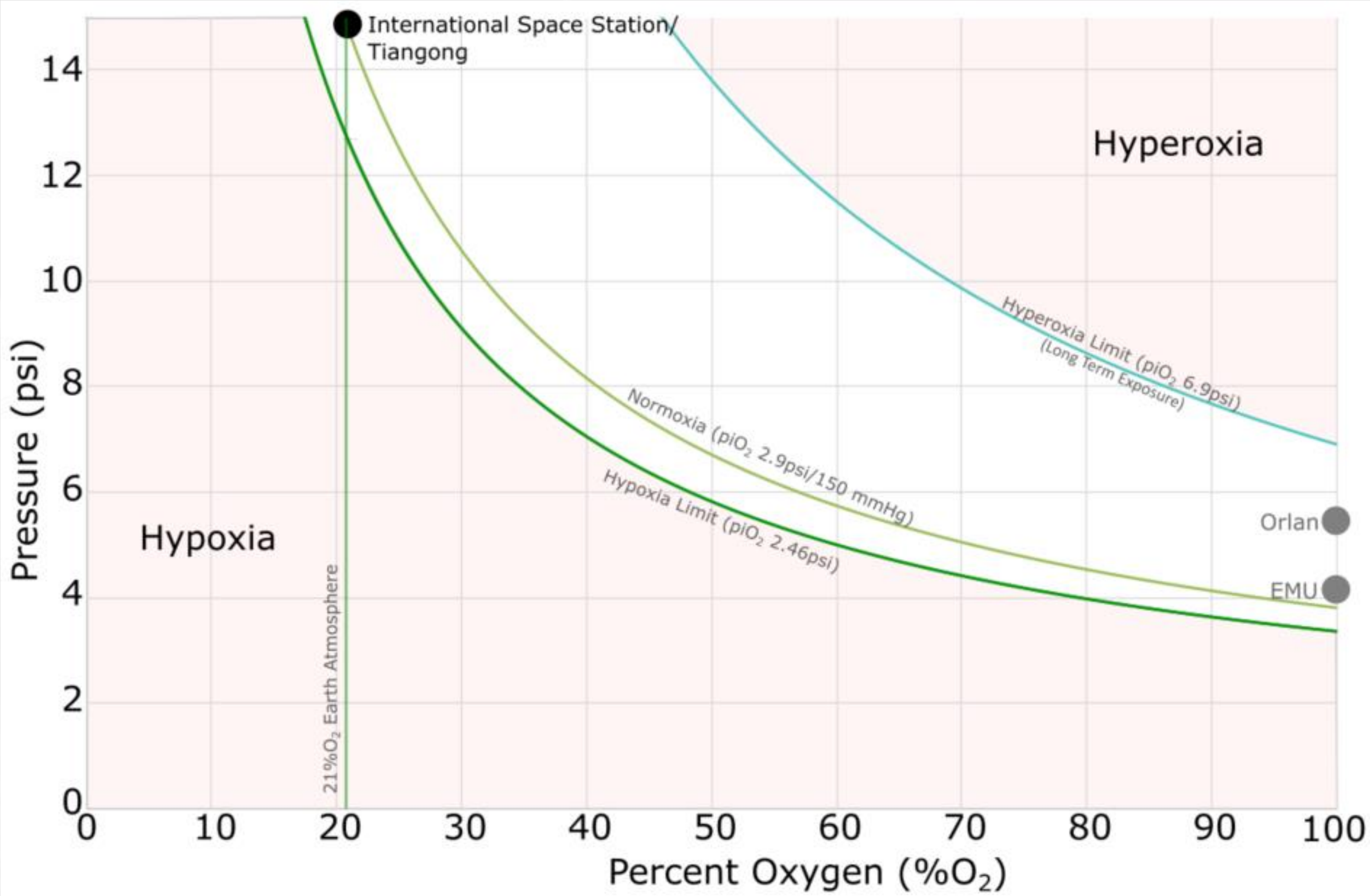
- 21% O_2, 78% N_2, 1% Ar & trace



Current: Vehicle and Suit Atmosphere

ISS

14.7 psia / 21% O_2 / 79% N_2 Cabin
Suit pressure - 4.3 psid (EMU), 5.8 psid (Orlan)



Conditions for Decompression Sickness (DCS)

- Decrease in Pressure
- Change in Phase State

Supersaturation

- Tissue pN_2 > Ambient Pressure

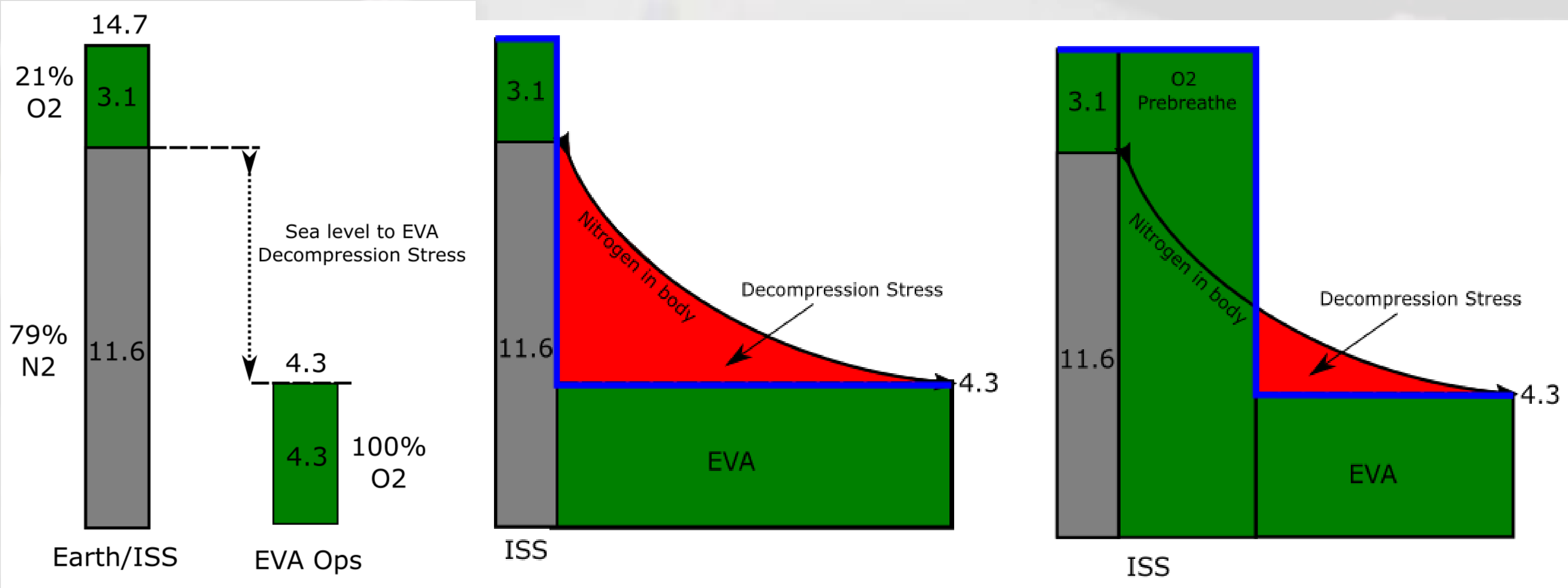
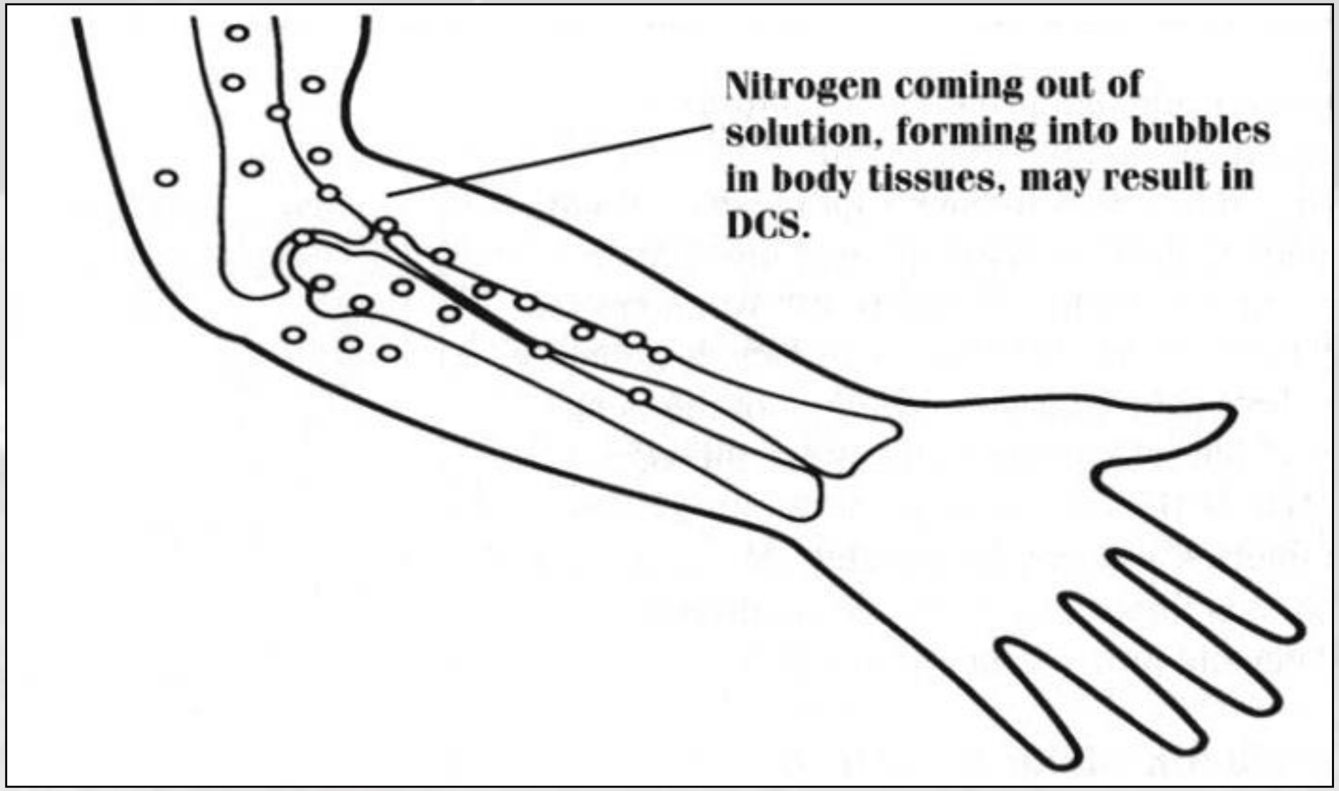


Figure: Alejandro Garbino, MD, PhD

Decompression Sickness (DCS)

- **Health risk** - Overarching medical and operational philosophy is that it is always better to **prevent** DCS than to treat DCS
- **Mission Risk** - DCS symptoms would most likely occur during an EVA and result in EVA termination, additional crew time/resources to treat DCS, and subsequent loss of mission objectives



Prebreathe (PB): Moving from Vehicle to Suit

ISS

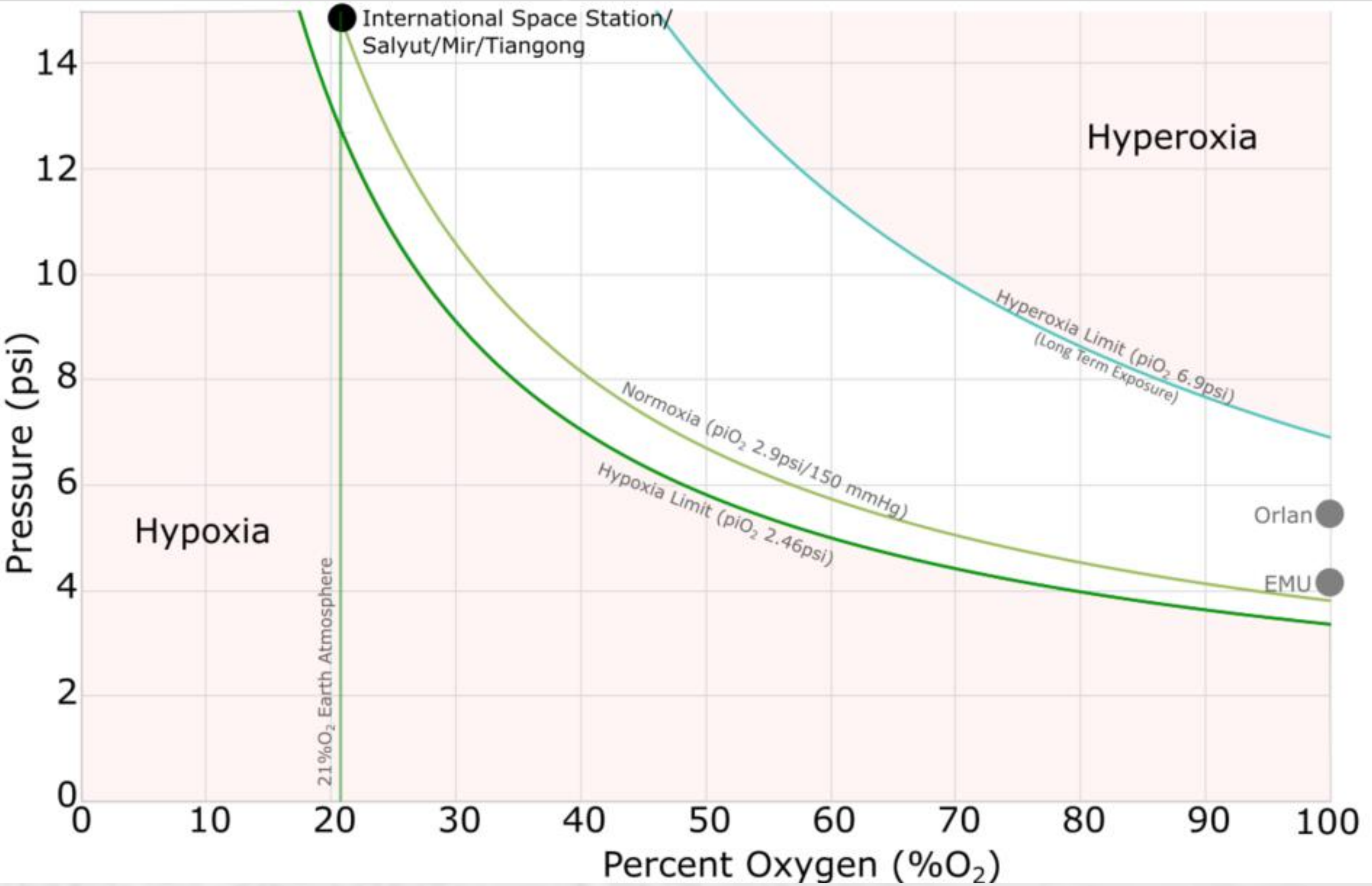
14.7 psia / 21% O_2/ 79% N_2 Cabin

Suit pressure - 4.3 psid (US EMU)

- Complex operational protocols require mask PB, airlock isolation, exercise, ground support
- 5-6 hours total prep time (2.5-3 hours dedicated to PB) prior to EVA

Suit Pressure – 5.8 psid (Russian Orlan)

- Similar EVA prep procedures but use of higher pressure reduces PB time to 30-40 min



History: Vehicle and Suit Atmosphere

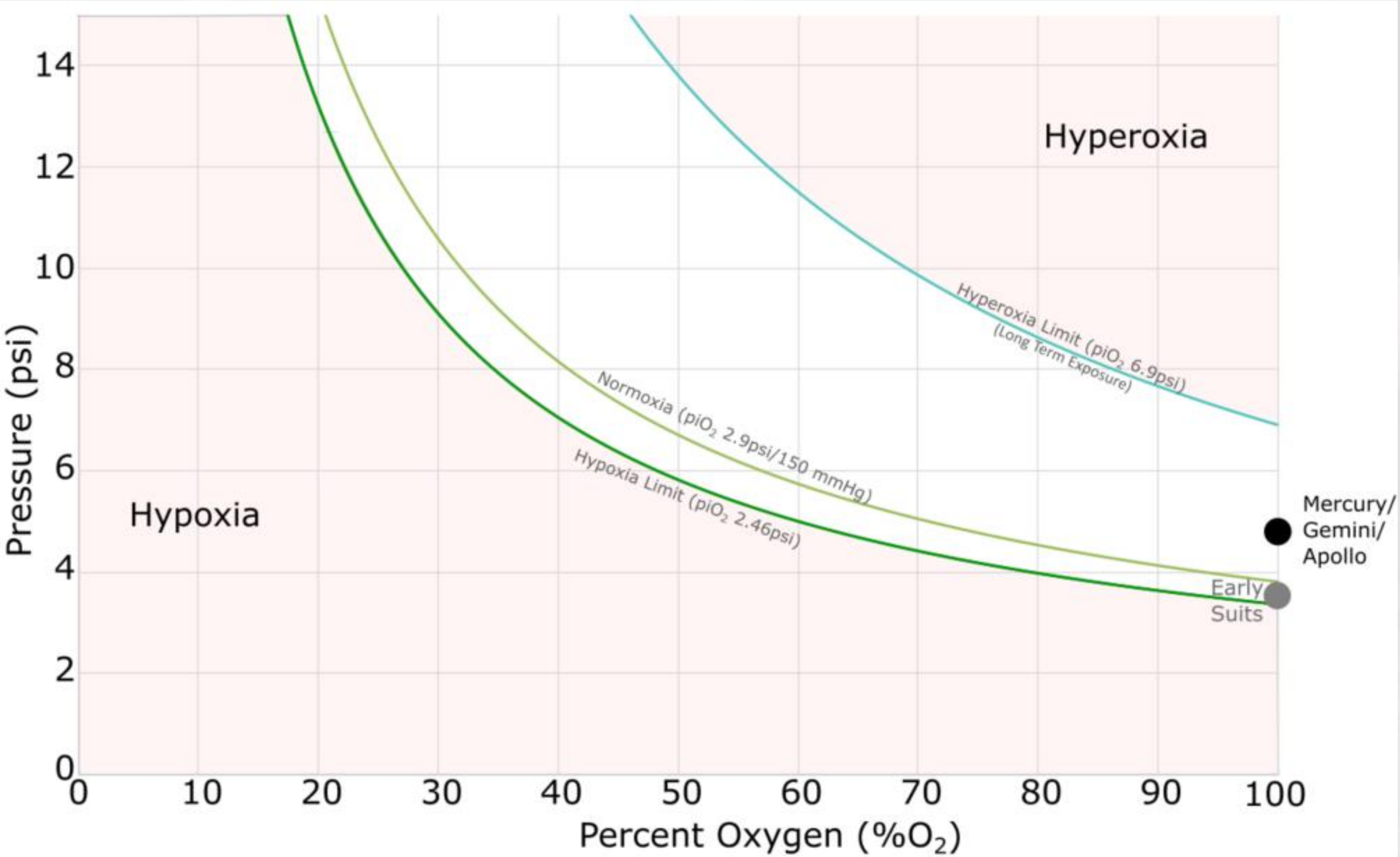
Apollo

16 psia/60% O_2 on Pad
3-hr PB on launch pad
Aerospace Med 1970; 41:1162-5.

*DCS - experienced in transit

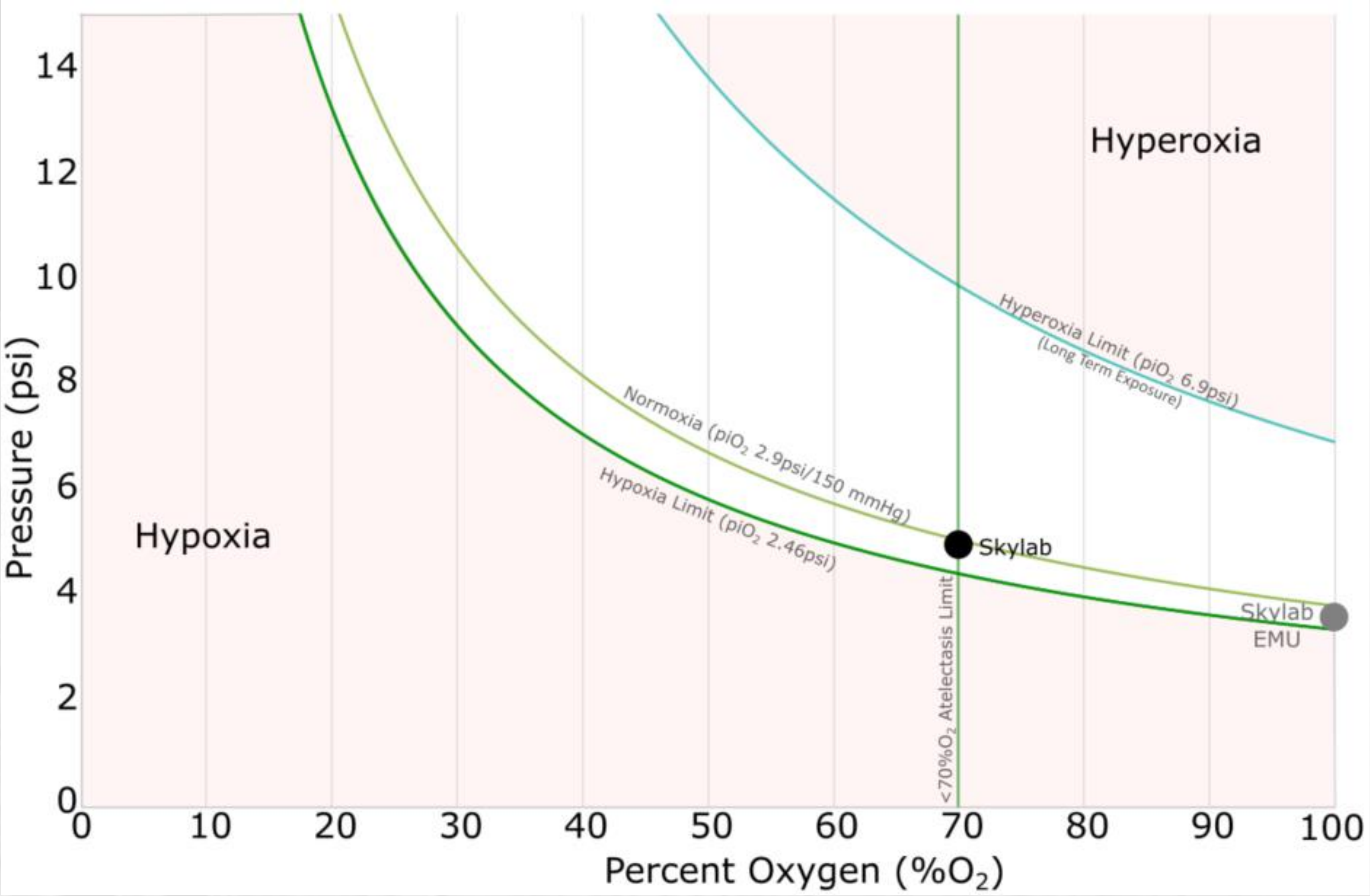
5 psia / 100% O_2 Cabin

3.7-4.0 psid suit pressure
- Minimum pressure to avoid hypoxia
- *No EVA DCS risk = No PB*



History: Vehicle and Suit Atmosphere

Skylab



5 psia / 70% O_2 Cabin

- Maintains P_IO_2 = 150 mmHg for normoxic environment
- Inclusion of 30% N_2 prevents atelectasis and was needed due to increased mission duration

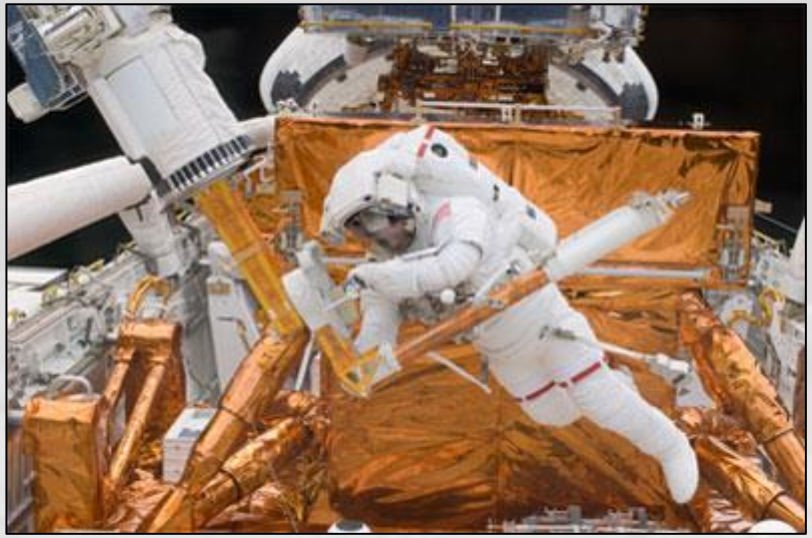
3.7-4.0 psid suit pressure

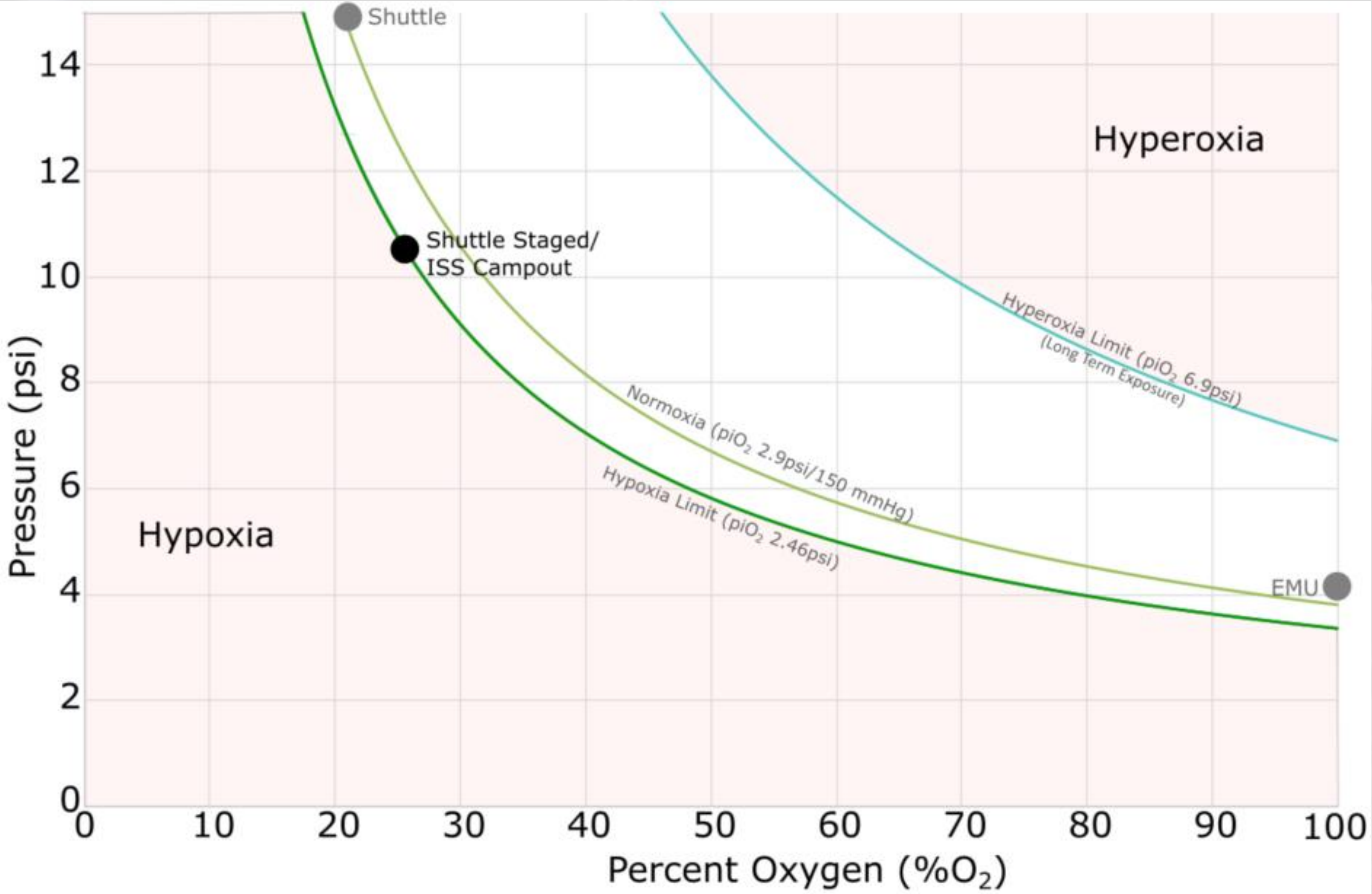
- *No EVA DCS risk = No PB*

History: Vehicle and Suit Atmosphere

Moon to Mars: Exploration Atmosphere

Shuttle





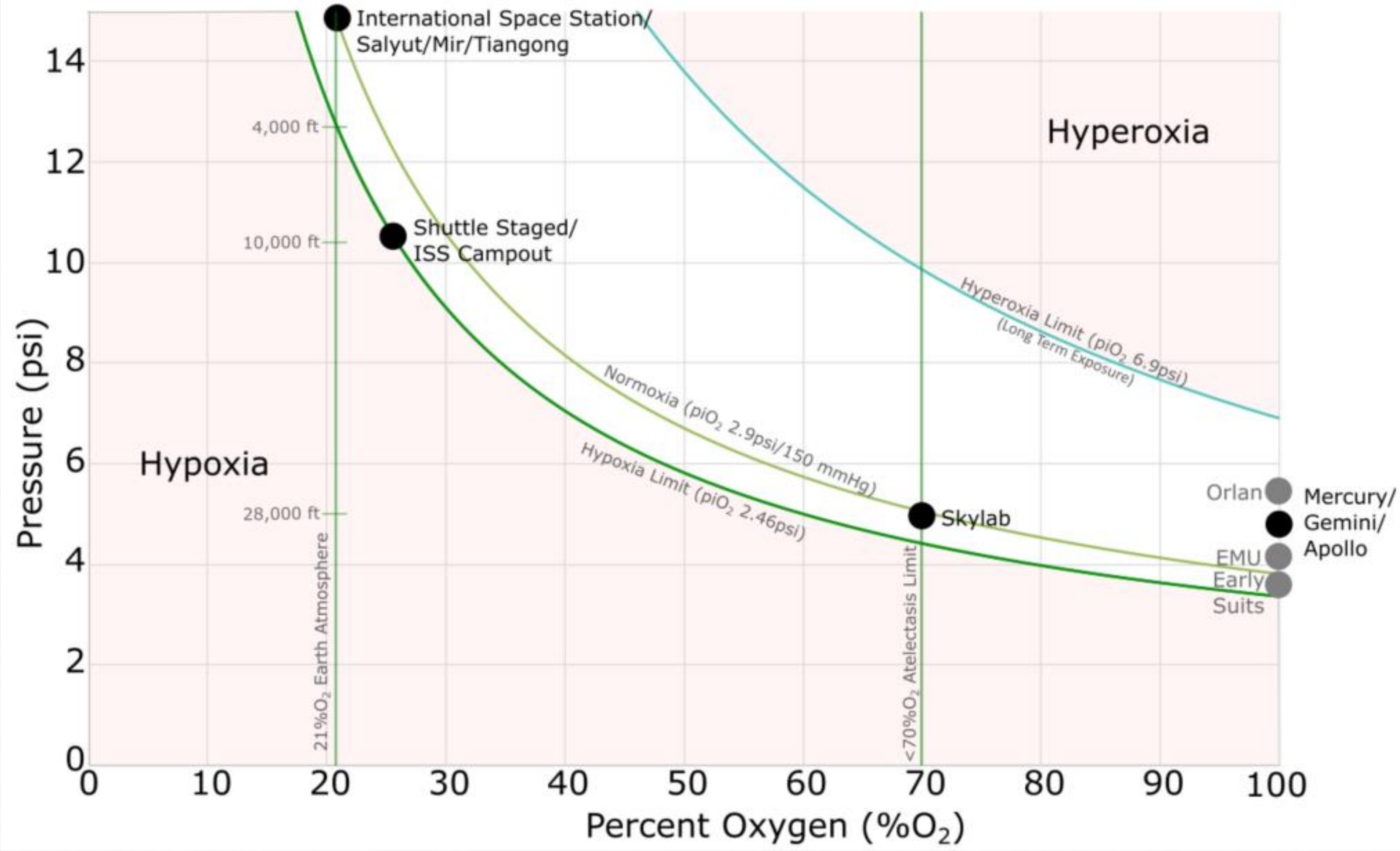
14.7 psia / 21% O_2 Cabin
Suit pressure increased to 4.1-4.3 psid
4-hour pre-EVA PB required

- Used only 6 times due to crew dislike

Shuttle retroactively certified to
10.2 psia / 26.5% O_2 Cabin
40-70 min in-suit PB pre-EVA

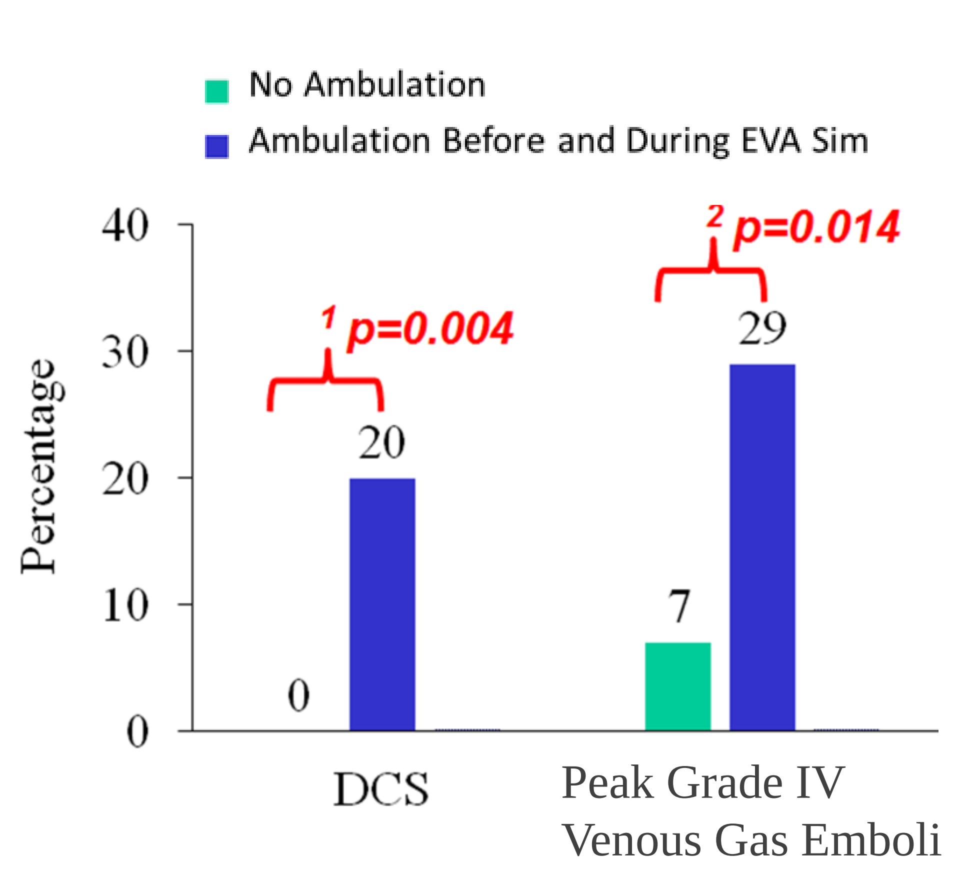
- *Efficient mitigation of DCS risk*

Vehicle and Suit Atmosphere to Date



Micro- Versus Partial-gravity DCS Risk

- No ***reported*** cases inflight to date
  - Michael Collins on Gemini X & Apollo 11 believed he had symptoms of pain-only DCS in his left knee that eventually resolved (Biomedical Results of Apollo)
- Apollo had no risk during EVA
  - Denitrogenation on launch pad
  - 100% O_2 Cabin – Fire risk too great
  - Not an option for Artemis
- Shuttle/ISS has risk but no cases
  - Microgravity- upper body activity
  - Transition to ops increases safety margin
- Artemis (Lunar) *will be* ambulatory
  - Greater metabolic and joint forces
  - Transition to ops does not guarantee increased safety



Conkin J, Pollock NW, Natoli MJ, Martina SD, Wessell JH III, Gernhardt ML. Venous gas emboli and ambulation at 4.3 psia. Aerosp Med Hum Perform. 2017; 88(4):370–376.
Webb JT, Krock LP, Gernhardt ML. Oxygen consumption at altitude as a risk factor for altitude decompression sickness. Aviat Space Environ Med 2010; 81:987-92.
Webb JT, Morgan TR, Sarsfield SD. Altitude Decompression Sickness Risk and Physical Activity During Exposure. Aerosp Med Hum Perform. 2016: 87(6):516-20.

Moon to Mars: Exploration Atmosphere

Atmospheric Impacts on Suit Pressure and PB Time

(estimated)

Model* estimates to achieve 3% per person per EVA DCS Risk

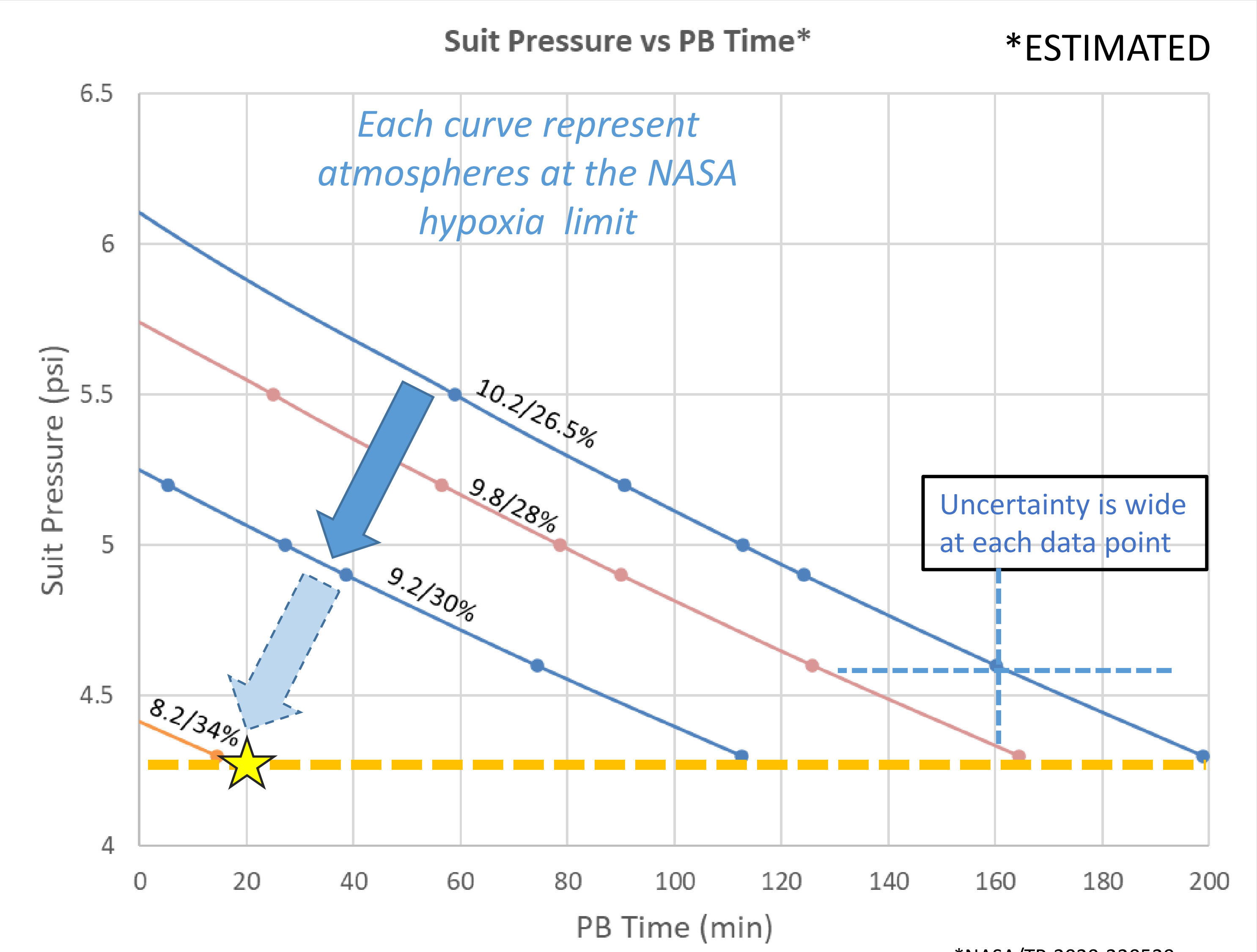
Any movement toward the origin

- optimizes timeline efficiency
- minimizes consumables
- decreases human workload

Every incremental increase in O_2% drives us down and left towards less suit pressure and shorter prebreathe duration

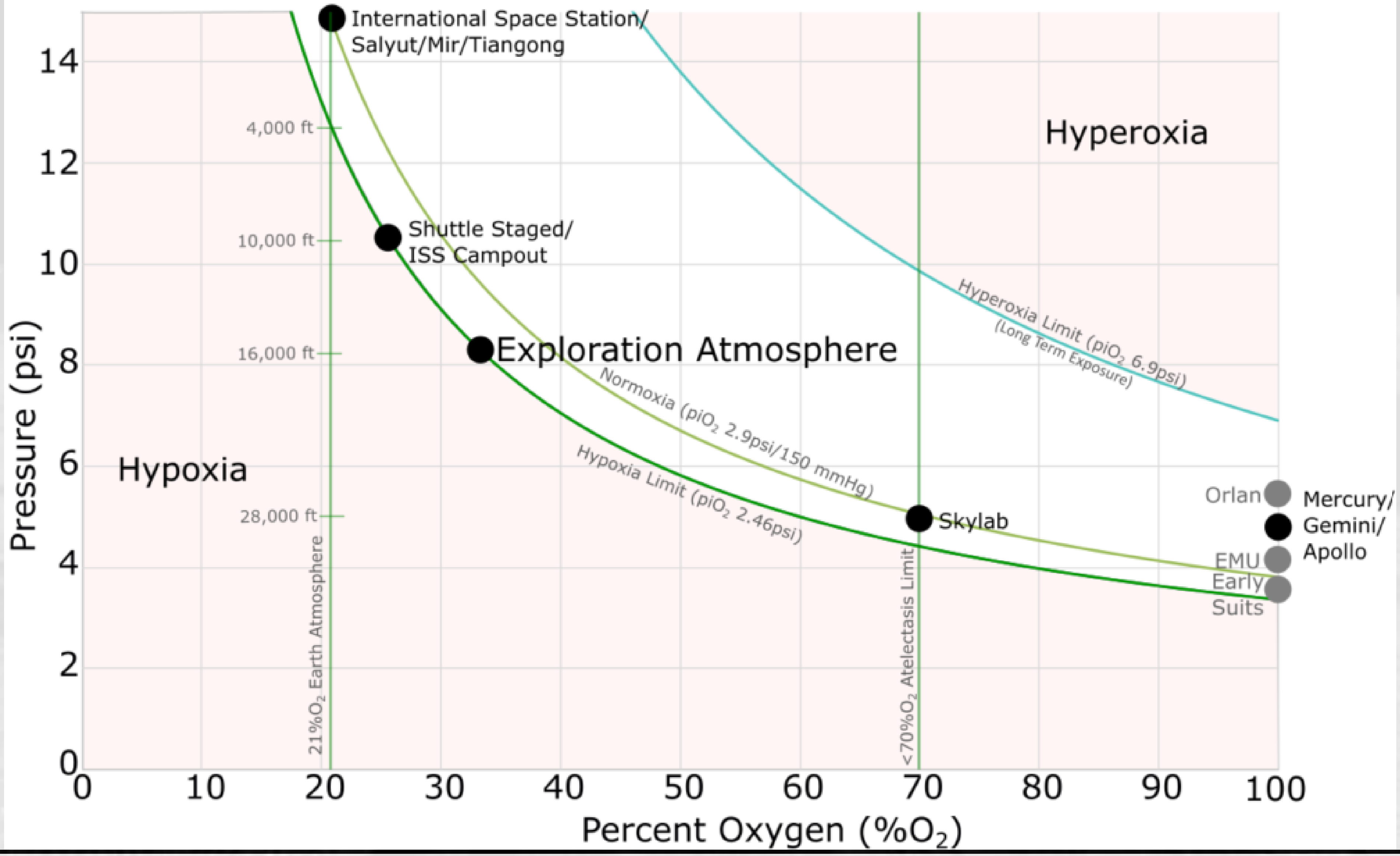
☆ Validated test point

Abstract 12 - AsMA Annual Conference, 2024.

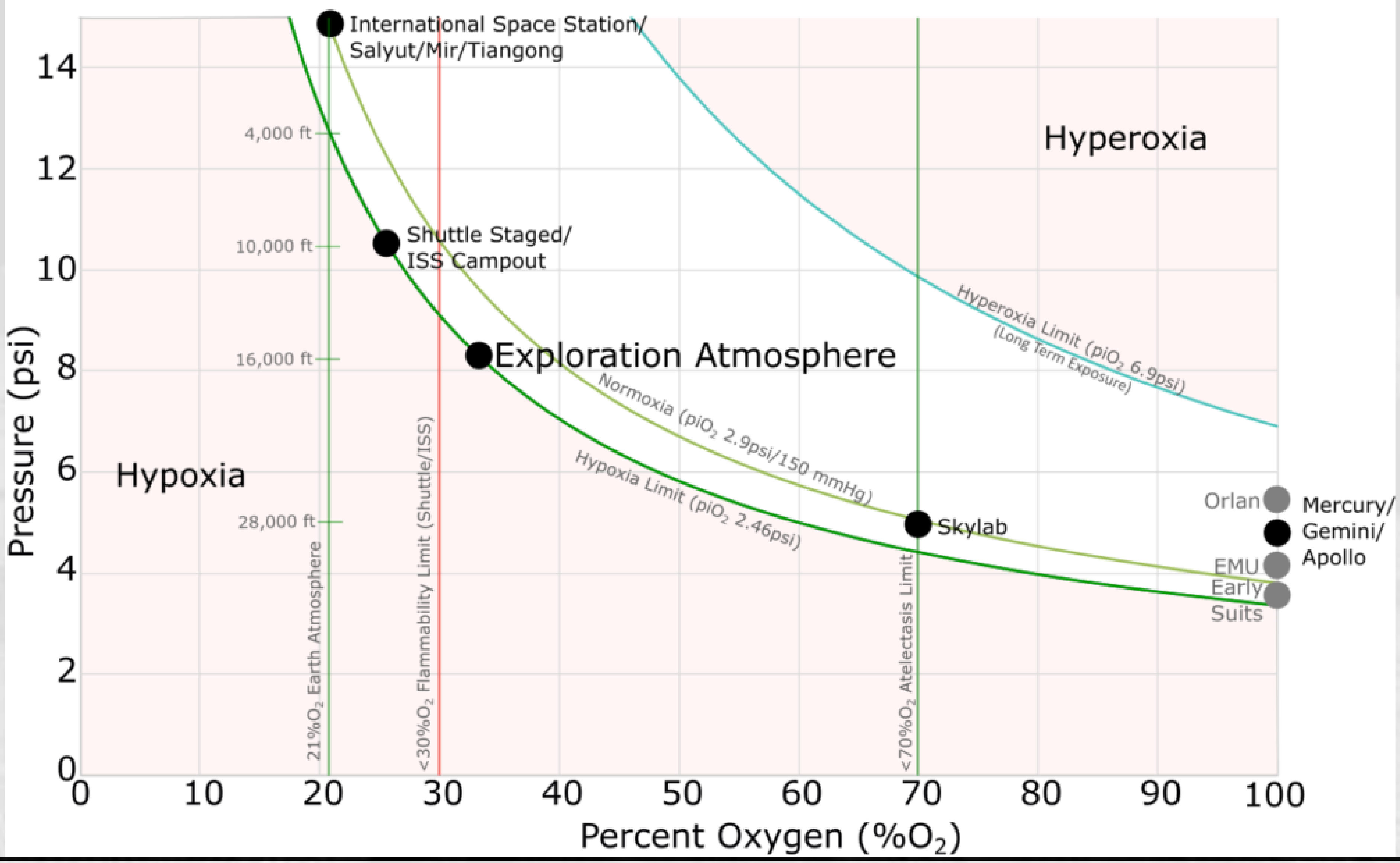


*NASA/TP-2020-220529

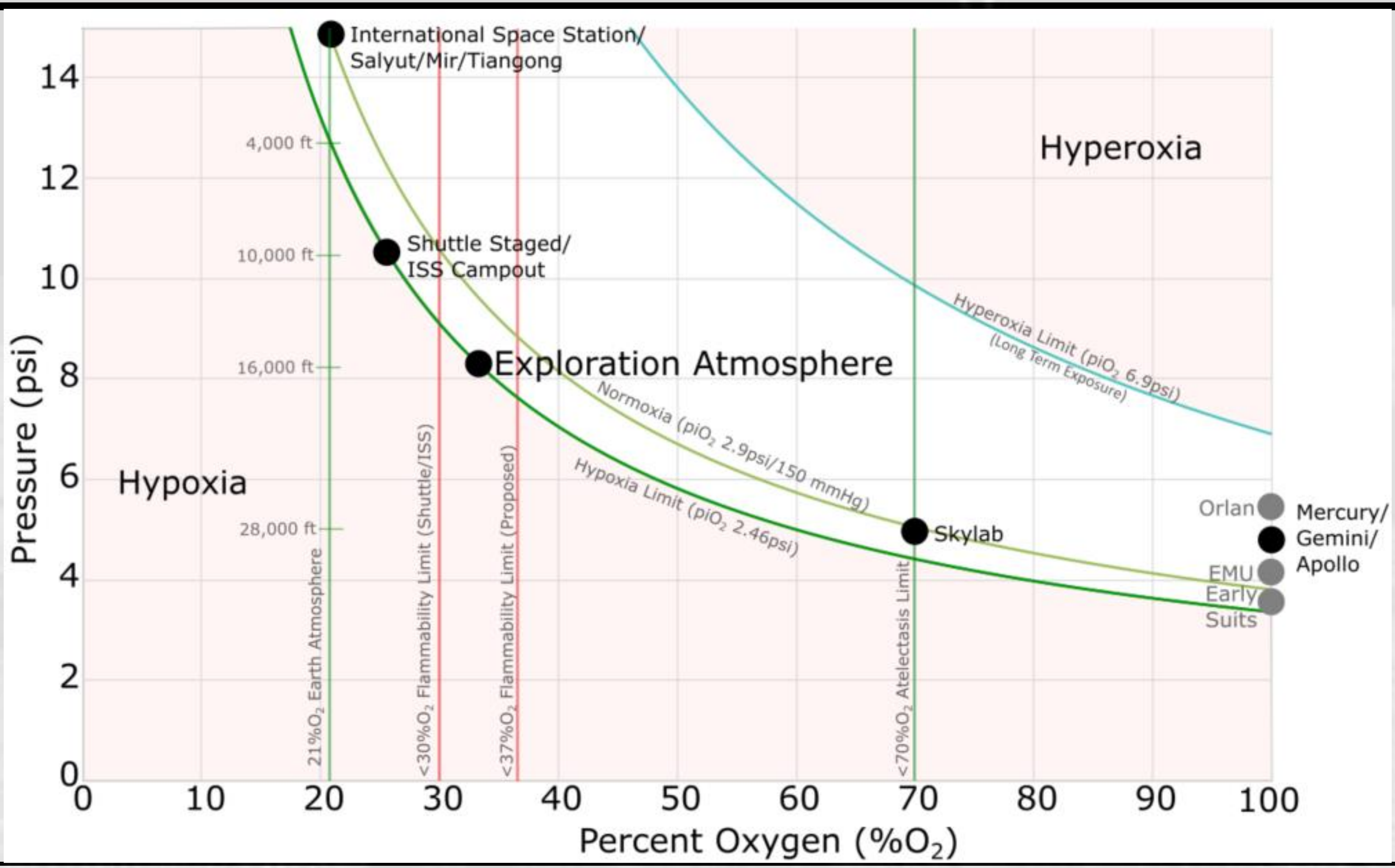
Exploration Atmosphere



Exploration Atmosphere



Exploration Atmosphere



Historical Lessons Learned from Apollo I

In a **post Apollo I mockup test**, fire spreads rapidly through the command module cabin in pure oxygen at 16.7 psi

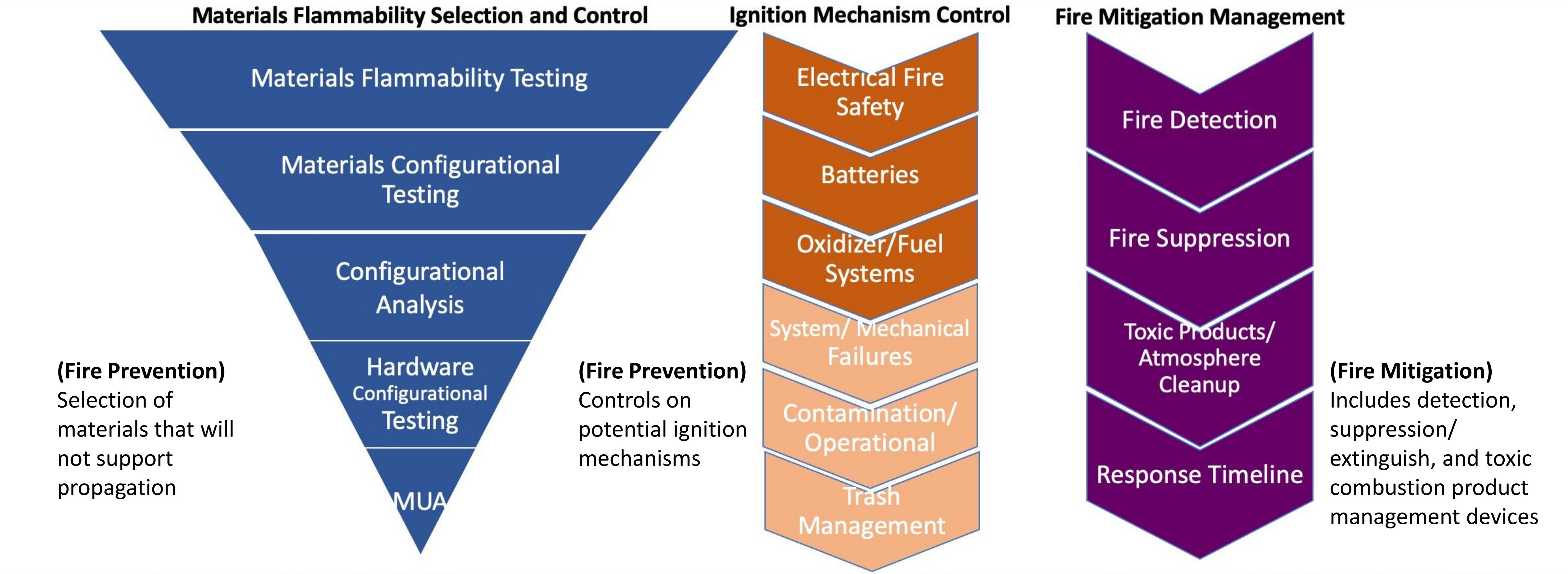
Note the explosive burning of Velcro attached to cabin walls, which helped spread the blaze.

- **Oxygen-enriched flammability testing was not standardized by NASA before the Apollo program**
- Manned Spacecraft Center laboratories began looking into test method standardization for elevated oxygen environments;1964 workshops identified key criteria:
  - Need for non-metallic materials flammability screening test
  - Clear acceptance / rejection criteria
  - Generation of list of acceptable/ not acceptable materials
- Apollo 1 fire occurred January 27, 1967; in 1968, NASA announced 60%O_2@16 PSI launchpad ops, Apollo program continued with 100% O_2 in flight (4.3 psia nominal, 6 psia max)
- *"It soon became apparent that so many tests of a highly varied nature were being run at different locations that it was not possible to correlate the results of these tests, and it was decided that it would be **necessary to establish a standard set of test methods and criteria**" – Johnston & Pippen, 1970*

NASA Fire Safety Approach

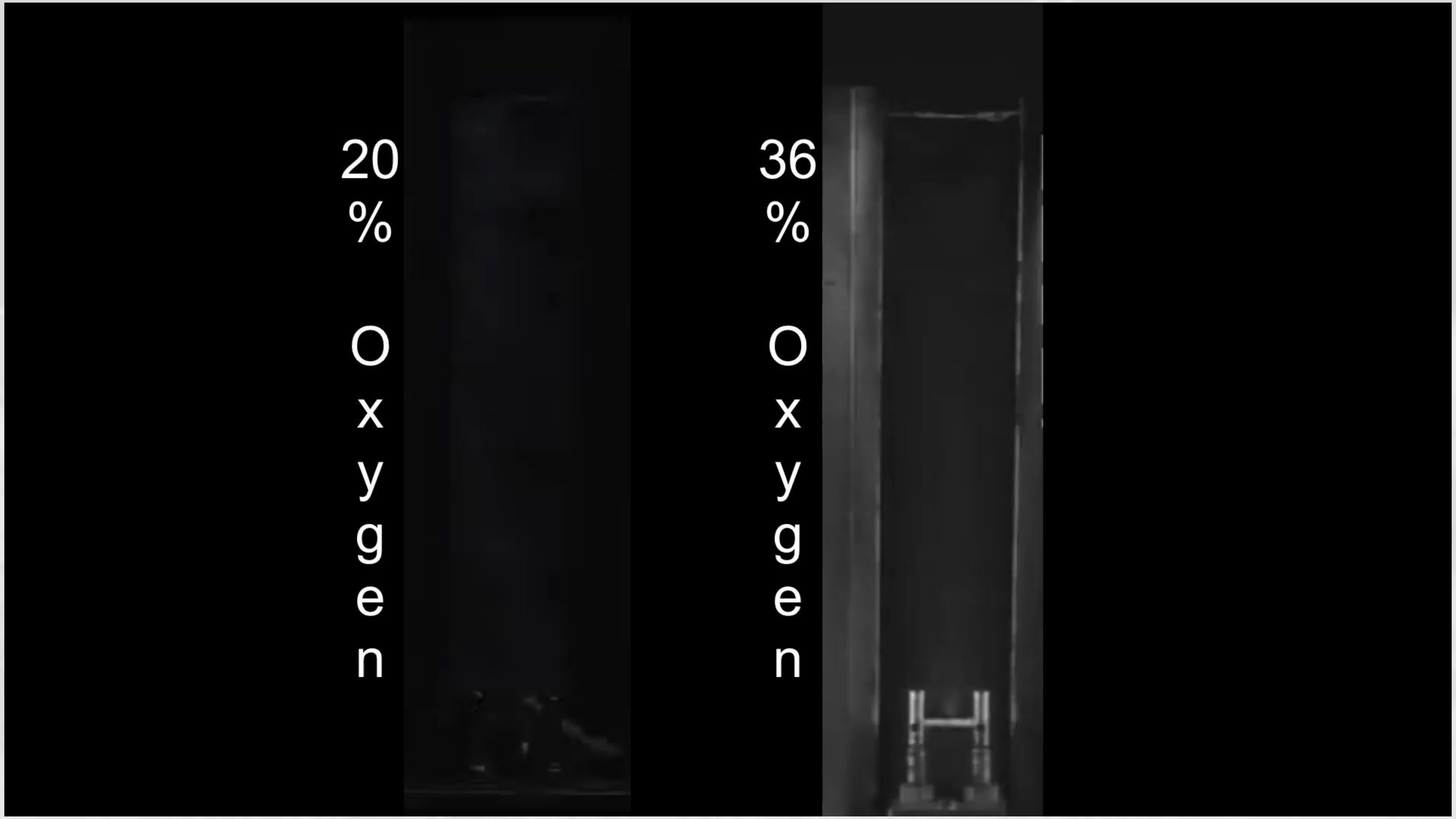
Three-pronged approach - provides robust spacecraft fire safety management plan

- Misses or weaknesses in one component → compensated for on others, safeguarding against an overall system failure
- Each component - intended to be fully independent, cannot be waived based on the execution of others



Cotton Sweatshirt Comparison

20% O_2
14.7 psi



36% O_2
8.2 psi

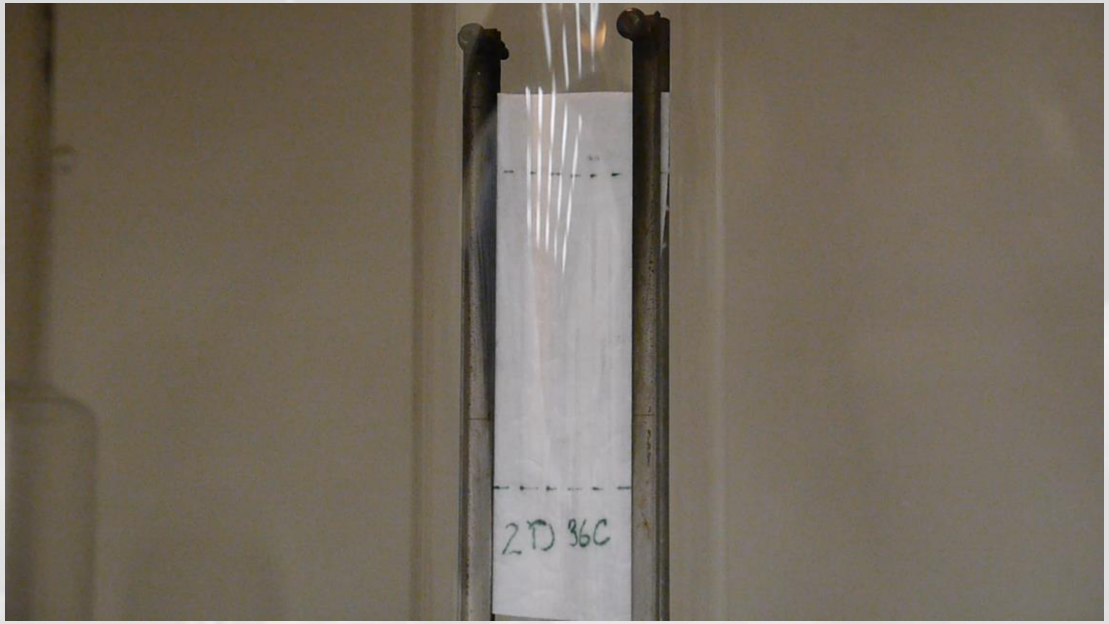
Due to desired properties of cotton, it will likely be used for underwear and towels. Though flammable in air, ignition and propagation occurs more readily in oxygen-enriched exploration atmospheres.

Susana Harper, White Sands Test Facility

Dried Hygiene Wipe Comparison

21% O_2, 14.7 psi

36% O_2, 14.7 psi

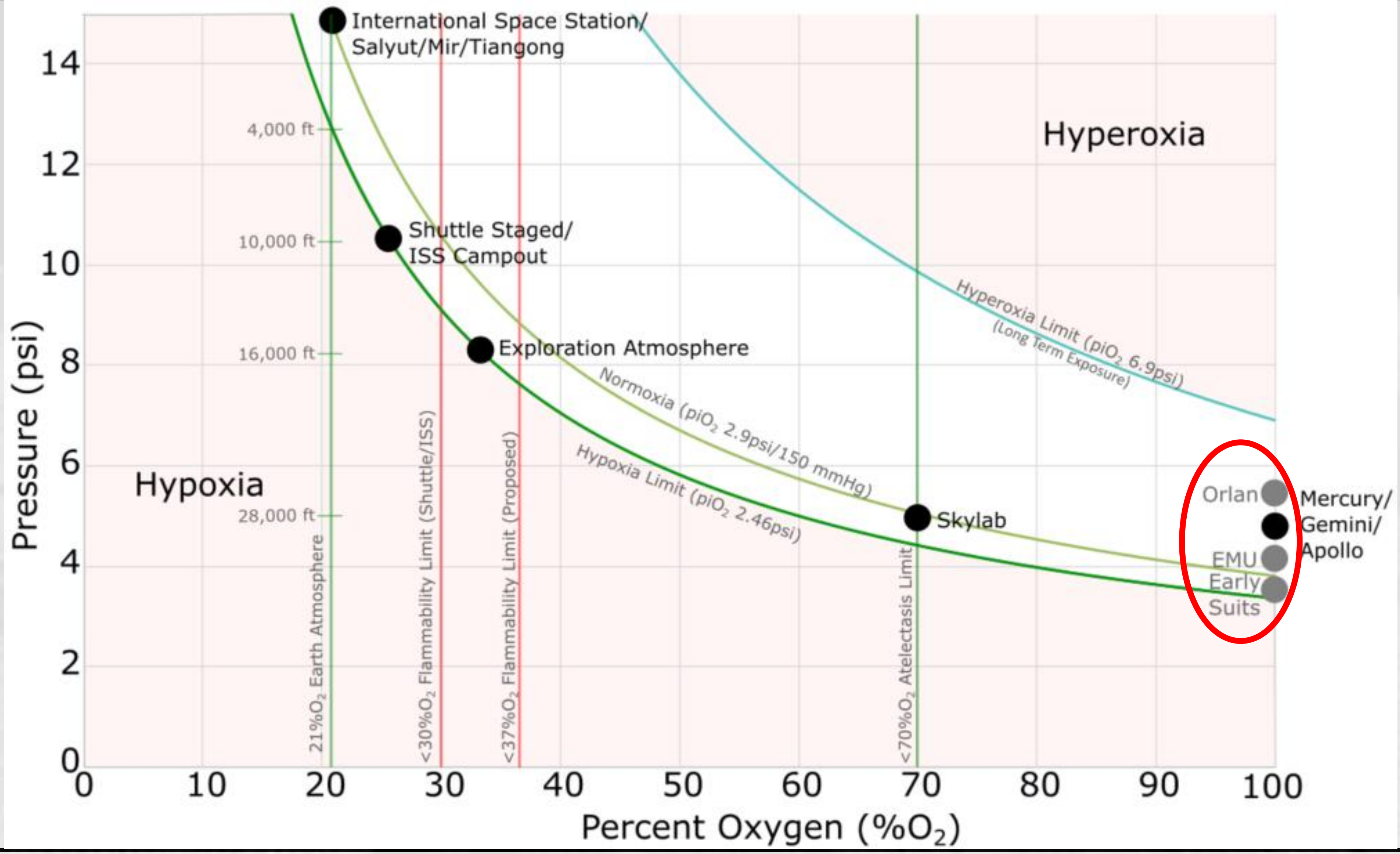


Ignition time and flame spread occur rapidly at 36% oxygen.

Flammability data from ignition of flammable materials provides guidance for flammability configuration analyses required to justify the use of flammable materials in spacecraft flight hardware and operational controls.

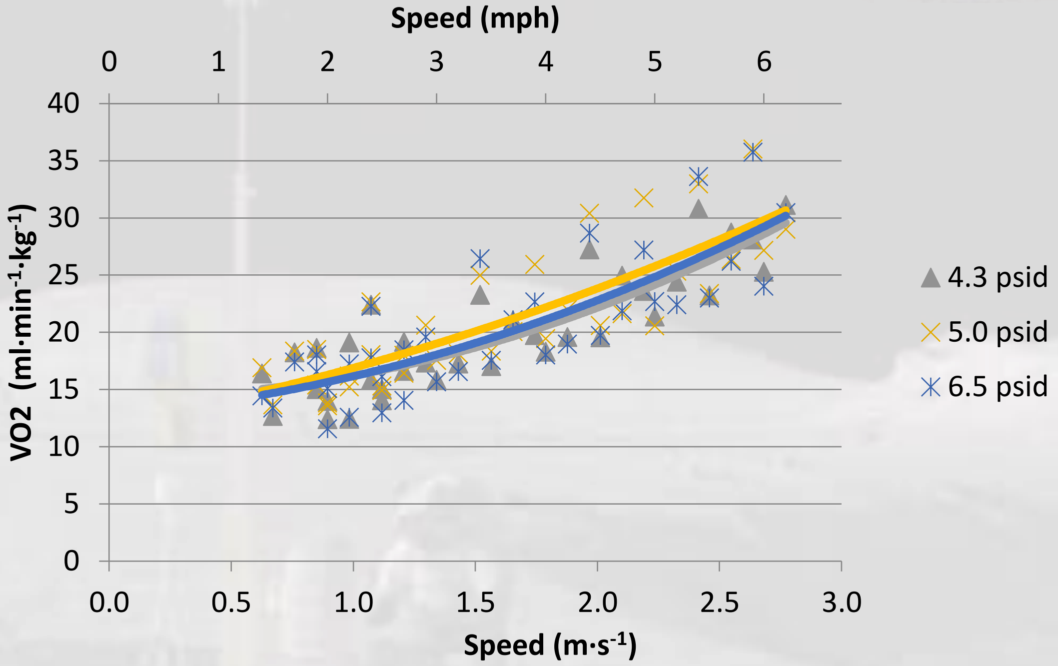
JSC Advanced Materials Lab

Suit Pressure and Physiologic Responses



Data with Suit Pressures > 4.3 psid

- Metabolic rate not affected by suit pressures from 4.3-6.5 psid in Artemis-like Lunar suit with treadmill ambulation using overhead partial gravity offload (NASA/TP-2010-216115)
- Short durations at 8.0 psid during NBL testing using xEMU early prototype provided positive feedback
  - Gloves primary discernable difference between 4.0 psid and 8.0 psid (ICES-2018-71)
- 15 US Crew have done EVA (some several) in 5.8 psid Russian Orlan
- Planetary EVA is full body vs all upper body microgravity EVA
  - Hand/forearm fatigue may be most impacted
  - Crew can be trained to prepare for these impacts
- Data is very limited on human performance implications



Russian Orlan Suit @ 5.8 psia

Exploration Atmosphere Considerations

Exploration Atmosphere – Start with Engineering Solutions

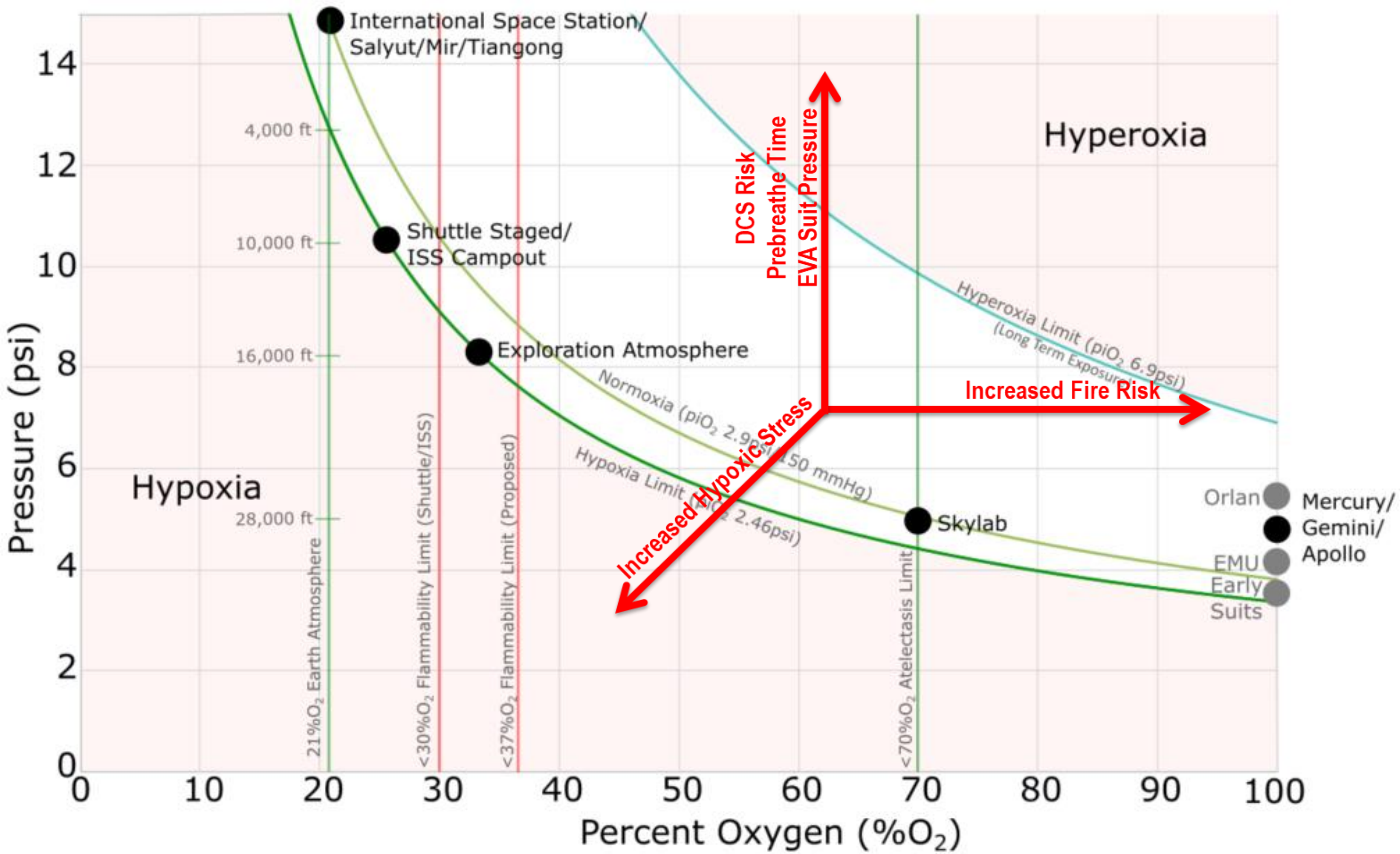


Figure: Alejandro Garbino, MD, PhD, modified by M. Walton

Exploration Atmosphere Considerations

- Significantly higher EVA frequency during Artemis versus ISS
  - Artemis includes back-to-back EVAs and multiple EVAs per person per week
  - ISS EVA is infrequent so 5-6 hours of EVA prep time considered acceptable
- Limited validated prebreathe protocols exist for planetary EVA
  - Apollo used 5 psia / 100% O_2 cabin to eliminate DCS risk during EVA
  - 20 minute protocol – valid only at 8.2 psia / 34% O_2
- Engineering solutions required to achieve mission success
  - Exploration Atmosphere
  - Variable Pressure EVA Suit

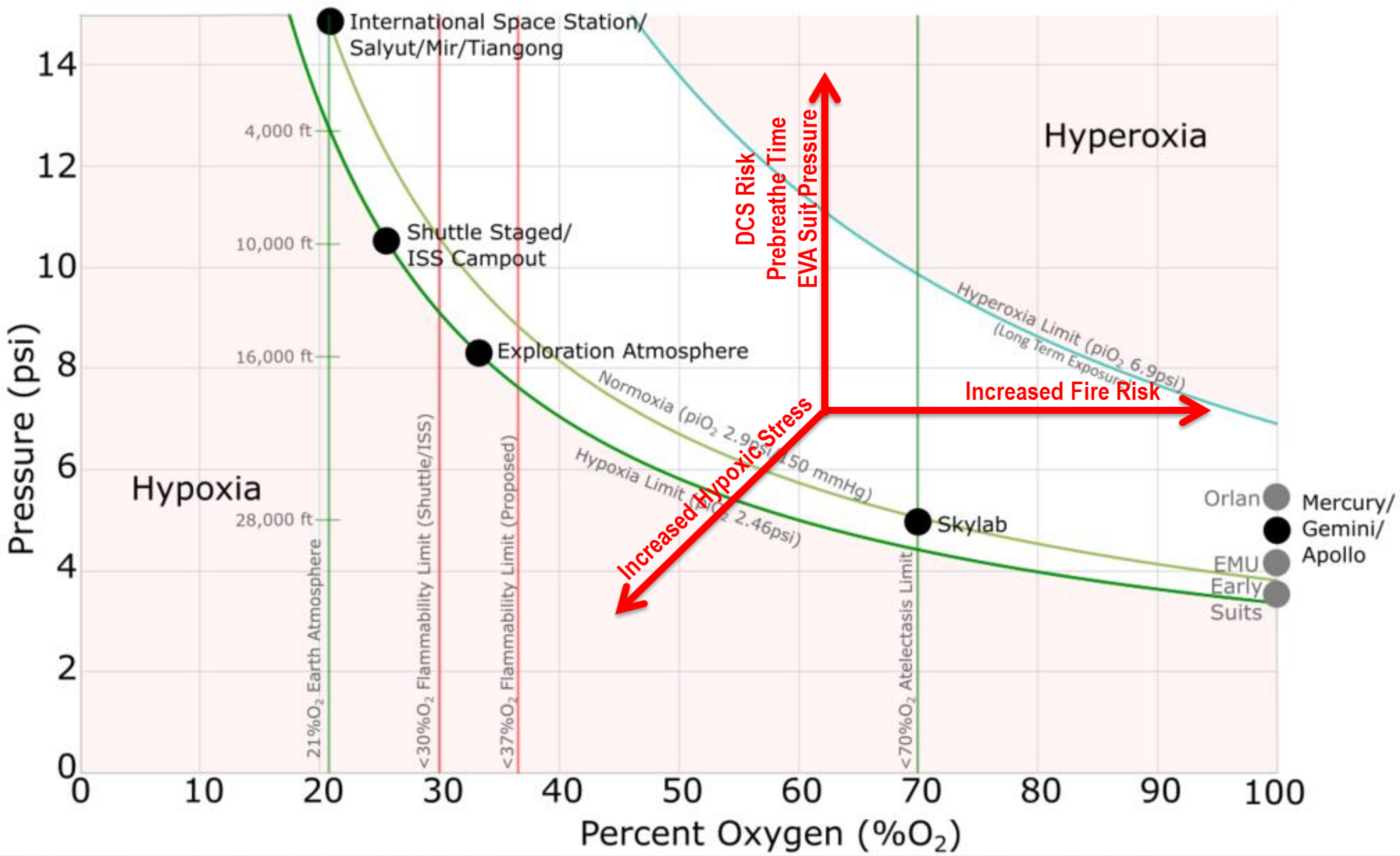


Figure: Alejandro Garbino, MD, PhD, modified by M. Walton

Thank you!

Questions?

13th TRISMAC

TRISMAC **2024**

June 24-26, 2024

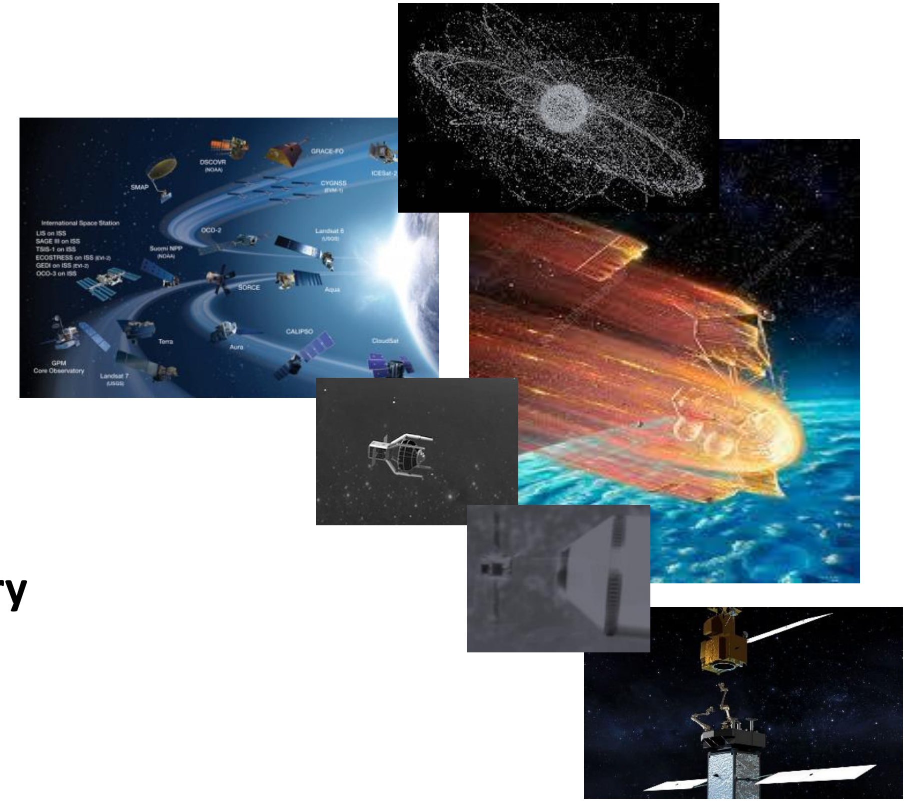
How can Mission Assurance support On-Orbit Servicing/ADR?

Trilateral Task Force Lead: Nancy J Lindsey (NASA – GSFC)

Members: Jesse Leitner (GSFC), Anthony DiVenti (NASA-OSMA), Toru Yoshihara (JAXA), Kenichi Sato (JAXA), Takashi Yamane (JAXA), Osamu Yamada (JAXA), Fabrice Cosson (ESA), Silvana Radu (ESA), Sergio Ventura (ESA), Antonio Harrison Sanchez (ESA), Todd Paulos (JPL)

How can Mission Assurance support On-Orbit Servicing/ADR?

Agenda



- **Servicing/ADR Support Discovery Process**
  - **Policies**
  - **Research**
- **Servicing/ADR Risk/Safety Support Codifications**
  - **Tactics**
  - **Tasks**
- **Summary**

Servicing/ADR Support Discovery Process

- **Servicing/ADR Support Discovery Process**
  - Policies
  - Research
- Servicing/ADR Risk/Mission Assurance Support Codifications
  - Tactics
  - Tasks
- Summary

1. Review and Compare Servicing/ADR Policies

   ↓

2. Research and Compare Servicing/ADR Mission Plans, Goals, and Needs

   ↓

3. Identify and Codify Objectives, Strategies, and Support Solutions for assuring Servicing/ADR success

   ↓

4. Sharing Findings to Enhance Servicing/ADR Practices. Designs, and Policies

Review and Compare Servicing/ADR Policies

- Servicing/ADR Support Discovery Process
  - Policies
  - Research
- Servicing/ADR Risk/Mission Assurance Support Codifications
  - Tactics
  - Tasks
- Summary

	International (IADC & ITU) [1, 20]	United States [10, 11, 13, 14, 17]	Japan [3]	France [19] (France is part of Europa but has specific National requirements as well)	Europe
Additional Spacekeeping (Servicing and Debris Removal)	**IADC 2007: "Retrieval is also a disposal option."** **ISO/CD 24330 (under development until 2022)** **Space systems — Rendezvous and Proximity Operations (RPO) and On Orbit Servicing (OOS) — programmatic principles and practices** **ISO (24113:2019) does not address servicing or proximity operations.**	**United States Government (USG) ODMSP –Rendezvous, proximity operations, and satellite servicing: In developing the mission profile for a structure, the program should limit the risk of debris generation as an outcome of the operations. The program should (1) limit the probability of accidental collision, and (2) limit the probability of accidental explosion resulting from the operations. Any planned debris generated as a result of the operations should follow the standard practices for mission-related debris set forth in Objective 1 - CONTROL OF DEBRIS RELEASED DURING NORMAL OPERATIONS.** **5-4. Safety of Active Debris Removal (ADR) operations: In developing the mission profile for an ADR operation on a debris structure, the program should limit the risk of debris generation as an outcome of the operation. The program should (1) avoid fragmentation of the debris structure, (2) limit the probability of accidental collision, and (3) limit the probability of accidental explosion resulting from the operations. Any planned debris generated as a result of the operations should follow the standard practices for mission-related debris set forth in Objective 1. The operations should be designed for the debris structure to follow applicable PMD practices set forth in Objective 4 - POSTMISSION DISPOSAL OF SPACE STRUCTURES** **2020 National Space Policy: "Evaluate and pursue, in coordination with allies and partners, active debris removal as a potential long-term approach to ensure the safety of flight in key orbital regimes."** **SPD-3: "The United States should pursue active debris removal as a necessary long-term approach to ensure the safety of flight operations in key orbital regimes. This effort should not detract from continuing to advance international protocols for debris mitigation associated with current programs. "** FCC: Proximity Operations 59 (FCC-CIRC1811-02). With increasing interest in satellite servicing and other non-traditional missions, there have been an increasing number of commercial missions proposed that involve proximity operations and rendezvous of spacecraft. We propose that applicants be required to disclose whether the spacecraft will be performing any space rendezvous or proximity operations. The statement would indicate whether the satellite will be intentionally located or maneuvering near another spacecraft or other large object in space. Such operations present a potential collision risk, and operators will need to address that risk, as well as any risk of explosions or generation of operational debris that might occur through contact between spacecraft, as part of debris mitigation plans. Accordingly, we propose a disclosure requirement regarding these types of operations FCC 20-54 Proximity Operations 122. In the Notice, the Commission noted the increasing number of commercial missions proposed involving proximity operations and rendezvous of spacecraft. The Commission proposed that applicants be required to disclose whether the spacecraft is capable of, or will be, performing rendezvous or proximity operations. The Commission also sought comment on whether the rules should include anything more specific regarding information sharing about proximity operations with the 18th Space Control Squadron or any successor civilian entity. We adopt a disclosure requirement that would identify situations where there are planned rendezvous and proximity operations and provide a vehicle for further review of those operations. **The disclosure requirement follows the general approach in the revised ODMSP of analyzing such operations within the framework of standard debris mitigation objectives—limiting debris release, preventing accidental explosions, and limiting collision risk.** Commenters generally supported this approach. We note the evolving and developing nature of these operations, and accordingly find that more specific technical or operational requirements are premature at this time. Member of CONFERS (The Consortium for Execution of Rendezvous and Servicing Operations) Studies	JERG-2-026 **On-orbit service:** Intentional interference by a servicing spacecraft with a client spacecraft for refueling, resupplying, adding or replacing functionalities and assisting PMD. Active Debris Removal (ADR) for inactive spacecraft / target debris and transportation to/from a space station is also a part of on-orbit servicing. ADR shall be taken in to **(1) Avoid unintended generation of debris caused by a collision upon RPO, physical contact and docking with a target as well as the loss of debris mitigation functions are defined as a critical hazard (e.g., serious effect on environment)**.(2) Conduct a hazard analysis of the entire system integrating a servicing spacecraft, target and ground system, and take safety measures to address the identified hazards and hazard causes based on fault tolerance. (3) Additional fault tolerance or equivalent measures are considered when a collision could lead to a catastrophic consequence such as serious threat to the manned spacecraft because of its size, orbit, and/or payload properties. (4) Avoid inducing failures direct or indirect (impingement, contamination, etc.) in servicing of client system. (5) Inability to separate client and servicing if required.	In 2019, France released its Space Defense Strategy, in which it acknowledged the increasing importance in-orbit services will have in the future due to the high number of objects in orbit and the need to remove debris. France is involved in the development of IOS in the field of Active Debris Removal, reconfiguration, and de-orbiting. France has contributed to the development of Space Debris Mitigation Guidelines of the Committee, the European Code of Conduct for Space Debris Mitigation, and the IADC Space Debris Mitigation Guidelines. The French Technical Regulation is consistent with these guidelines, as well as with the ISO 24113 standard. France is currently using debris mitigation policies to guide Close Proximity Operations (CPO) and RPO.	ESA's Close Proximity Operations (CPO) Working Group is preparing the safety/sustainability requirements (e.g. technical, operational, verification & validation) for non-human rated missions executing rendezvous, proximity and capture operations. The CPO Working Group will provide technical inputs to the European Cooperation for Space Standardization (ECSS) Space Traffic Management Working Group on technical aspects concerning the development of worldwide RPO) and OOS draft guidelines and best practices handbook for 2022 release. Currently using debris mitigation policy to guide CPO and RPO. Member of CONFERS

Common do no harm requirements: avoid debris generation

Common maintenance of compliance with debris mitigation policies

Slight variations in established policies

Common challenge of developing evolved reliability and hazard assessment tactics for Servicing/ADR

Research and Compare Plans, Goals, and Needs

- **Servicing/ADR Support Discovery Process**
  - **Policies**
  - **Research**
- **Servicing/ADR Risk/Mission Assurance Support Codifications**
  - **Tactics**
  - **Tasks**
- **Summary**

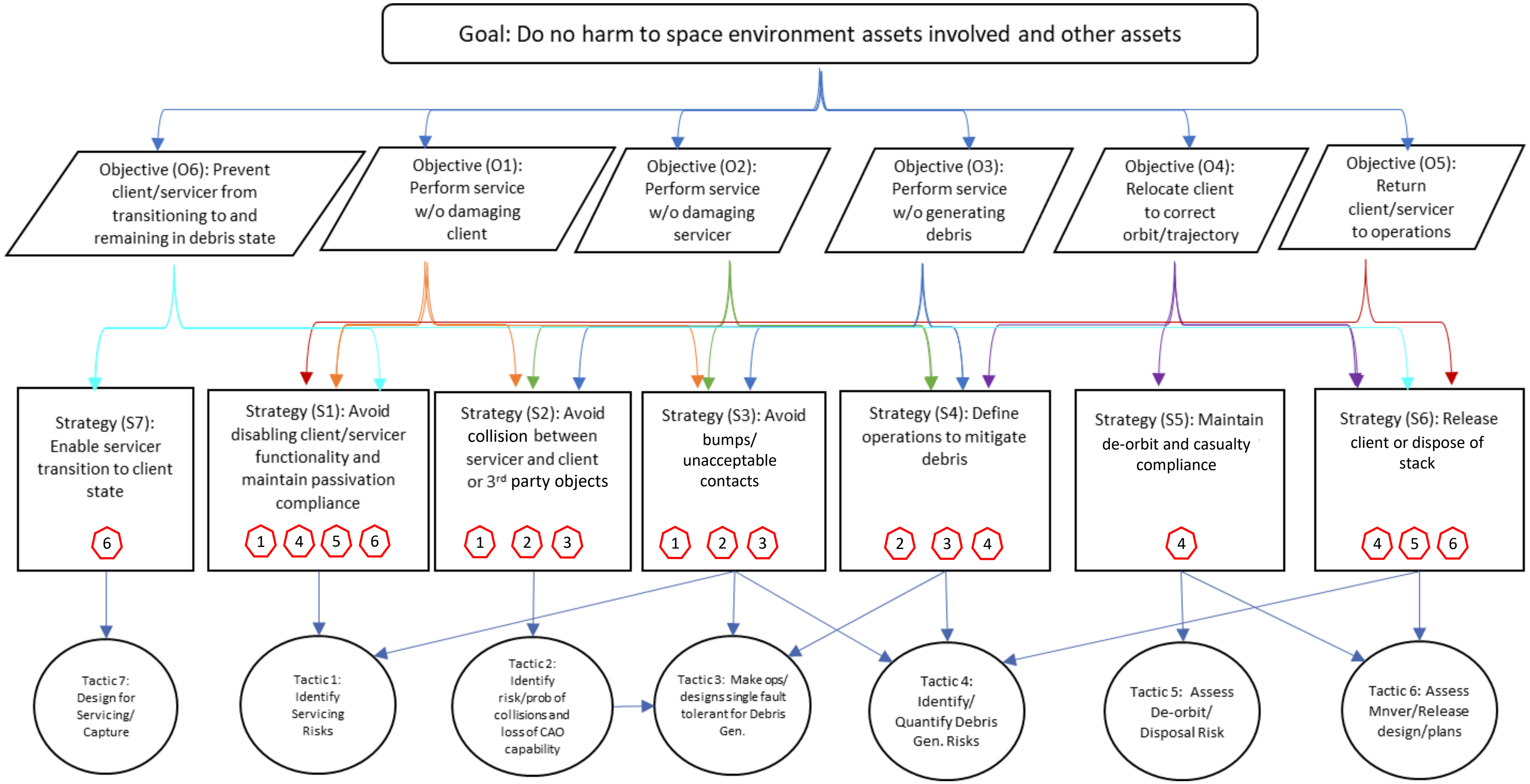
Name	Position	Relevant projects	Relevant Activities
Laura Delgado Lopez Frank Groen Matt Forsbacka/JC Liou Vicky Hwa	Senior Policy Analyst SMD/OTPS Dep Chief OSMA MASCD Director/ODPO Lead Sr Tech. Leader	N/A	Safe Rendezvous and Close Proximity Operations OSMA/MASCD/ODPO MPAD
Jason Emperador, Tammy L. Brown, Brian J Roberts	OSAM CSO OSAM Architecture Dep. Mgr, OSAM/NeXIS Dep. Program Mgr	RRM/OSAM projects	Safe Rendezvous and Close Proximity Operations
Ben Reed	Chief Technology Officer, Quantum Space	RRM projects	Safe Rendezvous and Close Proximity Operations Former Director of NASA's Exploration and In-Space Services Projects Division
Adina Cotuna	System Engineer	N/A	Safe Rendezvous and Close Proximity Operations Technical Lead of Close Proximity Operations (CPO) Working Group
Andrew Wolahan	System Engineer	ClearSpace-1 & other ADR / IOS projects	Safe Rendezvous and Close Proximity Operations Member of Close Proximity Operations (CPO) Working Group
Toru YAMAMOTO	Team Leader, Senior Researcher, Research Unit I, Research and Development Directorate	CRD2 (commercial removal debris demonstration)	R&D of - Active debris removal technologies - Guidance navigation and control technologies
Ryo NAKAMURA	Associate Senior Engineer, Research Unit I, Research and Development Directorate	CRD2 (commercial removal debris demonstration)	R&D of - Active debris removal technologies - Guidance navigation and control technologies

Stakeholder interviews led to identifying ADR/Servicing Objectives and that no new Reliability methods will be needed but current analysis methods will likely need to expand their scope to provide all the risk-to-value information needed.

- Servicing/ADR Support Discovery Process
    - Policies
    - Research
- Servicing/ADR Risk/Mission Assurance Support Codifications
    - **Tactics**
    - Tasks
- Summary

Tasks to Enable Viable Servicing/Active Debris Removal Objectives

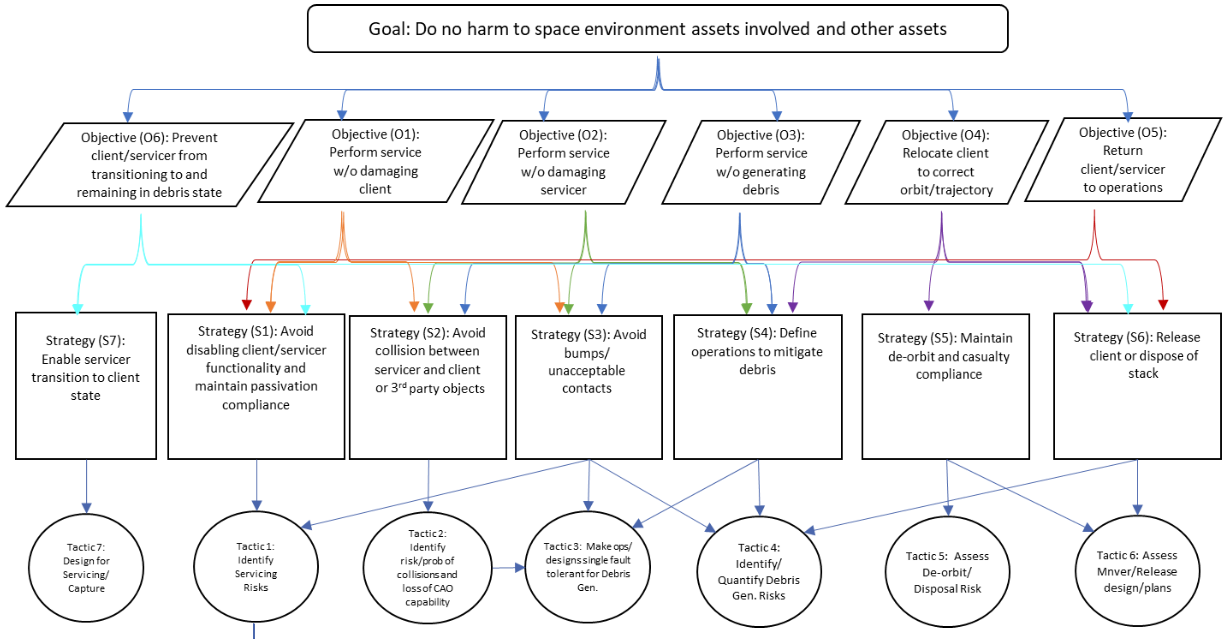
(NASA/SP-20230002885, ESA-TECQQD-TN-2023-000647, CAA-2022037)



Reviewers and Mission Assurance Experts can support these solutions and tactics by performing expanded and novel tasks with appropriate knowledge.

- Servicing/ADR Support Discovery Process
    - Policies
    - Research
- Servicing/ADR Risk/Mission Assurance Support Codifications
    - Tactics
    - Tasks
- Summary

Tasks to Enable Identification of Servicing/ADR Risks



RE Tasks

Task 1: Perform DNH/Failure Analysis (FMECA/FTA)
Task 2: Perform Probabilistic Assessment
Task 3: Perform Process FMECA/FT

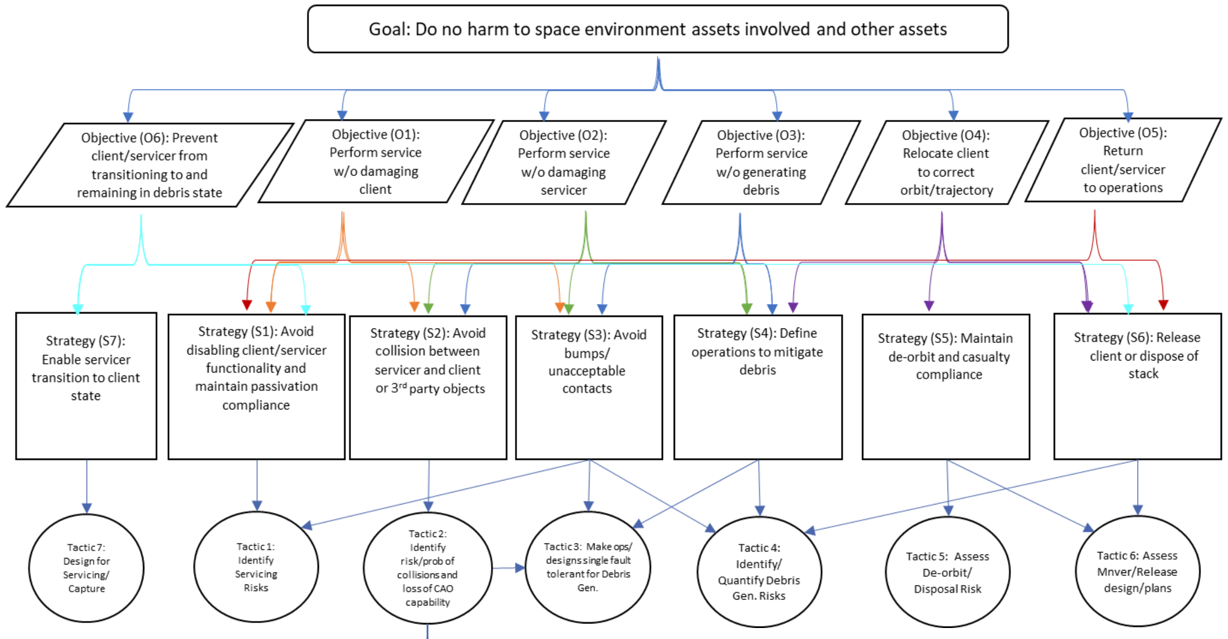
Knowledge Tasks

Task A: Life/Aging (systems/materials/structures) analysis of Client/Debris
Task B: Inspect Client from Ground, TLM, or On-orbit
Task D: Conduct Design Reviews to Ensure Serviceability Technology is present
Task E: Perform Orbit Analyses
Task G: Part/Material Testing/ Part/Material/Component Evaluation
Task H: Perform Entanglement/Release Risk and Hazard Assessments
Task I: Verify Trajectory is Safe
Task J: Perform collision avoidance operations
Task K: Select Capture method

Using failure and probability analyses to identify servicing/ADR risks is an achievable expansion in the practice (scope and focus) of the well-proven mission assurance methods.

Tasks to Enable Identification of Risk/Probability of Collisions and loss of CAO Capability

- Servicing/ADR Support Discovery Process
  - Policies
  - Research
- Servicing/ADR Risk/Mission Assurance Support Codifications
  - Tactics
  - Tasks
- Summary



RE Tasks

Task 2: Perform Probabilistic Assessment

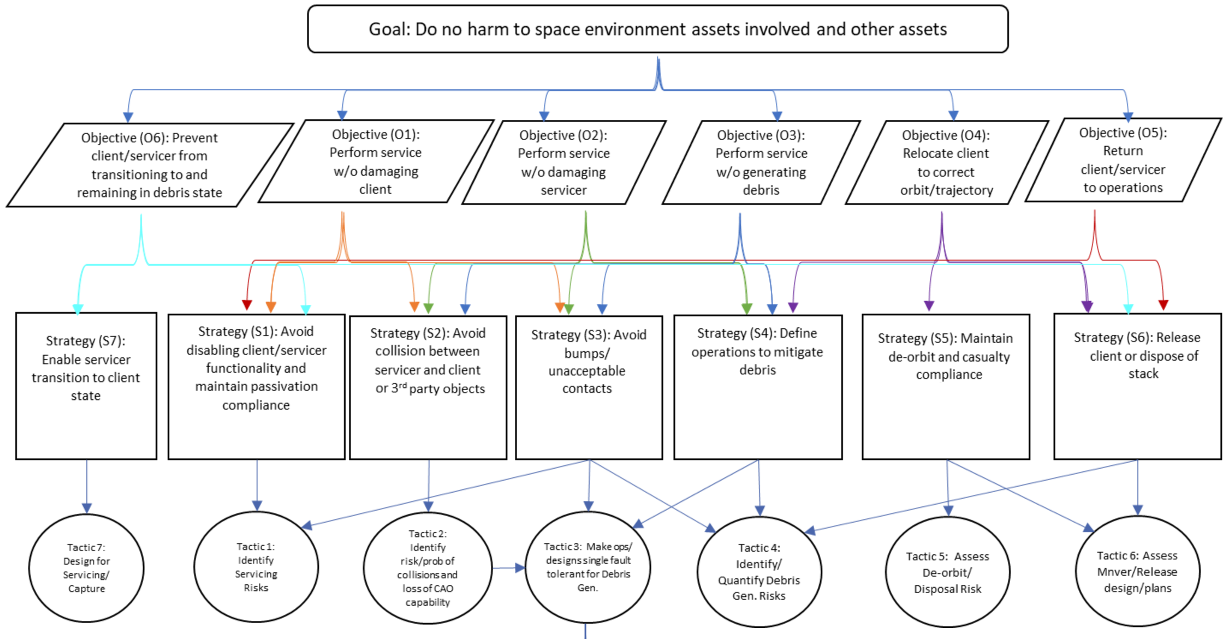
Knowledge Tasks

Task A: Life/Aging (systems/materials/structures) analysis of Client/Debris
Task B: Inspect Client from Ground, TLM, or On-orbit
Task E: Perform Orbit Analyses
Task G: Part/Material Testing/ Part/Material/Component Evaluation
Task I: Verify Trajectory is Safe
Task J: Perform collision avoidance operations

Applying probability analyses to assess collision risks is an achievable expansion in the practice (scope and focus) of the well-proven quantitative assurance methods.

- Servicing/ADR Support Discovery Process
  - Policies
  - Research
- Servicing/ADR Risk/Mission Assurance Support Codifications
  - Tactics
  - Tasks
- Summary

Tasks to Enable Operations/Designs to be Single Fault Tolerant for Debris Generation



RE Tasks

Task 2: Perform Probabilistic Assessment
Task 3: Perform Process FMECA/FT

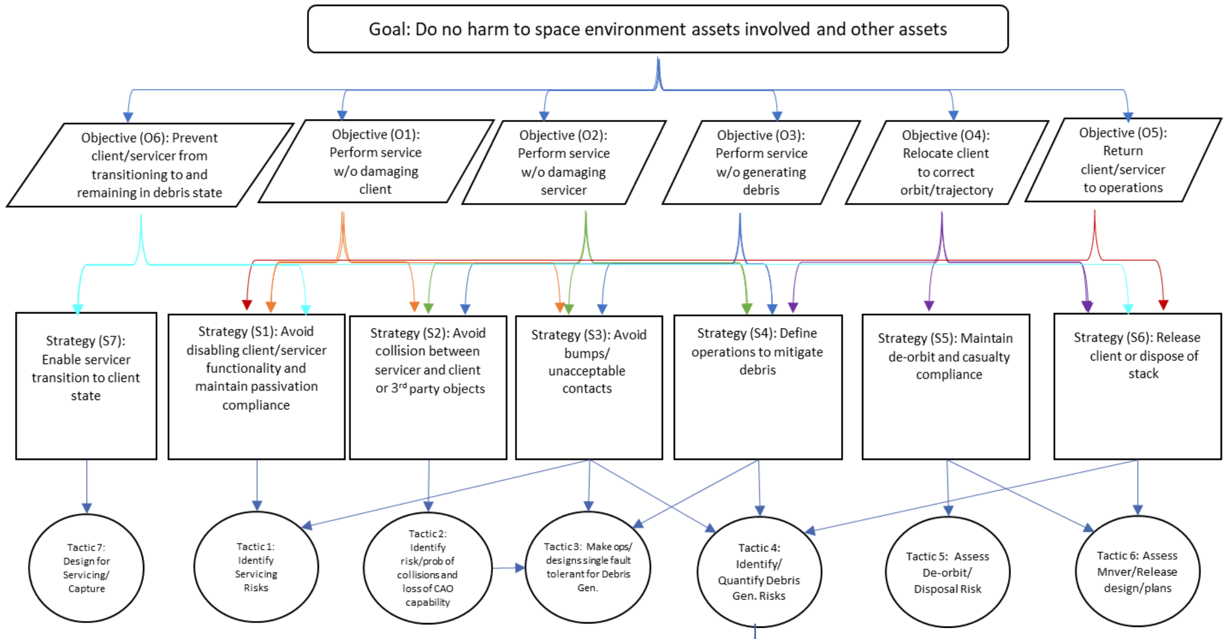
Knowledge Tasks

Task A: Life/Aging (systems/materials/structures) analysis of Client/Debris
Task B: Inspect Client from Ground, TLM, or On-orbit
Task C: Perform debris/break-up Testing /Modeling
Task D: Conduct Design Reviews to Ensure Serviceability Technology is present
Task E: Perform Orbit Analyses
Task G: Part/Material Testing/ Part/Material/Component Evaluation
Task H: Perform Entanglement/Release Risk and Hazard Assessments
Task I: Verify Trajectory is Safe
Task J: Perform collision avoidance operations
Task K: Select Capture method

Using hazard, failure, and probability analyses to refine designs/operations for minimum debris generation is an achievable with an expansion of the impact assessment focus.

Tasks to Enable Identification/Quantification of Debris Generation Risks

- **Servicing/ADR Support Discovery Process**
  - **Policies**
  - **Research**
- **Servicing/ADR Risk/Mission Assurance Support Codifications**
  - **Tactics**
  - **Tasks**
- **Summary**



RE Tasks

Task 3: Perform Process FMECA/FT

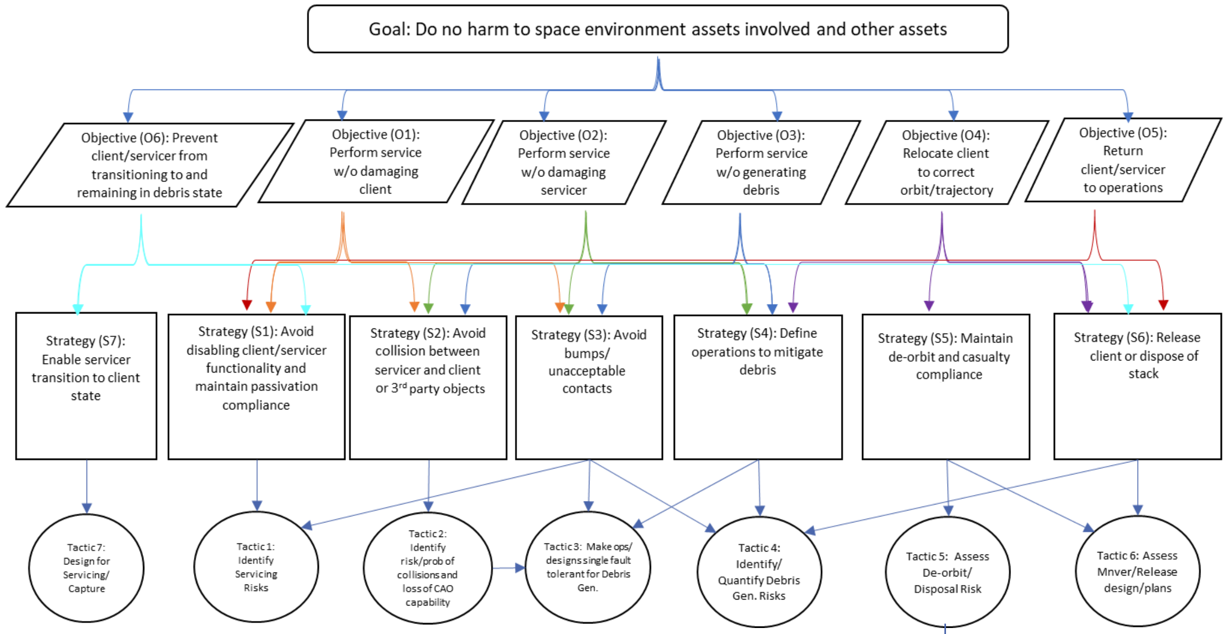
Knowledge Tasks

Task A: Life/Aging (systems/materials/structures) analysis of Client/Debris
Task B: Inspect Client from Ground, TLM, or On-orbit
Task C: Perform debris/break-up Testing /Modeling
Task D: Conduct Design Reviews to Ensure Serviceability Technology is present
Task G: Part/Material Testing/ Part/Material/Component Evaluation
Task H: Perform Entanglement/Release Risk and Hazard Assessments
Task K: Select Capture method

Using inspection and failure/hazard analyses to identify and quantify debris risks of a serving/ADR process is an achievable application of existing practices to a new question.

- **Servicing/ADR Support Discovery Process**
  - **Policies**
  - **Research**
- **Servicing/ADR Risk/Mission Assurance Support Codifications**
  - **Tactics**
  - **Tasks**
- **Summary**

Tasks to Enable Assessment of De-orbit/Disposal Risk



RE Tasks

Task 2: Perform Probabilistic Assessment
Task 4: Assess Probability of De-orbit

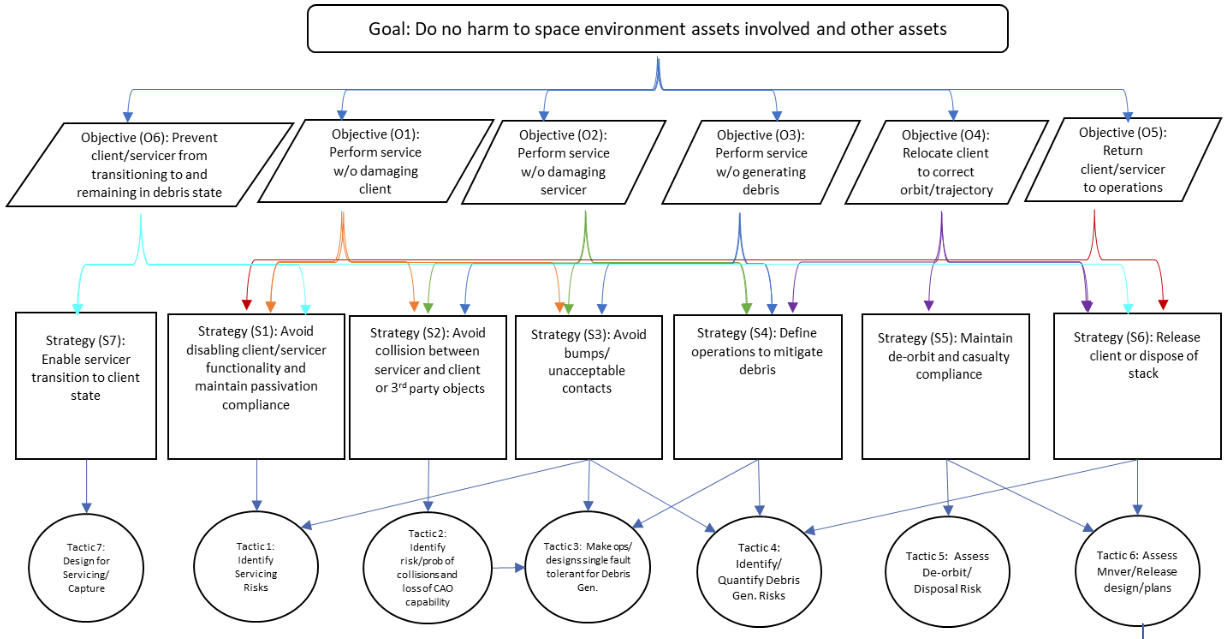
Knowledge Tasks

Task A: Life/Aging (systems/materials/structures) analysis of Client/Debris
Task B: Inspect Client from Ground, TLM, or On-orbit
Task E: Perform Orbit Analyses
Task F: Perform Casualty Analyses
Task G: Part/Material Testing/ Part/Material/Component Evaluation
Task I: Verify Trajectory is Safe
Task J: Perform collision avoidance operations

Servicing and ADR plans impact disposal risks. Assessing these risks is achievable by using proven methodology as documented in the Tri-Agency Reliability Engineering Guidance: Post Mission Disposal and Extension Assessment consensus document.

Tasks to Enable Assessment of Maneuver/Release Plans

- Servicing/ADR Support Discovery Process
  - Policies
  - Research
- Servicing/ADR Risk/Mission Assurance Support Codifications
  - Tactics
  - Tasks
- Summary



RE Tasks

Task 6: Perform Release Operations Risk Assessment

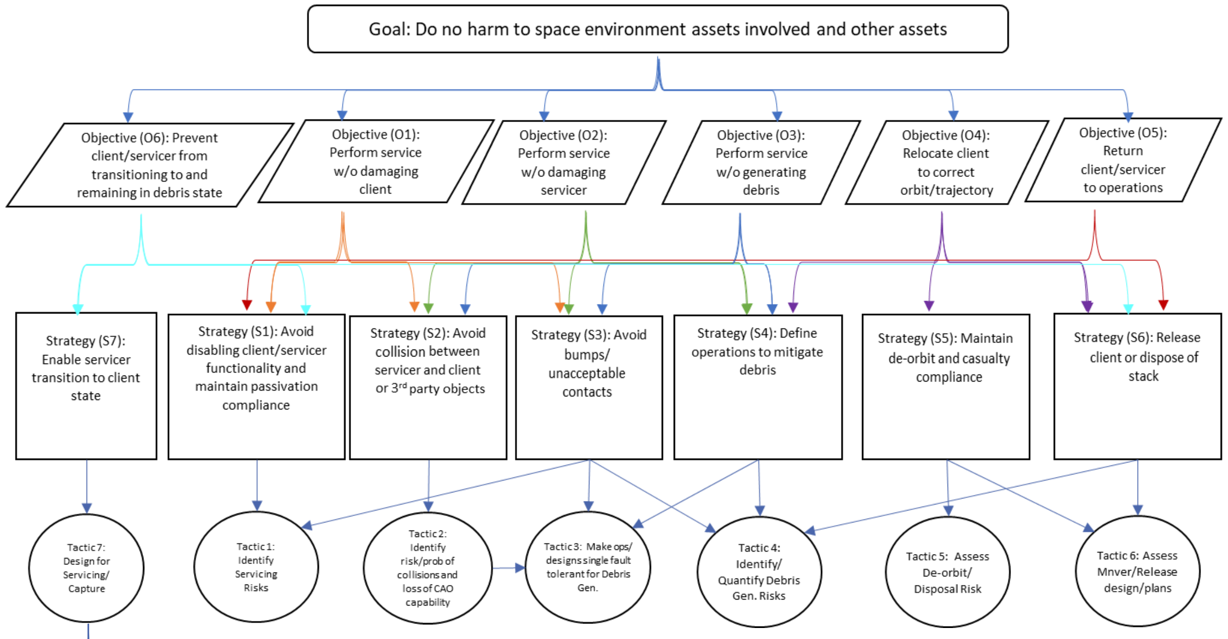
Knowledge Tasks

Task A: Life/Aging (systems/materials/structures) analysis of Client/Debris
Task B: Inspect Client from Ground, TLM, or On-orbit
Task C: Perform debris/break-up Testing /Modeling
Task E: Perform Orbit Analyses
Task G: Part/Material Testing/ Part/Material/Component Evaluation
Task H: Perform Entanglement/Release Risk and Hazard Assessments
Task K: Select Capture method

Using hazard, failure, and probability analyses to identify release/maneuvering risks is an achievable application of existing process assessment practices to new questions.

Tasks to Ensure Servicing/Capture Feasibility (Or Tasks to Assure Design Serviceability)

- Servicing/ADR Support Discovery Process
  - Policies
  - Research
- Servicing/ADR Risk/Mission Assurance Support Codifications
  - Tactics
  - Tasks
- Summary



RE Tasks

Task 1: Perform DNH/Failure Analysis (FMECA/FTA)
Task 5: Perform Serviceability/Maintainability Analyses

Knowledge Tasks

Task A: Life/Aging (systems/materials/structures) analysis of Client/Debris
Task B: Inspect Client from Ground, TLM, or On-orbit
Task D: Conduct Design Reviews to Ensure Serviceability Technology is present
Task E: Perform Orbit Analyses
Task G: Part/Material Testing/ Part/Material/Component Evaluation
Task H: Perform Entanglement/Release Risk and Hazard Assessments
Task I: Verify Trajectory is Safe
Task K: Select Capture method

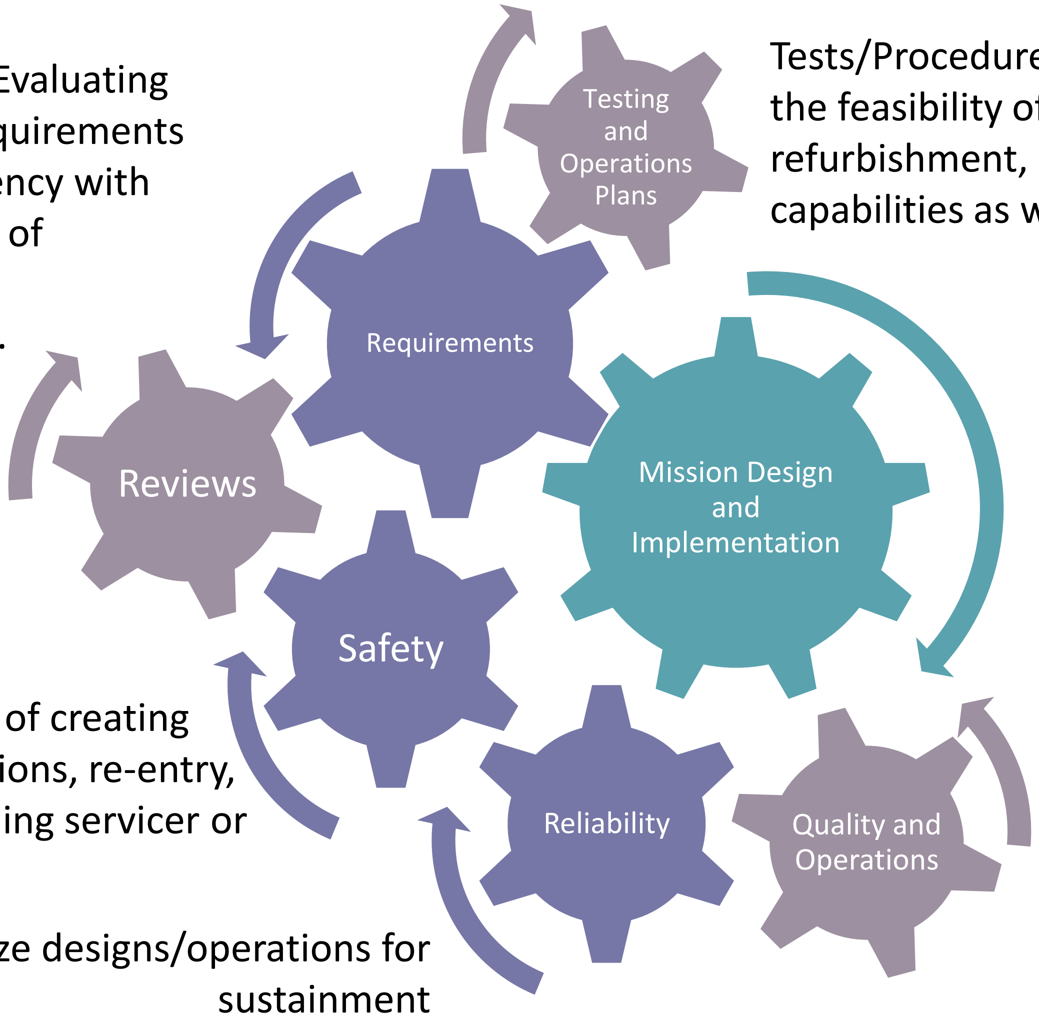
Using hazard, failure, and probability analyses to identify servicing risks is an achievable application in focus of existing process assessment practices. While Serviceability/ Maintainability Analysis is a new process (not a stand-alone event).

Serviceability Assessment/Maintainability Analysis

- **Servicing/ADR Support Discovery Process**
  - **Policies**
  - **Research**
- **Servicing/ADR Risk/Mission Assurance Support Codifications**
  - **Tactics**
  - **Tasks**
- **Summary**

Developing and Evaluating concepts and requirements for their consistency with the desired level of accessibility and Evolvability/ADR.

Tests/Procedures capture plausibility and the feasibility of contingencies, repair, refurbishment, and enhancement capabilities as well as system functionality;



Adopt servicer-cooperative ports/fittings, connectors, and ergonomic and location/capture features

Find the risk of creating debris, collisions, re-entry, and/or harming servicer or client.

Optimize designs/operations for sustainment

Verification and documentation of cooperative servicing/ ADR features and their functionality;

Serviceability Assessment/Maintainability Analysis will likely require multi-discipline expansion of proven methods and practices to assess adequacy, safety, and maintainability of designs, implementations, and operational/servicing plans.

Notional Task Planning to Enable Viable Servicing/Active Debris Removal Objectives

- Servicing/ADR Support Discovery Process
  - Policies
  - Research
- Servicing/ADR Risk/Mission Assurance Support Codifications
  - Tactics
  - Tasks
- Summary

Task Recommended / Mission Phase	Client Conceptual Design	Client Preliminary Design	Client Detailed /Critical Design	Client Implementation & Testing	Client Launch & Early Ops	Servicer Conceptual Design	Servicer Preliminary Design	Servicer Detailed Design	Servicer Implementation & Testing	Servicer Launch & Early Ops	Pre-Service & Proximity Ops: Client/ Servicer Ops	Pre-Service & Proximity Ops: Rendezvous & Inspection	Approach and Capture	Servicing	Re-orbit and/or Deorbit
Task 1: Perform DNH/Failure Analysis (FMECA/FTA)						Created	Update	Update	Update	Final		Update	Use as Anomaly Diagnostic tool		
Task 5: Perform Serviceability/ Maintainability Analysis	Created	Update	Update	Update	Final		Created	Update	Update	Final	Update	Update	Use as Anomaly Diagnostic tool		
Task D: Conduct Design Rvws to Ensure Serviceability Technology is present	Created	Updated	Updated	Updated	Updated	Created	Updated	Updated	Updated	Updated					
Task E: Perform Orbit Analyses	Created	Updated	Updated	Updated	Updated	Created	Updated	Updated	Updated	Updated	Updated Client	Updated (both)	Update (both)		Update (both)
Task F: Perform Casualty Analyses		Created	Updated	Updated			Created	Updated	Updated						Updated/ Verify

Task Recommended	Client Conceptual Design	Client Preliminary Design	Client Detailed /Critical Design
Task 1: Perform DNH/Failure Analysis (FMECA/FTA)			
Task 2: Perform Probabilistic Assessment			
Task 3: Perform Process FMECA/FT			
Task 4: Assess Probability of De-orbit		Created	Update
Task 5: Perform Serviceability/ Maintainability Analysis	Created	Update	Update
Task 6: Perform Release Operations Risk Assessment			
Task A: Life/Aging (systems/materials/ structures) analysis of Client/Debris		Created	Update
Task B: Inspect Client from Grnd, TLM, or On-orbit			
Task C: Perform debris/break-up Testing/Modeling*			Created

Reviewers and Mission Assurance Experts can support these solutions by performing expanded and novel Reviews, Hazard Analyses, Maintainability/Serviceability* Analyses, DNH/Ops/Process FMECA/FTs, Probabilistic Servicing/De-orbit Analysis, Ergonomic/Accessibility Testing, and Inspections with appropriate knowledge.

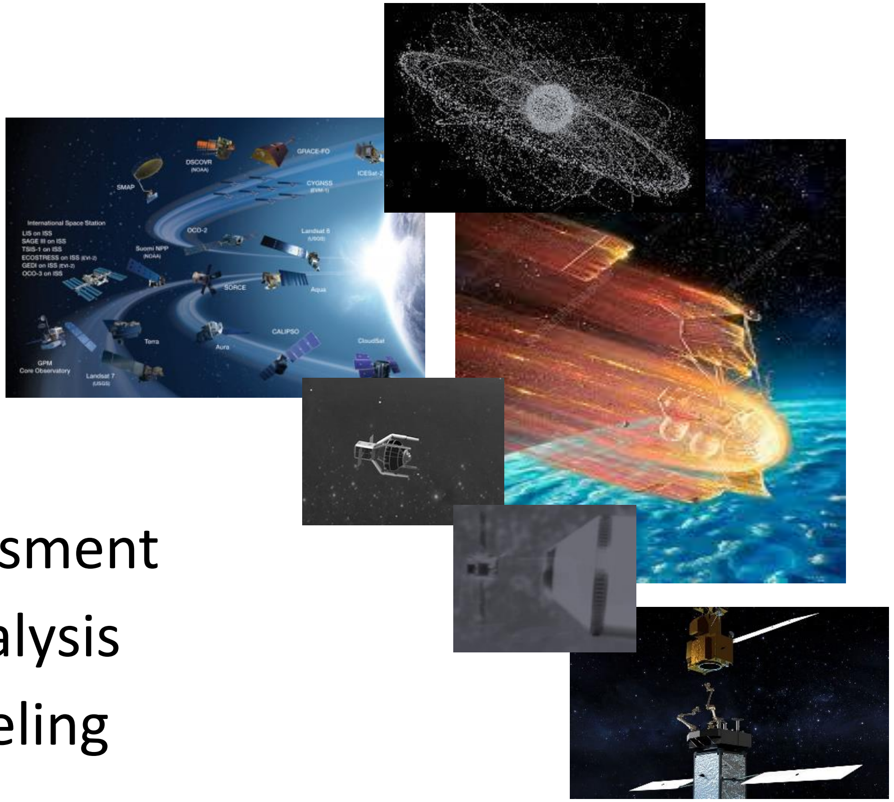
- Servicing/ADR Support Discovery Process
  - Policies
  - Research
- Servicing/ADR Risk/Mission Assurance Support Codifications
  - Tactics
  - Tasks
- **Summary**

Summary

Engaging Mission Assurance Support Provides:

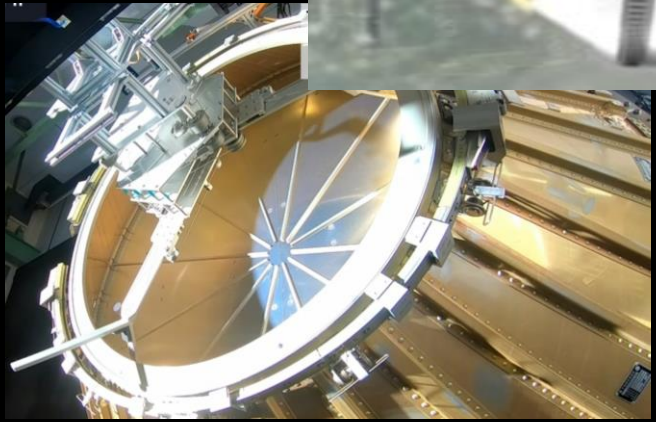
- Enhanced Failure Analysis
- Heightened Scenario Analysis
- Complex and Continual Asset Assessment
- Serviceability and Maintenance Analysis
- Situational Debris Generation Modeling and Testing
- Assurance of Servicer Viability and Feasibility

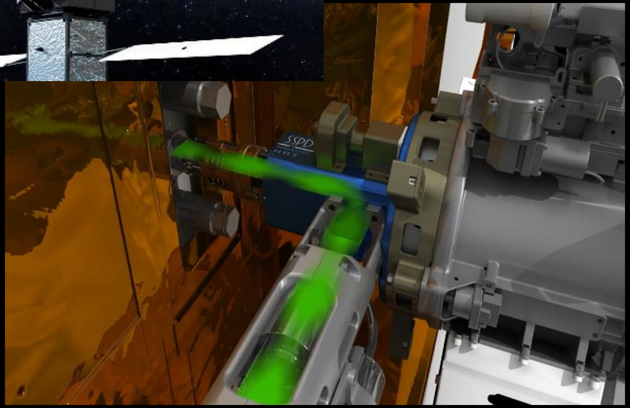
And assures Servicing/ADR feasibility, success, and safety.



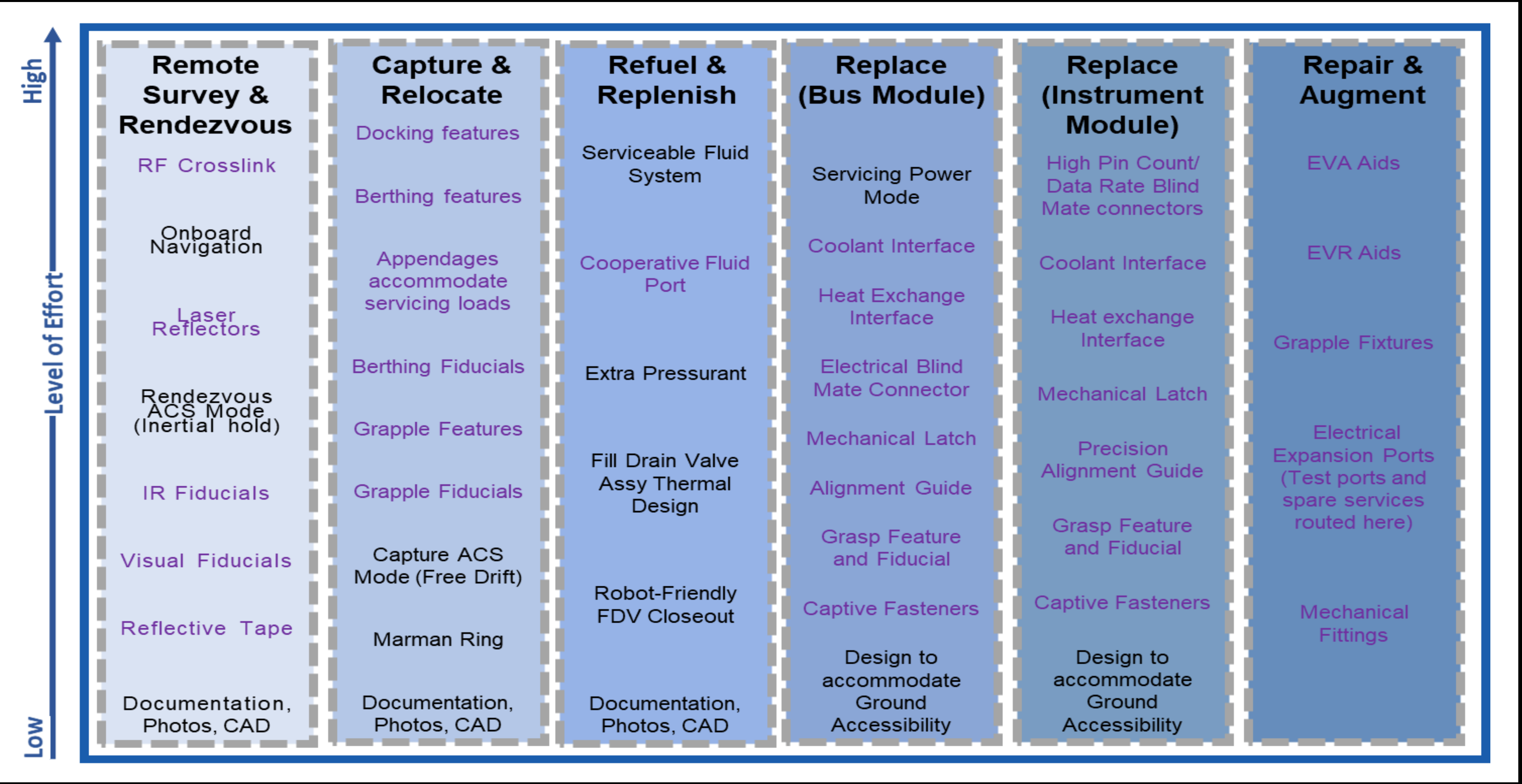
But all disciplines of Assurance Engineering need to support On-Orbit Servicing/ADR as early in the mission planning and formulation as possible.


Questions



BACKUP


High
Level of Effort
Low
Remote Survey & Rendezvous
RF Crosslink
Onboard Navigation
Laser Reflectors
Rendezvous ACS Mode (Inertial hold)
IR Fiducials
Visual Fiducials
Reflective Tape
Documentation, Photos, CAD
Capture & Relocate
Docking features
Berthing features
Appendages accommodate servicing loads
Berthing Fiducials
Grapple Features
Grapple Fiducials
Capture ACS Mode (Free Drift)
Marman Ring
Documentation, Photos, CAD
Refuel & Replenish
Serviceable Fluid System
Cooperative Fluid Port
Extra Pressurant
Fill Drain Valve Assy Thermal Design
Robot-Friendly FDV Closeout
Documentation, Photos, CAD
Replace (Bus Module)
Servicing Power Mode
Coolant Interface
Heat Exchange Interface
Electrical Blind Mate Connector
Mechanical Latch
Alignment Guide
Grasp Feature and Fiducial
Captive Fasteners
Design to accommodate Ground Accessibility
Replace (Instrument Module)
High Pin Count/ Data Rate Blind Mate connectors
Coolant Interface
Heat exchange Interface
Mechanical Latch
Precision Alignment Guide
Grasp Feature and Fiducial
Captive Fasteners
Design to accommodate Ground Accessibility
Repair & Augment
EVA Aids
EVR Aids
Grapple Fixtures
Electrical Expansion Ports (Test ports and spare services routed here)
Mechanical Fittings

Reliability Task Force Status/Closure

- **Previous TOR Status - Complete**

✓ Capture a Comprehensive set of Regulations/Documents on Spacekeeping.

- ISO 24113:2019
- JMR-003C/D
- JERG-2-026
- NASA STD 8719.14b
- ODMSP
- 2020 National Space Policy (US)
- 2018 Space Policy Directive-3 (US)
- NPR 8715.6B
- AF91-202
- ESSB-ST-U-007
- Space Activity Act
- FCC 20-54/04-130

Establish Similarity/Differences in Regulations/Documents on Spacekeeping. ✓

- ✓ Created/updated an International policy table
- ✓ Shared Regulation and Policy documents
- ✓ Discussed similarities and differences

✓ Compare reliability estimation methods for mission extension and post mission.

- ✓ Conducted methodology sharing briefings from each agency
- ✓ Shared example analyses
- ✓ Discussed similarities and differences

Establish common framework for extension and post mission disposal analysis. ✓

- ✓ Draft a Trilateral PMD/Extension Analysis Guidance Document
- ✓ Share the Draft Trilateral PMD/Extension Analysis Guidance Document (internally)
- ✓ Acquire each agency's release authorization
- ✓ Share the Trilateral PMD/Extension Analysis Guidance Document (externally)

https://ntrs.nasa.gov/api/citations/20210024973/downloads/Methodology%20Consensus%20Guidance%20Document%20(signed)1_19_22.pdf
https://ntrs.nasa.gov/api/citations/20220017699/downloads/Example%20Addendum%20(Final).pdf

Reliability Task Force Status/Closure

- **Current TOR Status - Complete**

Capture a Comprehensive set of Regulations/Documents on Servicing

- JERG-2-026
- IDA - On-Orbit Manufacturing and Assembly of Spacecraft
- IADC-02-01(2007)
- ISO/CD 24330
- 2020 National Space Policy (US)
- ODSMP
- 2018 Space Policy Directive-3 (US)
- Planned ECSS/ESA CPO Guidance Handbook
- NASA On-Orbit Satellite Servicing Study Project Report
- NASA COLA Handbook

✓ Review/Establish Similarity/Differences in Regulations/Documents on Servicing Reliability

Complete Recommendations for Agency Servicing/ADR Servicing/ADR Documents

✓ Codify technical considerations and reliability analyses for servicing/ADR
✓ Document Codifications
✓ Acquire each agency's release of
  ✓ Reliability Servicing/ADR Support White Paper
  ✓ Tri-Agency Reliability Engineering Post Mission Disposal and Extension Assessment Guidance Addendum

Provide Recommendations to Agency and ISO Efforts for Servicing Documents

✓ Codify technical considerations and analysis for reliability and viability of servicing
✓ Discuss analysis approach similarities and differences for serving for:
  - Mission Operations
  - Mission Disposal
✓ Expand scope and participation (Design/Safety/Mainatainbilty/Etc.)

Released
https://ntrs.nasa.gov/citations/20230002885

Release/Enhance PMD/Extension common guidance and examples

✓ Acquire each agency's release authorization
✓ Share the Trilateral PMD/Extension Analysis Guidance Document (externally)
✓ Provide/supplement the guidance document with examples.
✓ Engage in example discussions to share value assessments and approaches (common learning)
✓ Explore operational and analysis methodology advancements and update guidance as warranted and found via expanded data sharing.

21

Recommended Path Forward

Leverage TF Servicing/ADR Documents to guide agency and commercial space system/service providers.

- Refine current Code of Conduct (Policies/Requirements)
- Share codifications for Servicing/ADR with the greater space community via presentations/discussions

Review/Explore operational and analysis Methods for Serviceability Analysis

- Explore operational and analysis methodology advancements.
- Review/Establish best practice MTTF/MTTR /REL estimation
- Expand participation (Design/Safety/ Mainatainbilty/Etc.) for innovation, similarities and differences discussions

Expand/Capture Comprehensive Knowledge Gathering/Sharing Solutions

- Operations
- Integration and Test
- Design
- Sensor Optimization and Processing/Automation
- On-orbit Inspection
- Digital catalogs of knowns
  - In-orbit return of experience/lessons learned
  - Failure modes
  - Hazards

Update guidance as warranted and best Practice/Policy Recommendations

- Provide/supplemental guidance
- Provide roadmap of Serviceability assessment
- Provide Policy/practice recommendation to each agency
  - Reliability
  - Design
  - Operations
  - And others

Current Spacekeeping Strategies

- **Code of Conduct (Policies/Requirements)**
- **Design for Servicing/ADR**
- **Servicing**
- **Active Debris Removal (ADR)**

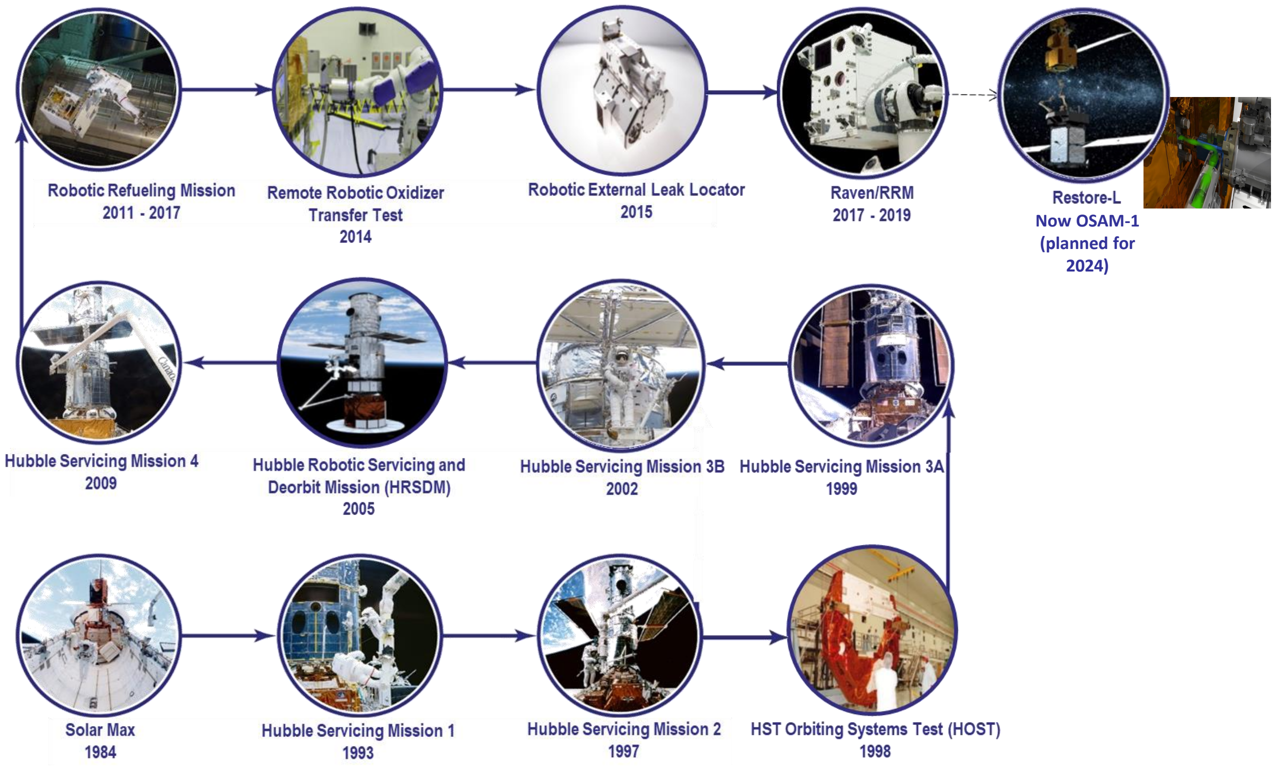
- Mitigate Debris generation in deployment and operations
- Minimize on-orbit break-ups caused by propellants, batteries, pressure vessels, self-destruct, wheels, or any other stored energy by Passivation and design
- NASA/DOD/ESA/JAXA Disposal minimum probability 0.9 requirement
- Limit natural-decay time from LEO NASA/DOD/ESA/JAXA to 25 years
- Retrieval of unusable satellites (or relocating to non-useful regions) within 5 years while mitigating debris generation
- Allowances for > 100 years of orbital storage/disposal
- Conduct Servicing or Active Debris Removal (ADR) while mitigating debris generation and/or collision/explosion risks
- Conduct Servicing while avoiding damage to client or servicer.

esa JAXA Jet Propulsion Laboratory California Institute of Technology NASA

Current Spacekeeping Strategies

- **Code of Conduct (Policies/Requirements)**
- **Design for Servicing/ADR**
- **Servicing**
- **Active Debris Removal (ADR)**

NASA has a long history of servicing and is continuing to advance those techniques:



esa JAXA Jet Propulsion Laboratory California Institute of Technology NASA

Current Spacekeeping Strategies

- **Code of Conduct (Policies/Requirements)**
- **Design for Servicing/ADR**
- **Servicing**
- **Active Debris Removal (ADR)**

ESA/JAXA are advancing ADR techniques with ClearSpace-1 and CRD2:

National Aeronautics and Space Administration

Lunar Surface Challenges TRISMAC 2024

NASA EHP SMA – Steven M. Fuqua

June 24-26, 2024

- Extravehicular Activity (EVA) and Human Mobility System Program (EHP)
- New NASA program established 2022
- Spacesuits, EVA Tools, and Rovers
- Early stages of Artemis surface exploration begin with EHP

Image: Artist's render of an Artemis astronaut collecting a sample on the lunar surface.

Next-Generation Spacesuits

- Being built to support both ISS and Artemis III+
- Increased flexibility and mobility for exploring new regions more efficiently
- Increased size range and modular design to accommodate a wider range of crew members
- Rechargeable systems enable more spacewalks and longer stays on surface
- Specialized tools to collect samples and returned them safely to Earth
- Axiom Space and Collins Aerospace have been chosen to provide EVA services

Image: Artist's render of an Artemis astronaut collecting samples on the lunar surface.

Axiom Extravehicular Mobility Unit Spacesuit

- Will be worn by the first woman on the Moon during the Artemis III mission
- Built on the heritage of NASA's xEMU design and the Agency's decades of spacesuit research and development
- Incorporates the latest technology, enhanced mobility, and added protection from hazards at the Moon
- Axiom will also provide next generation lunar tools to support the Artemis missions

Image: An Axiom Space engineer uses tongs to pick up a simulated lunar rock while wearing the AxEMU (Axiom Extravehicular Mobility Unit) spacesuit during testing at NASA's Johnson Space Center.

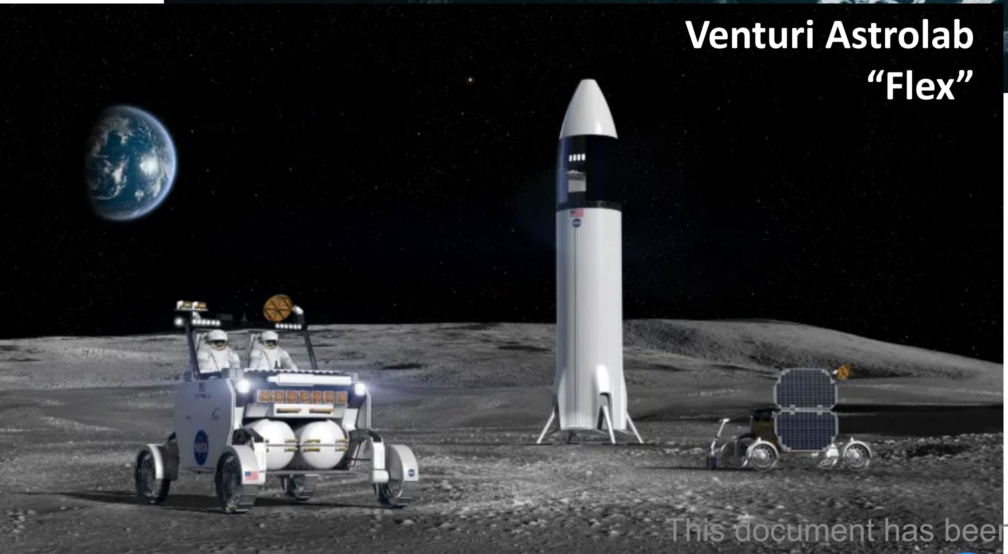
Collins Aerospace Next-Generation Extravehicular Mobility Unit

- Will be the next-generation of spacesuits NASA astronauts wear on the International Space Station (ISS)
- Designed to fit the diverse astronaut corps size range and to provide increased range of motion and flexibility
- Will incorporate new technology that is more efficient, more durable, and requires less maintenance than the current suit used by NASA astronauts on the ISS

Image: Collins Aerospace's chief test astronaut John "Danny" Olivas demonstrates a series of tasks during testing of Collins' next-generation spacesuit while aboard a zero-gravity aircraft.

Lunar Outpost
“Lunar Dawn”

Intuitive Machines
“Moon Racer”



Venturi Astrolab
“Flex”

Lunar Terrain Vehicle

- Initial surface transportation system for Artemis V+
- Significantly extends the range of crew excursions
- Enables more science, resource prospecting, and exploration on the lunar surface
- Tele-operation performs remote science during the non-crewed periods
- Transports and deploys small payloads and logistics
- Robotic manipulator supports science activities
- Provides video and imagery of landings, points of interest, and crew activities
- Informs and guides the design and execution of future lunar and Mars surface mobility solutions
- April 2024 awardees: Lunar Outpost, Intuitive Machines, Venturi Astrolab

Pressurized Rover

- Pressurized mobile habitation to enable long-range surface exploration in shirtsleeve environment for Artemis VII+
- Allows astronauts to explore outside the vehicle in their spacesuits
- Habitation for up to 30 days for 2 crew
- Volume for spares and logistics
- Power generation and energy storage for lunar environment
- Dust and radiation protection
- Supports multiple missions over 10-year lifetime
- Capability identified in current concepts for first human mission to Mars
- April 2024 - International Partner agreement with JAXA completed

EHP CHALLENGES

“Survive the Night”

Lunar South Pole

- The rovers initially used on the surface of the Moon for Artemis missions will be at least partially solar powered
- On the lunar South Pole, sunlight is always low on the horizon and has extended night periods (can be two-week cycles of darkness)
- Analysis indicates a “follow the sun” strategy will not be feasible in the Moon’s South Pole regions
- Vehicles will need to “hibernate” and survive up to 150 hours of darkness

Image: Apollo 15 mission commander David R. Scott with the Lunar Roving Vehicle on the edge of Hadley Rille (Rima Hadley) during the first moonwalk of the mission.

Communications/Navigation

- No real communication or navigation infrastructure is in place for early Artemis missions (limited comm satellites, no cell towers)
- Surface vehicles and spacesuits serve as communication relay equipment on lunar surface
- South Pole's rocky and mountainous terrain interferes with communication signals and with limited sunlight and long dark shadows, extended periods of darkness complicate simple navigation techniques
- Signals require boosting after only a few kilometers, so traverse distances are limited until comm infrastructure is in place
- No consistent magnetic field like on Earth for navigation (no true North, standard compass will not work)
- Size and relative distance of objects is very difficult for the crew to ascertain

EHP CHALLENGES

Dust Mitigation

During six Apollo missions, lunar dust clogged mechanisms, scratched optical covers, compromised seals, jammed geo-tools, irritated eyes and lungs, blocked vision during landing, and coated surfaces resulting in degraded system performance

- The Moon endures frequent micrometeorite impacts due to the lack of an atmosphere, creating a thin layer of highly broken and fragmented lunar material at the top of the regolith coating the lunar surface
- Lunar dust in the surface environment is negatively charged and susceptible to electrostatic buildup
- Lunar dust is abrasive; lack of water transport erosion and low gravity on the Moon allows dust to remain jagged
- Fine-grained, with a significant fraction that is smaller than the human eye can resolve...so visibly clean is NOT clean
- Unpredictable - behavior of lunar dust in space is governed by different forces than on Earth
- Difficult to analyze because behavior cannot be replicated without low gravity and zero atmosphere, making model validation difficult

@NASAARTEMIS

This document has been approved for public release per DAA #20240006980.”

OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION

Security–Regolith Explorer Spectral Interpretation, Resource Identification, and Security–Regolith Explorer

https://www.nasa.gov/?search=OSIRIS-REx

SAFETY & MISSION ASSURANCE

OSIRIS-REx Lessons Learned and Relearned

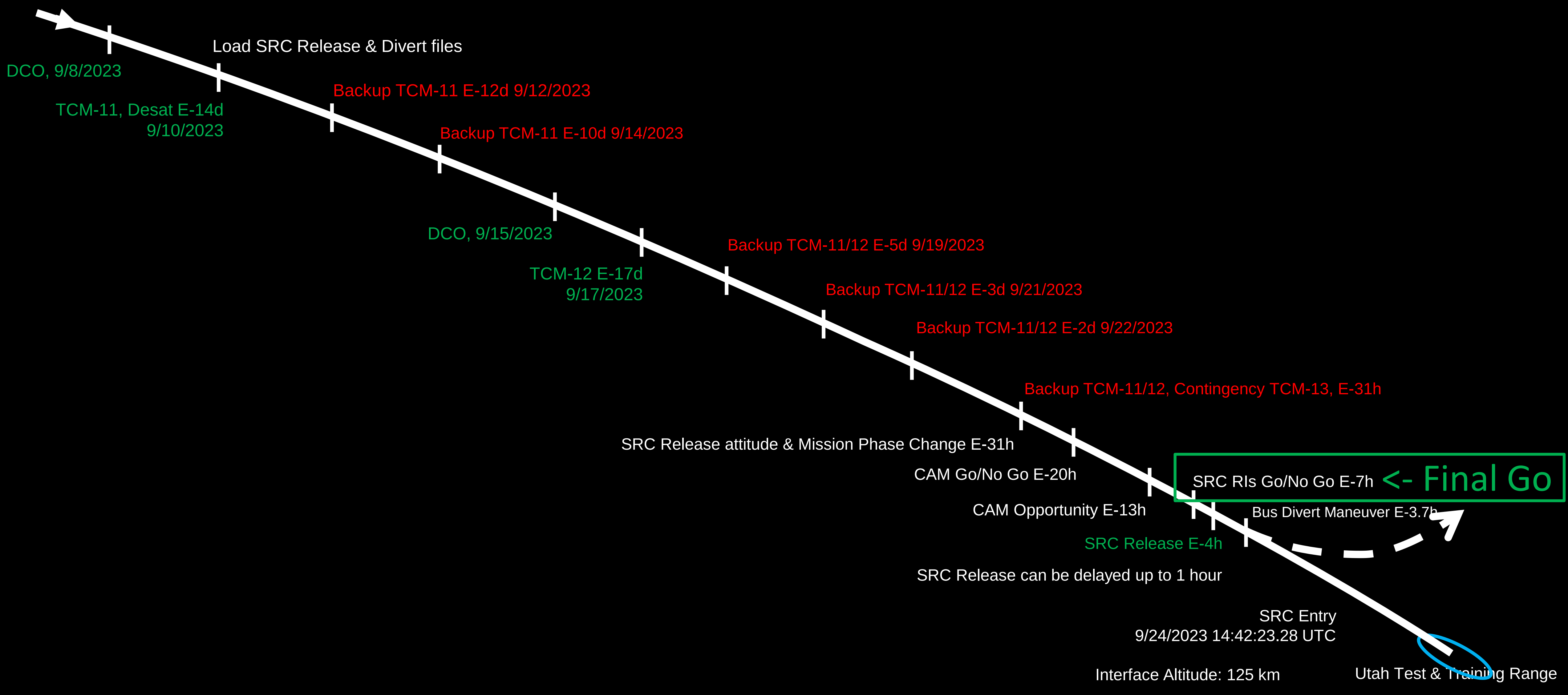
Ronald Perison
NASA/GSFC
ronald.e.perison@nasa.gov

SAFETY & MISSION ASSURANCE

Overview

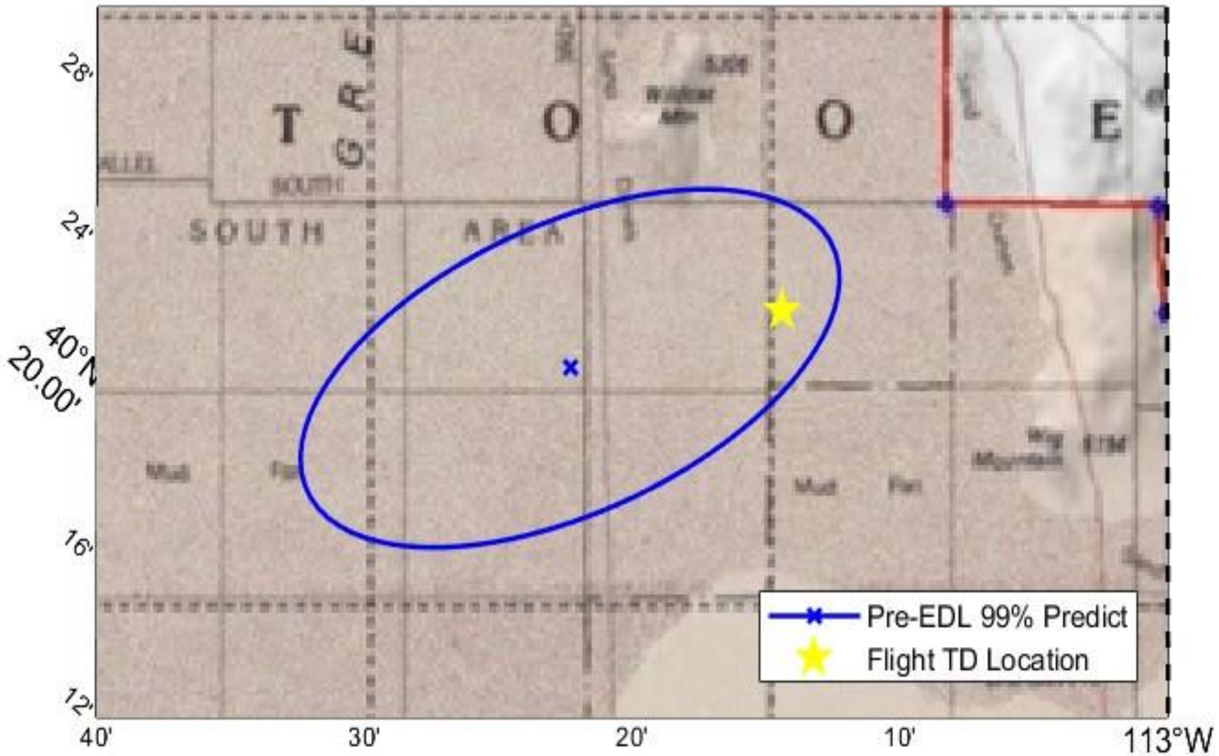
- This presentation focuses on the off-nominal parachute deployment of the OSIRIS-REx Sample Return Capsule (SRC) during earth entry on the final phase of flight
- The parachutes deployed later than planned although the actual landing and recovery were nominal
- The investigation by the joint NASA/Industry team discovered several Lessons Learned in the process of the Sample Return Capsule development effort, which largely treated this item through a Heritage "lens" since it was based on a previous NASA mission
- The evaluation of the returned flight hardware verified a miswiring of the harness sending signals from the electronics box to the parachutes which is consistent with video and timeline observed during decent and landing of the Sample Return Capsule

SMA
SAFETY & MISSION ASSURANCE



Load SRC Release & Divert files
DCO, 9/8/2023
Backup TCM-11 E-12d 9/12/2023
TCM-11, Desat E-14d
9/10/2023
Backup TCM-11 E-10d 9/14/2023
DCO, 9/15/2023
Backup TCM-11/12 E-5d 9/19/2023
TCM-12 E-17d
9/17/2023
Backup TCM-11/12 E-3d 9/21/2023
Backup TCM-11/12 E-2d 9/22/2023
Backup TCM-11/12, Contingency TCM-13, E-31h
SRC Release attitude & Mission Phase Change E-31h
CAM Go/No Go E-20h
SRC RIs Go/No Go E-7h
<- Final Go
CAM Opportunity E-13h
Bus Divert Maneuver E-3.7h
SRC Release E-4h
SRC Release can be delayed up to 1 hour
SRC Entry
9/24/2023 14:42:23.28 UTC
Interface Altitude: 125 km
Utah Test & Training Range

Overview (continued)



SAFETY & MISSION ASSURANCE

SAFETY & MISSION ASSURANCE

Heritage vs New Design

- Spacecraft components, particularly the Sample Return Capsule, were reviewed and evaluated for heritage based on orbital environment and application
- The implementation of build, inspection, and test was not always consistent for heritage vs new design items by the joint NASA/Industry team

Heritage Reviews

- The team did not consistently apply the design review rigor otherwise used on new and highly modified designs
- Drawing configuration review on “build to print” components was inconsistent from a process standpoint

Lessons Learned – The Good

- The overall Mission Design utilized appropriate redundancy and resiliency in the spacecraft and instruments to successfully execute the mission
  - The main parachute had enough strength to withstand higher than expected loads during the late deployment during reentry
  - The sample collected from asteroid Bennu far exceeded the mass needed to achieve mission success
- The mission Team had excellent and timely communications between NASA, Industry, and Academia partners
- Proactive Risk Management practices helped resolve technical, safety and programmatic risks before they became big issues
- The earth reentry of the Sample Return Capsule executed flawlessly
- The spacecraft consumable resources (power, fuel) were conserved and enabled OSIRIS-REx to continue an extended mission called APEX

SMA SAFETY & MISSION ASSURANCE

Lessons Learned (Relearned)

- The team did not apply sufficient rigor in some of the heritage elements
  - In some of the instructions and drawings, ambiguous language or/and drawing nomenclature introduced some uncertainty in intent or sequence of steps including interfaces and labeling on drawings
- Not rigorously adhering to “test as you fly” allowed an escape that may have flagged the parachute issue prior to flight

SAFETY & MISSION ASSURANCE

Lessons Learned (Relearned)

- The drawings were based on a 15-year-old design and some of the human expertise from that timeframe have retired
- Shortcomings in some configuration control of drawings have been identified. Thus, QA inspection of product to drawings that were not correct did not find the shortcomings

SAFETY & MISSION ASSURANCE

Conclusions

- Employing targeted, well thought out redundancy and resiliency in the mission design of the spacecraft, science instruments, and mission operations is a key factor in mission success
  - For example, the parachutes were single string, but the extra margin in them allowed them to handle the unexpected high loads from the late deployment
- Iterative Risk Management practices involving Management, Engineering and Safety and Mission Assurance needs to be proactive
- Rigorous review of heritage drawings and instructions are always needed to ensure proper configuration control is maintained
  - Drawing revisions and change notices always need to be verified
- "Test as you Fly" needs to be followed
- Sufficient budget and schedule, including reserves, for the mission allowed it to execute largely as planned with appropriate staffing

SMA
SAFETY & MISSION ASSURANCE

National Aeronautics and Space Administration

Moon to Mars Safety and Mission Assurance

Nathan Vassberg

M2M SMA Director

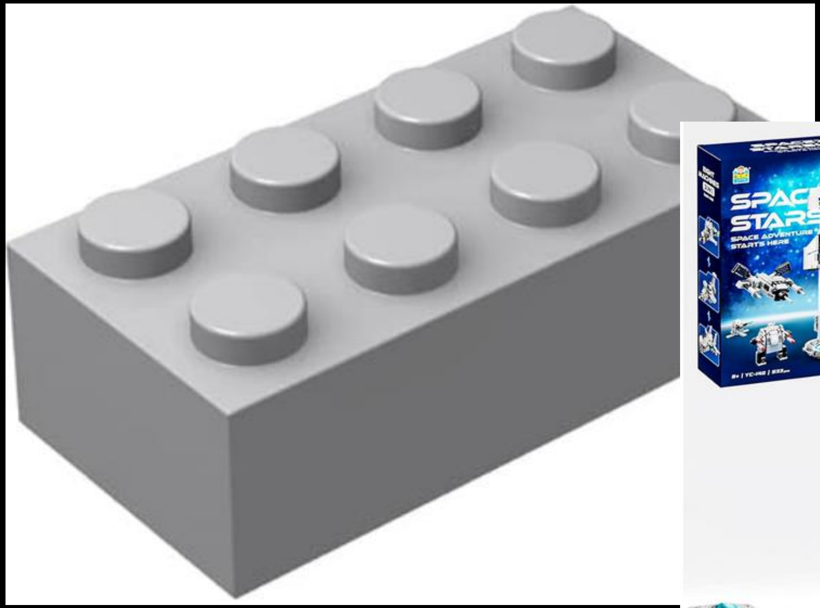
June 2024


ARTEMIS
ARTEMIS ACCORDS
Angola
Argentina
Australia
Bahrain
Belgium
Brazil
Bulgaria
Canada
Colombia
Czech Republic
Ecuador
France
Germany
Greece
Iceland
India
Israel
Italy
Japan
Luxembourg
Mexico
Netherlands
New Zealand
Nigeria
Poland
Republic of Korea
Romania
Rwanda
Saudi Arabia
Singapore
Spain
Ukraine
United Arab Emirates
United Kingdom
United States of America
Uruguay
United for Peaceful Exploration of Deep Space
AA-04.30.48

Artemis - SUCCESS and PREPARATION

Play Video Here

Exercise in Integration



Artemis: A Foundation for Deep Space Exploration


Space Launch System


Orion Spacecraft


Human Landing System


Surface Operations

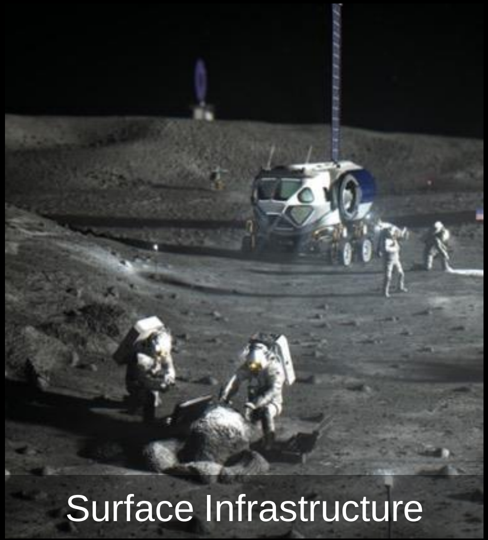

Gateway


Exploration Ground Systems


Space Communications & Navigation


Surface Mobility


Spacesuits


Surface Infrastructure

ARTEMIS I
First mission
(uncrewed flight test)

COMPLETED

ARTEMIS II
First crew

ARTEMIS III
First human
surface landing

Artist's Concept

ARTEMIS IV
First lunar space station
assembly mission

Artist's Concept

Gateway

Human landing system, spacesuits

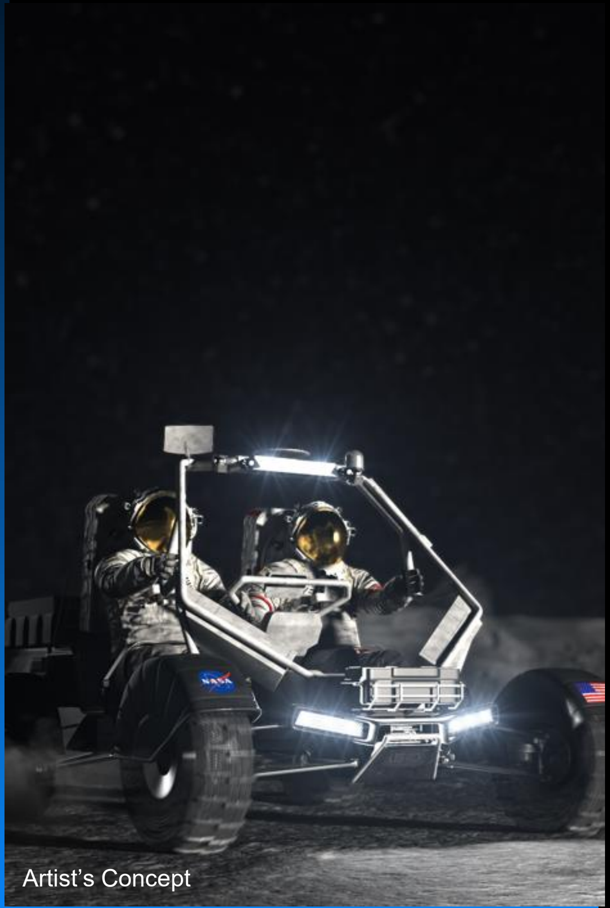
Crew

Space Launch System rocket, Orion crew spacecraft, Exploration Ground Systems

Conducting science and demonstrating technology and operations

ARTEMIS V

First unpressurized rover



Artist's Concept

ARTEMIS VI

Gateway assembly complete

Artist's Concept

ARTEMIS VII AND BEYOND

Longer missions = preparation for human Mars missions
Access to more of the Moon = new scientific discoveries

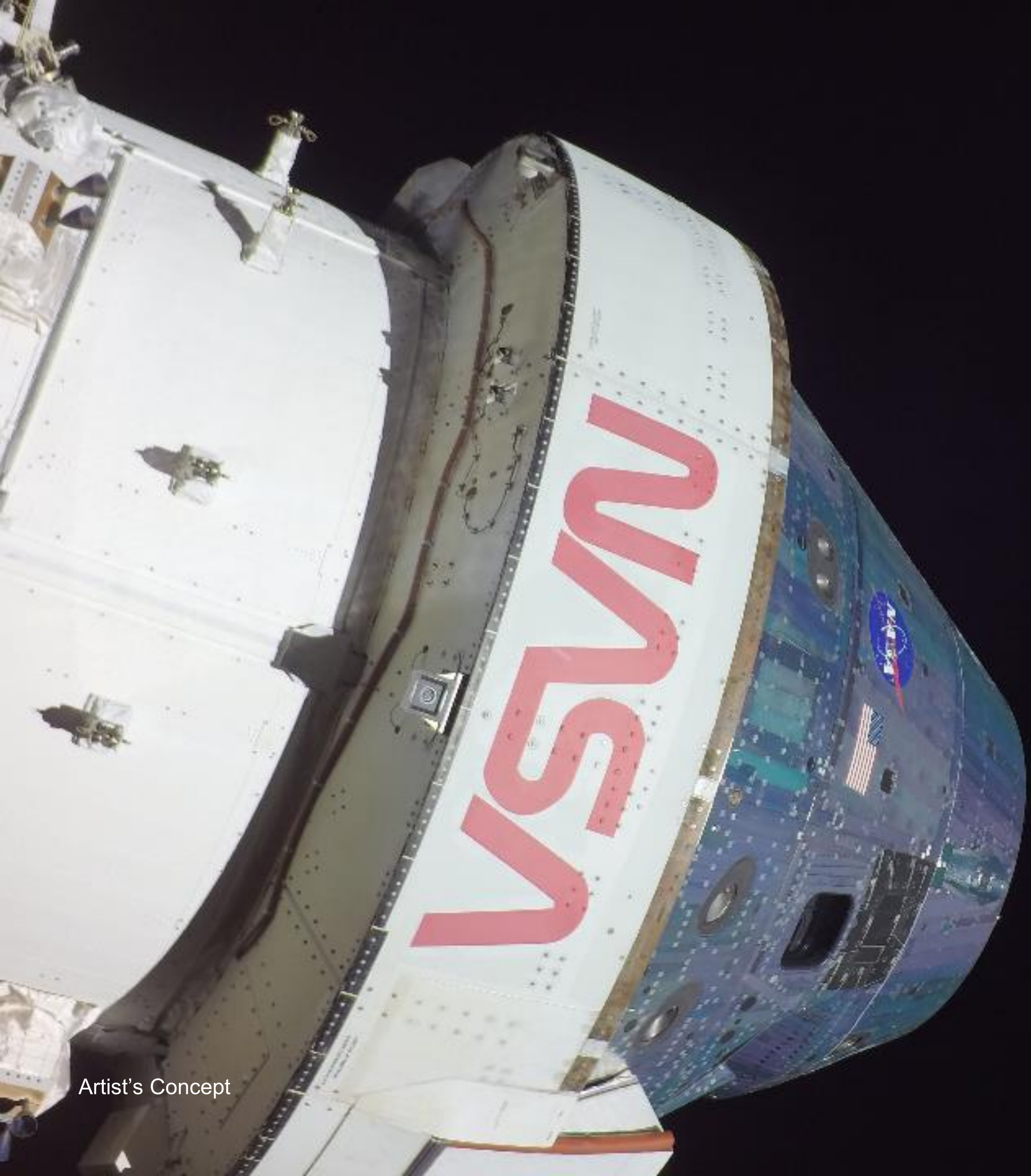
Artist's Concept

Pressurized rover, surface habitat, and other new elements

Gateway airlock module

Lunar terrain vehicle; Gateway refueling and robotics

Crew conducting science and demonstrating technology in orbit and on the surface;
Space Launch System rocket; Orion crew spacecraft; Exploration Ground Systems; Gateway space station



Artist’s Concept

Artemis II

ARTEMIS FIRSTS:

- Crewed integrated flight test of the Space Launch System (SLS) rocket, Orion spacecraft, and Exploration Ground Systems (EGS) at KSC
- Active Orion Launch Abort System (LAS)
- Demonstration of Orion life support systems
- Proximity operations demonstrations
- Human data collection in transit to and from the Moon, in lunar orbit, and through reentry and splashdown
- Conducting new science and technology demonstrations in orbit

NEW ELEMENTS:

- Orion life support systems
- Launch Complex 39B emergency egress system for crew and new liquid hydrogen system

COMMON ELEMENTS:

- SLS rocket Block 1 configuration
- Orion crew spacecraft
- Mobile Launcher 1

ENSURING CREW SAFETY IS OUR TOP PRIORITY!

THE ARTEMIS II CREW

The Artemis II crew represents thousands of people working tirelessly to bring us to the stars. This is their crew. This is our crew. This is humanity's crew.

Jeremy Hansen
Mission Specialist
Canadian Space Agency Astronaut

Reid Wiseman
Commander
NASA Astronaut

Victor Glover
Pilot
NASA Astronaut

Christina Hammock Koch
Mission Specialist
NASA Astronaut

Artemis II Progress

NASA Artemis Launch Director Charlie Blackwell-Thompson monitors activities during the Artemis II terminal countdown simulation

The first Artemis II launch simulation inside the Firing Room at the Launch Control Center at NASA's Kennedy Space Center. The team rehearses the steps to launch Artemis II mission

Artemis II crew members Reid Wiseman (foreground) and Jeremy Hansen participate in training in the Orion simulator

Artemis II crew during URT-10 Navy Diver Training at the Neutral Buoyancy Lab

U.S. Navy personnel grab onto a mockup of the Orion spacecraft during a practice procedure of the Underway Recovery Test 11 (URT-11)

NASA Artemis II crew members are assisted by U.S. Navy personnel as they exit a mockup of the Orion spacecraft in the Pacific Ocean during URT-11

The four Artemis II astronauts practiced procedures to exit the Orion spacecraft in an emergency

Orion test article delivered to NASA's Armstrong Flight Research Center

Artemis III

Artist's Concept

ARTEMIS FIRSTS:

- Human landing in South Pole region and return
- Orion to human landing system direct mission including crew docking activity
- Use of Near Rectilinear Halo Orbit (NRHO)
- Four astronauts to lunar orbit
- Two astronauts to lunar surface to collect scientific samples and data
- Conducting new science and technology demonstrations

NEW ELEMENTS:

- Orion full up rendezvous, proximity operations, and docking systems
- Starship human landing system
- Advanced spacesuits and tools to explore the surface and collect samples

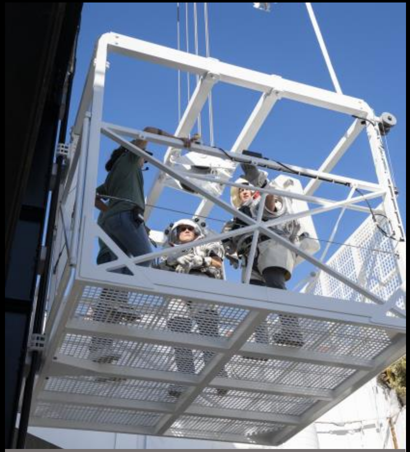
COMMON ELEMENTS:

- SLS rocket Block 1 configuration
- Orion crew spacecraft
- Mobile Launcher 1

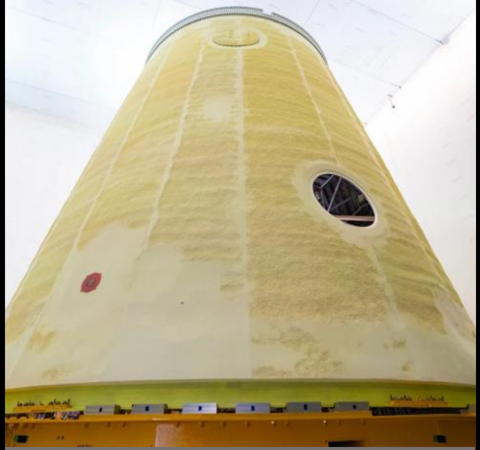
Artemis III Progress


Image: SpaceX

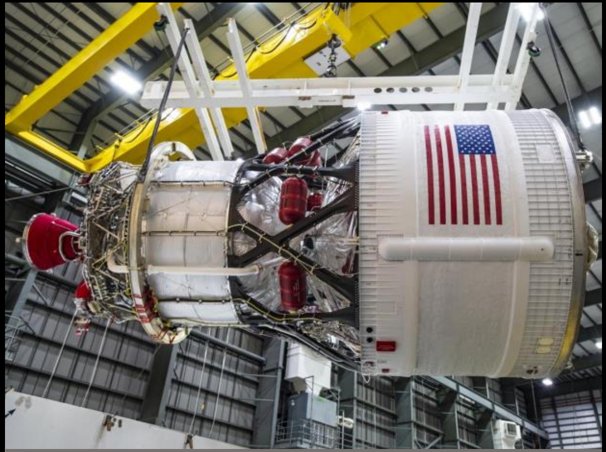
Starship second integrated flight test



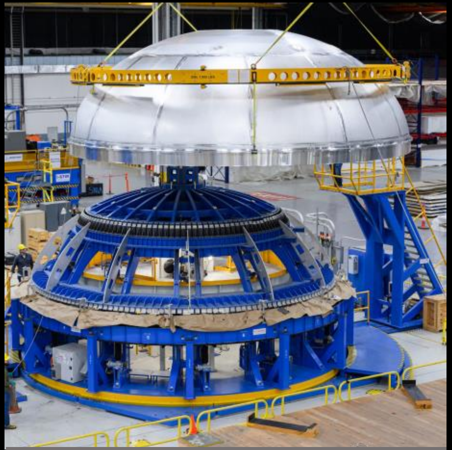
Starship Human Landing System elevator astronaut testing



Frangible joint assembly installed onto the Launch Vehicle Stage Adapter

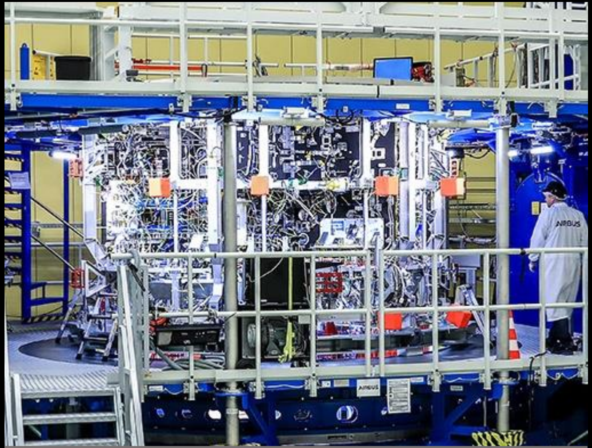


Artemis III Interim Cryogenic Propulsion Stage being processed



Artemis III Space Launch System Core Stage Liquid Oxygen Aft Dome

Starship Human Landing System docking system



European Service Module-3 integration in Bremen cleanroom

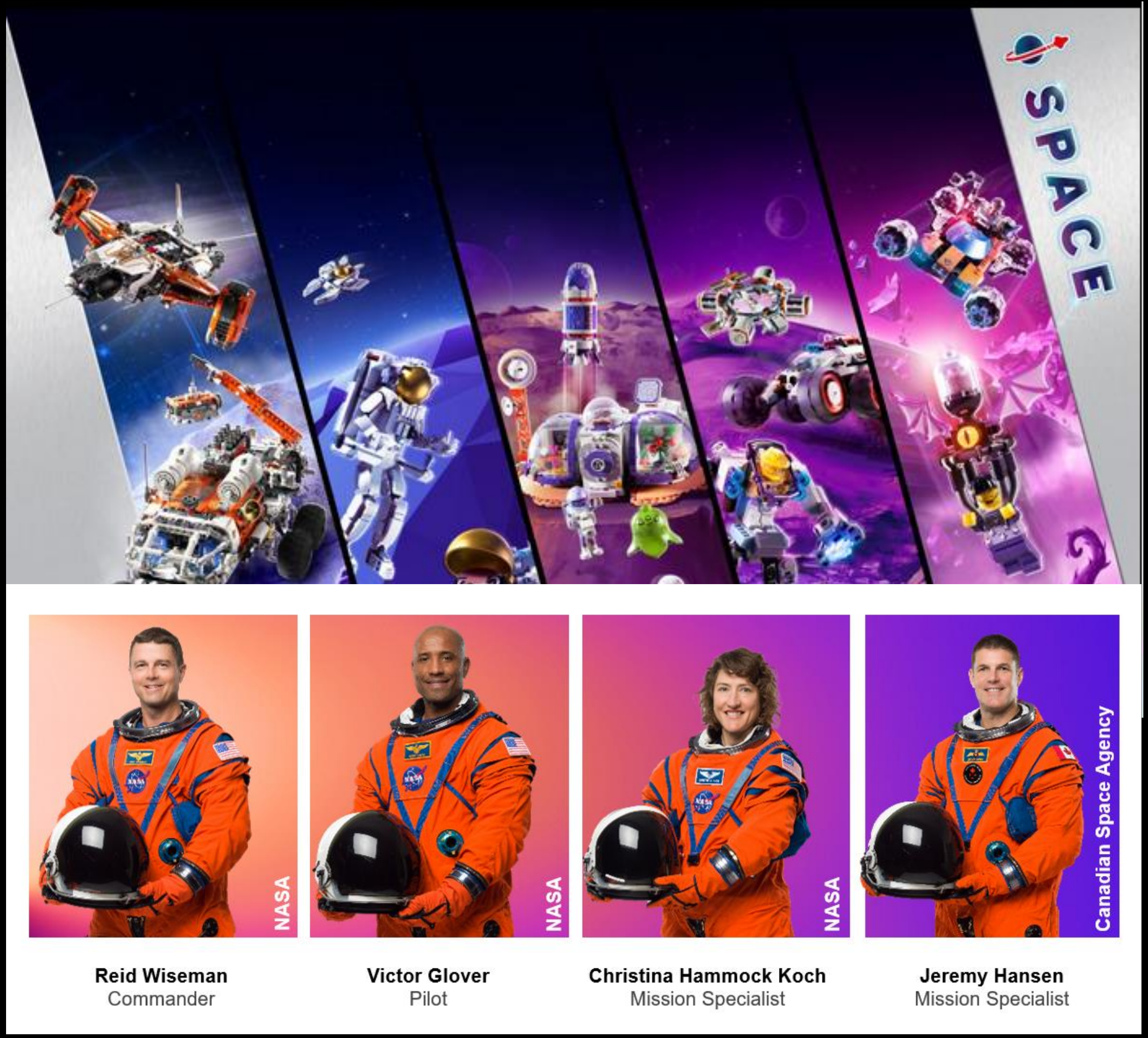
Crew Module-3 integration

Artemis III booster segments

M2M SMA – What is Important?

- Culture
- Integration
- Governance
- SMA Products
- Cross-Program SMA Products
- Communication
- Risk Leadership/Management

Summary/Conclusions



- "Thanks to our NASA Team, our Industry Partners, our International Partners…" Reid Wiseman
- "We are going to the Moon TOGETHER," Jeremy Hansen
- "It is the next step on the journey that gets humanity to Mars," Victor Glover
- "Am I excited, ABSOLUTELY YES!" Christina Koch
- M2M is about great people doing the amazing things
- Like Legos – just have to follow instructions and put the pieces together one at a time

Vassberg Artemis II- SUCCESS and PREPARATION_2-Min Presenter Short

Vassberg Artemis II- SUCCESS and PREPARATION_2-Min Presenter Short.mp4 (sharepoint.com)