

Engineering a Medical System for Human Spaceflight

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Aerospace Medicine Clerkship

Conflicts of Interest Disclosure

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I have financial interests in the above entities.

The opinions shared here are my own and not necessarily reflective of the above institutions.

Outline

- **An Historical Look at Exploration Medicine**
- **Upcoming Missions and Medical Challenges**
- **Risk and Spaceflight Events**
- **Getting the Medicine into the Engineering System**



AN HISTORICAL LOOK AT EXPLORATION MEDICINE



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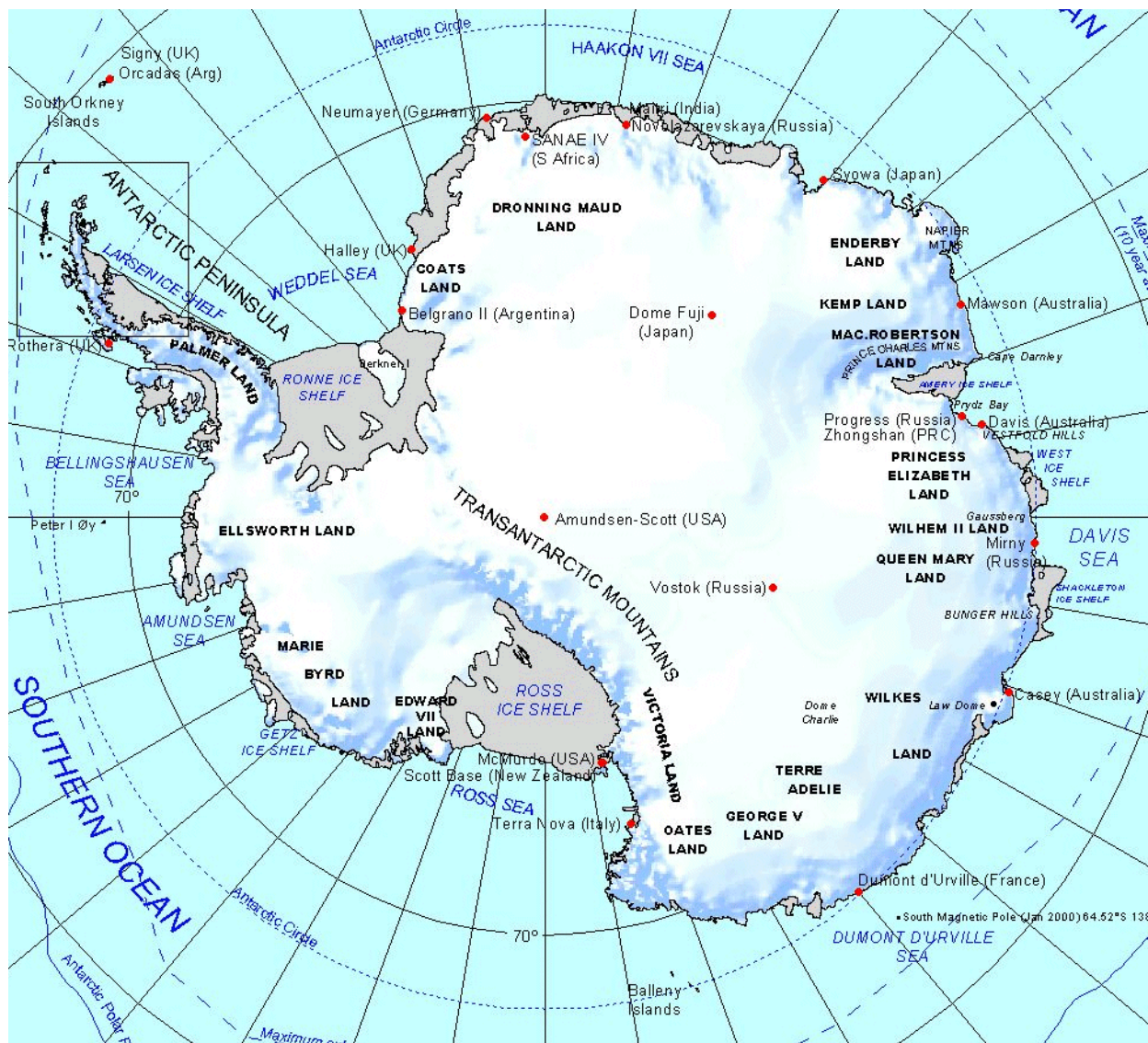
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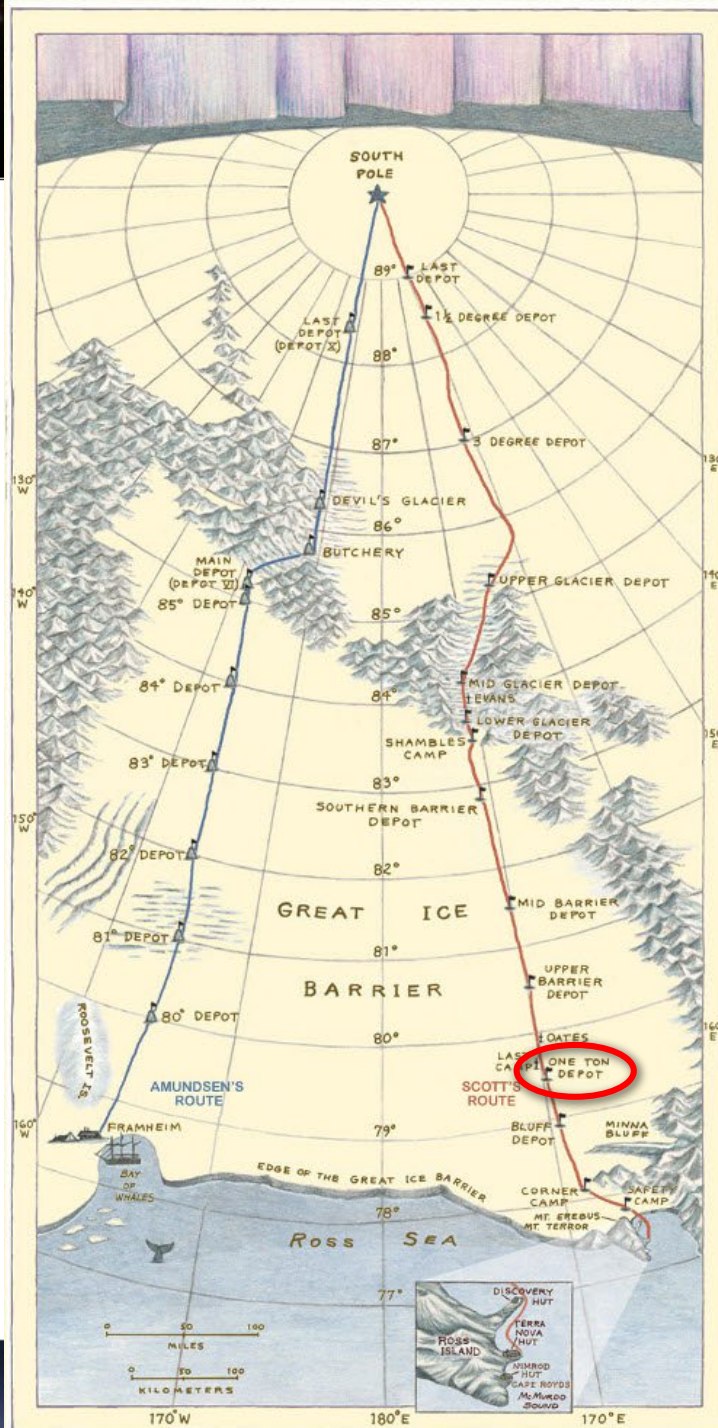
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Observation Hill





1911 - 1912



Amundsen and Scott Pole Race

Differences between Scott and Amundsen expeditions



Scott

- Overttechnologization (16 men, 23 dogs, 10 ponies, 13 sledges, 2 motor sledges)
- Followed what was tried before “because it worked”
- Thin margin of error
- Last minute decisions
- Died 12 miles short of his last food depot



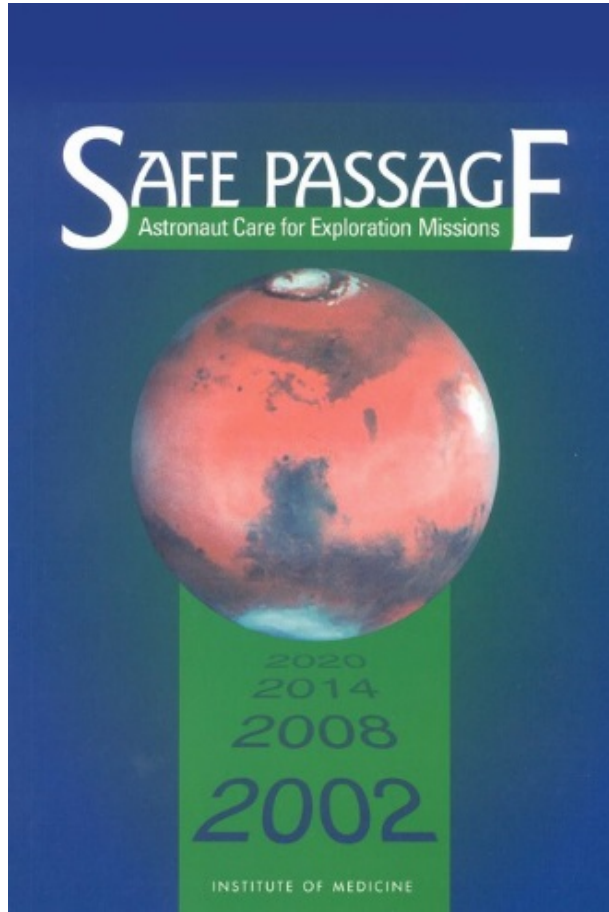
Amundsen

- Focused preparation (5 men, 20 dogs)
- Made a new path
- Significant margin of error
- Lots and lots of preparation and field testing
- Got to Pole first and lived

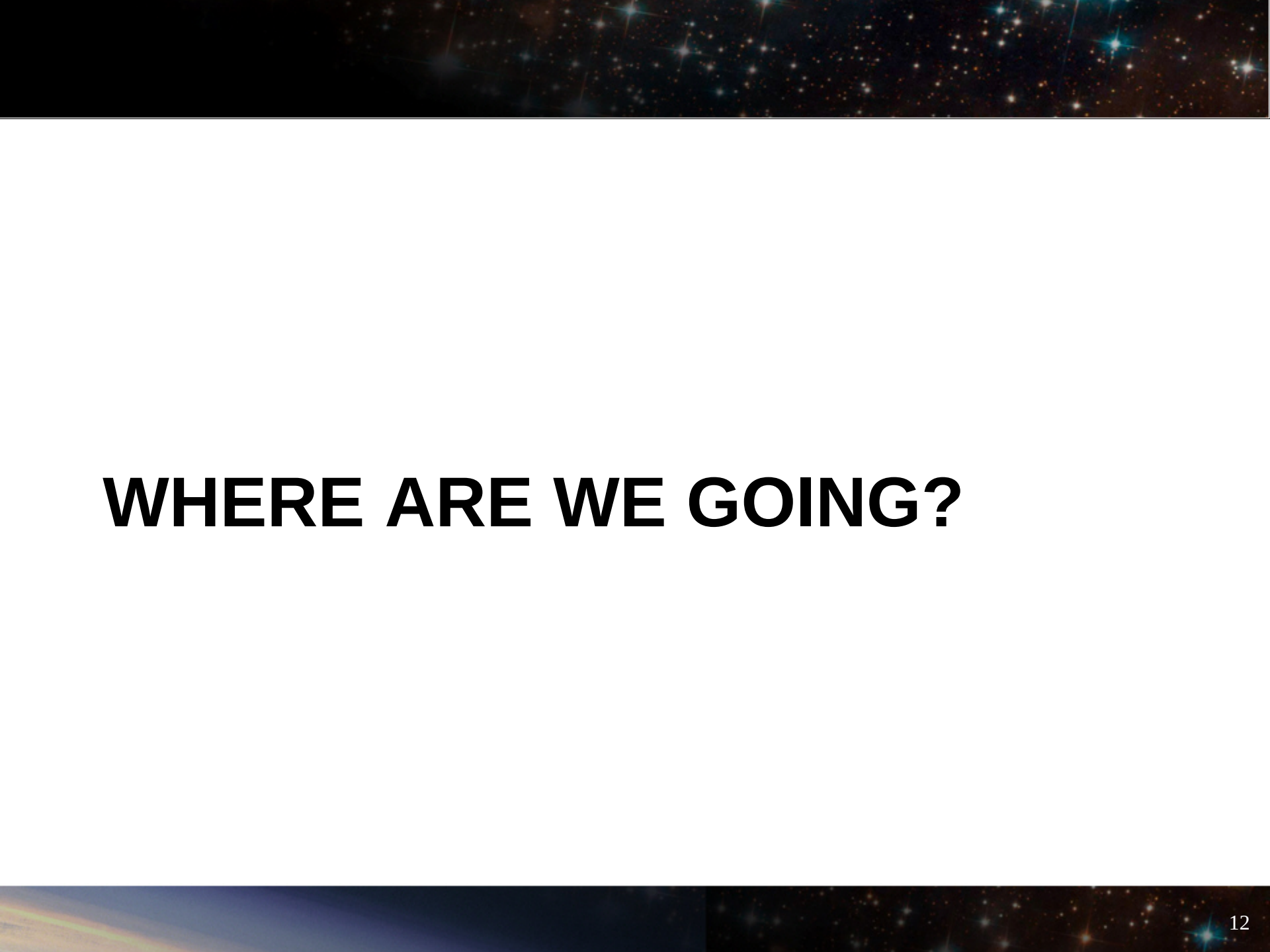


There are evidence-based ways to systematically identify and match what is needed from a health perspective with what gets fielded in a mission

Our work continues...



- *From Conclusion 6:*
- *“The human being must be integrated into the space mission in the same way in which all other aspects of the mission are integrated.”*



WHERE ARE WE GOING?

NASA Human Spaceflight Missions

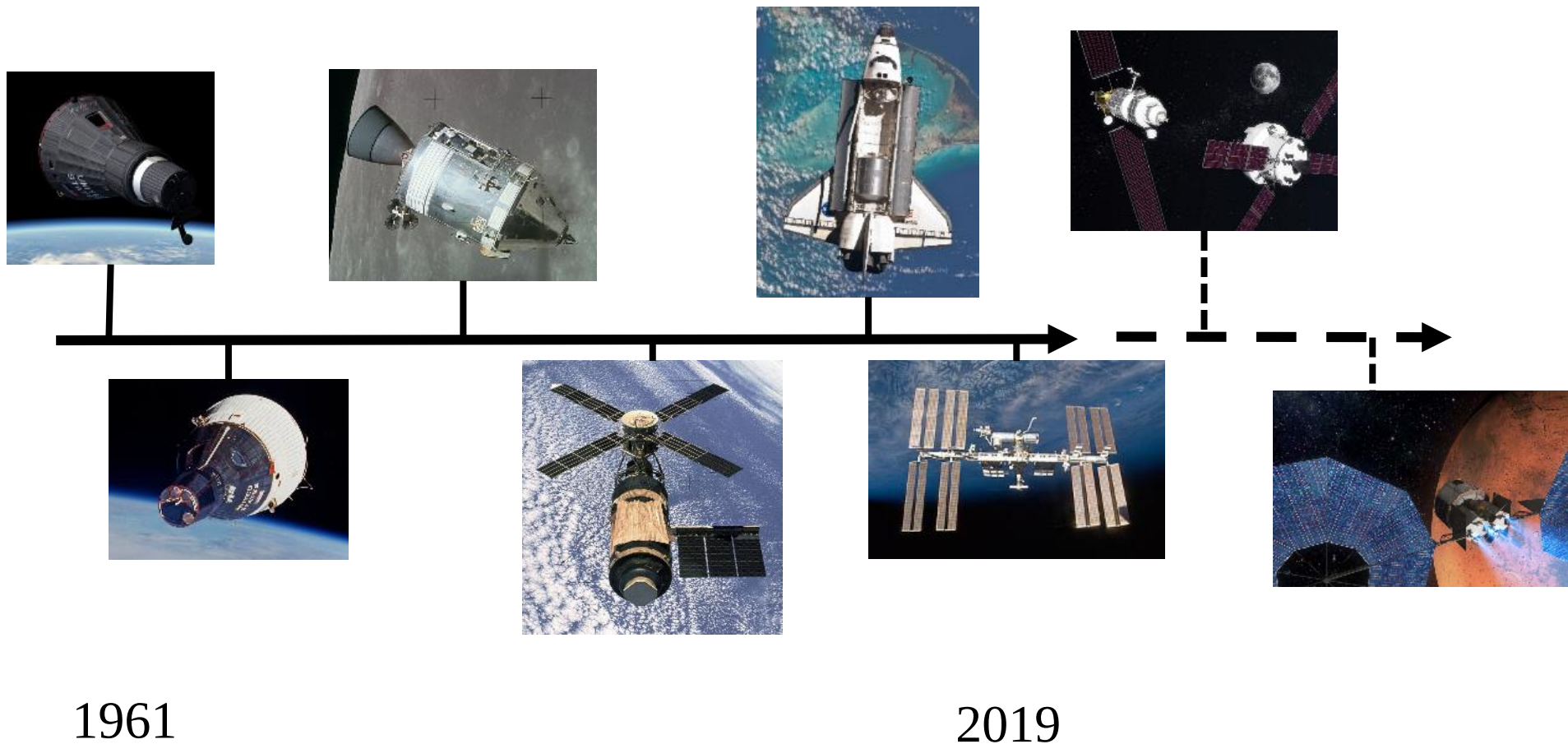
- Soyuz Launch and Landings
- International Space Station
- Commercial Crew Program
- MultiPurpose Crew Vehicle
- Gateway Habitat
- Deep Space Transport
- Mars Missions

Near Term (Current - 5 yrs)

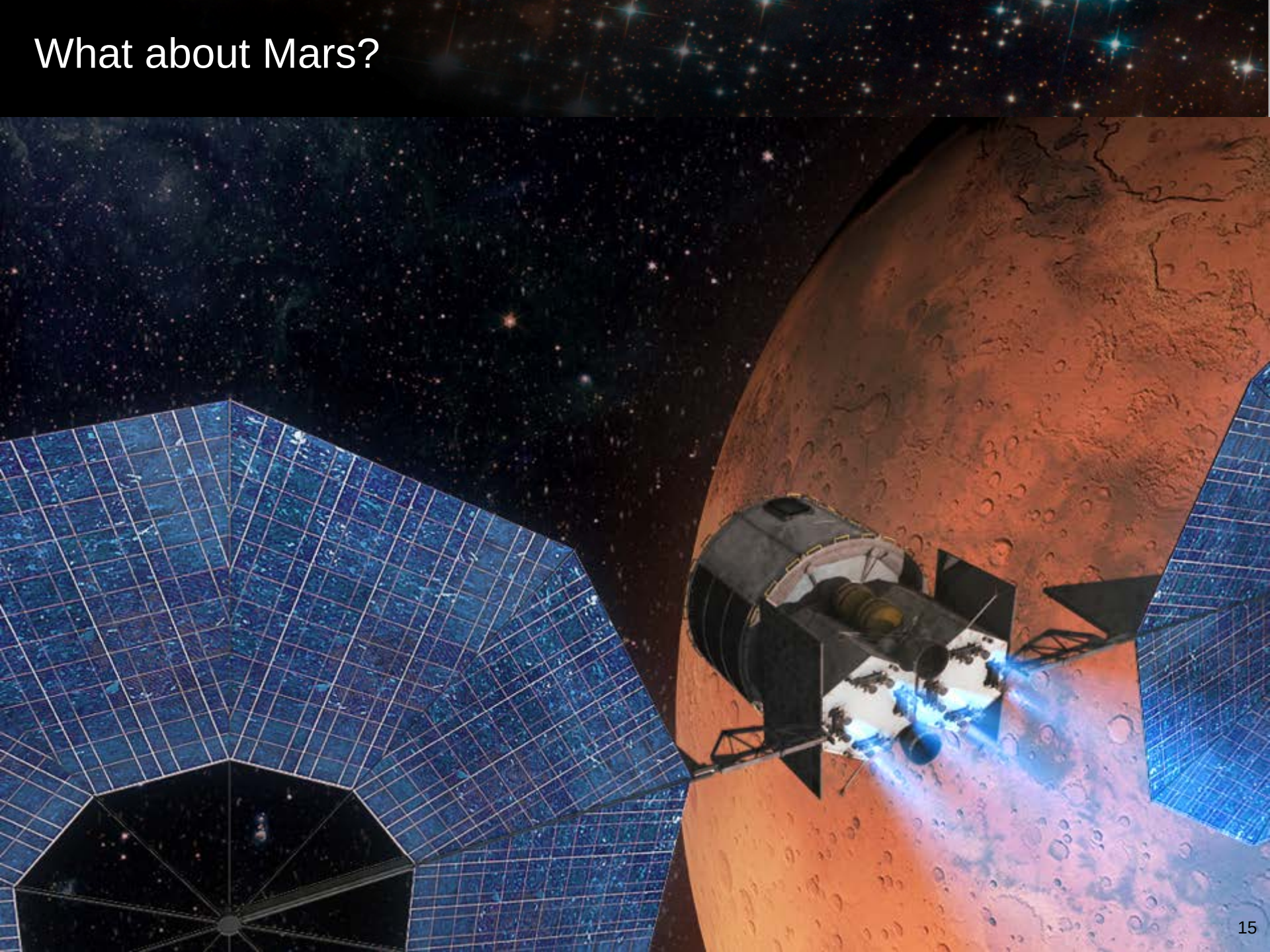
Medium Term (within 10 yrs)

Long Term (10 – 20 yrs)

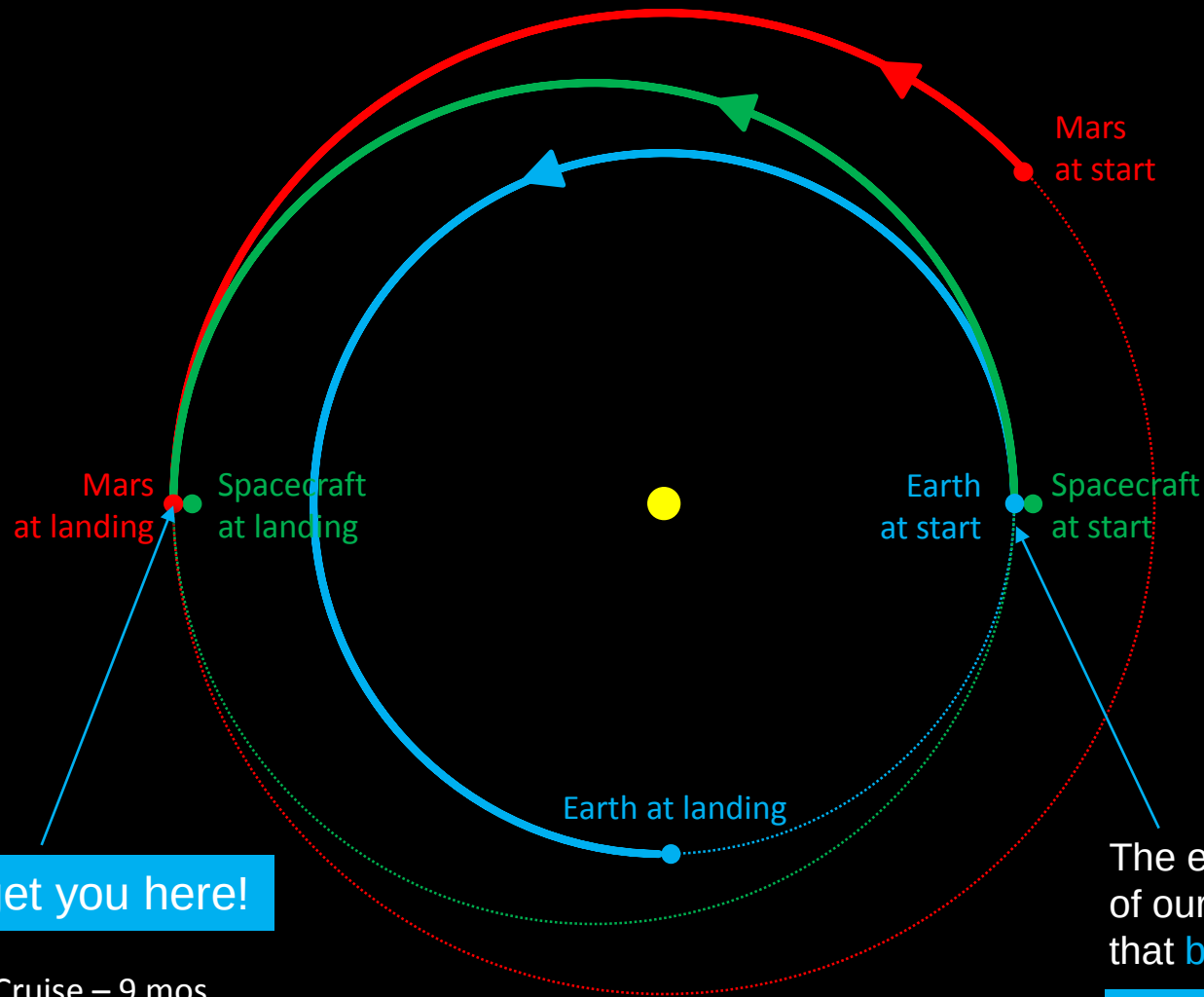
Space Medicine History



What about Mars?



No comparable human experience for Mars



Will not get you here!

Trans-Mars Cruise – 9 mos
Full Mission - ~34 mos

The entire experience
of our species fits into
that blue dot.

What got you here...

Can we just use what we already know?



- Real Time Communications
- Medical Evacuation Capability
- Consumables Resupply



RISK

- The possibility of losing something of value.
- The intentional interaction with uncertainty.
- Rolling the dice on whether sh** happens today.

Hazards of Spaceflight

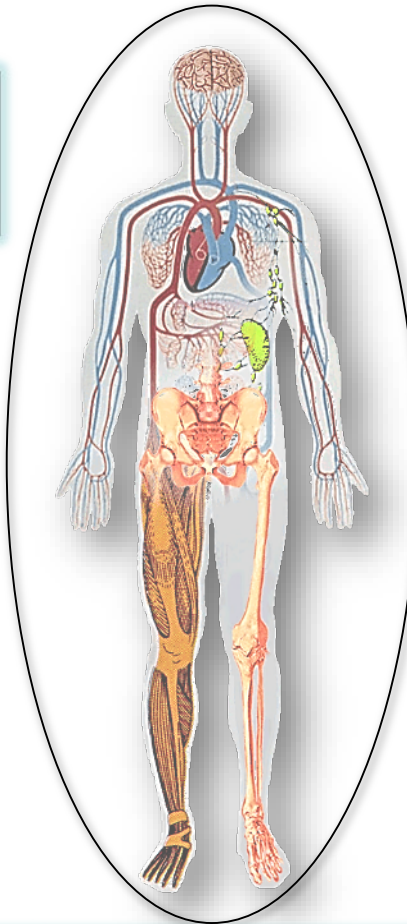
Hazards Drive Human Spaceflight Risks

Altered Gravity - Physiological Changes

Balance Disorders
Fluid Shifts
Cardiovascular Deconditioning
Muscle Atrophy
Bone Loss

Space Radiation

Acute In-flight effects
Long term cancer risk



Distance from earth

Drives the need for additional
“autonomous” medical care capacity –
cannot come home for treatment

Hostile/ Closed Environment

Vehicle Design
Environmental – CO₂ Levels, Toxic
Exposures, Water, Food
Decreased Immune Function

Isolation & Confinement

Behavioral aspect of isolation
Sleep disorders
Team dynamics

Exploration Medical Conditions

SKIN

- Burns secondary to Fire
- Skin Abrasion
- Skin Laceration

EYES

- Acute Glaucoma
- Eye Corneal Ulcer
- Eye Infection
- Retinal Detachment
- Eye Abrasion
- Eye Chemical Burn
- Eye Penetration

EARS, NOSE, THROAT

- Barotrauma (sinus block)
- Nasal Congestion (SA)
- Nosebleed (SA)
- Acute Sinusitis
- Hearing Loss
- Otitis Externa
- Otitis Media
- Pharyngitis

DENTAL

- Abscess
- Caries
- Exposed Pulp
- Tooth Loss
- Crown Loss
- Filling Loss

CARDIOVASCULAR

- Angina/Myocardial Infarction
- Atrial Fibrillation / Atrial Flutter
- Cardiogenic Shock secondary to Myocardial Infarction
- Hypertension
- Sudden Cardiac Arrest
- Traumatic Hypovolemic Shock

GASTROINTESTINAL

- Constipation (SA)
- Abdominal Injury
- Acute Cholecystitis
- Acute Diverticulitis
- Acute Pancreatitis
- Appendicitis
- Diarrhea
- Gastroenteritis
- Hemorrhoids
- Indigestion
- Small Bowel Obstruction

Pulmonary

- Choking/Obstructed Airway
- Respiratory Infection
- Toxic Exposure: Ammonia
- Smoke Inhalation
- Chest Injury

*SA – Space Adaptation

NEUROLOGIC

- Space Motion Sickness (SA)
- Head Injury
- Seizures
- Headache
- Stroke
- Paresthesia
- Headache (SA)
- Neurogenic Shock
- VIIP (SA)

MUSKULOSKELETAL

- Back Pain (SA)
- Abdominal Wall Hernia
- Acute Arthritis
- Back Injury
- Ankle Sprain/Strain
- Elbow Dislocation
- Elbow Sprain/Strain
- Finger Dislocation
- Fingernail Delamination (EVA)
- Hip Sprain/Strain
- Hip/Proximal Femur Fracture
- Knee Sprain/Strain
- Lower Extremity Stress fracture
- Lumbar Spine Fracture
- Shoulder Dislocation
- Shoulder Sprain/Strain
- Acute Compartment Syndrome
- Neck Injury
- Wrist Sprain/Strain
- Wrist Fracture

PSYCHIATRIC

- Insomnia (Space Adaptation)
- Late Insomnia
- Anxiety
- Behavioral Emergency
- Depression

GENITOURINARY

- Abnormal Uterine Bleeding
- Acute Prostatitis
- Nephrolithiasis
- Urinary Incontinence (SA)
- Urinary Retention (SA)
- Vaginal Yeast Infection

INFECTION

- Herpes Zoster (shingles)
- Influenza
- Mouth Ulcer
- Sepsis
- Skin Infection
- Urinary Tract Infection

IMMUNE

- Allergic Reaction
- Anaphylaxis
- Skin Rash
- Medication Reaction

ENVIRONMENT

- Acute Radiation Syndrome
- Altitude Sickness
- Decompression Sickness (EVA)
- Headache (CO2)

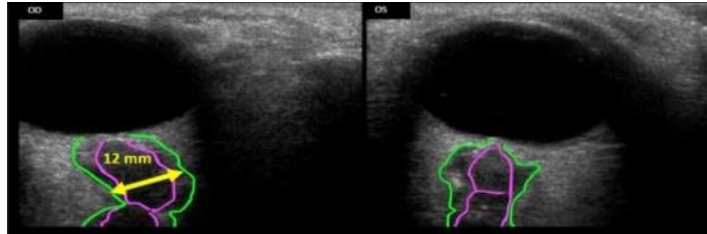
Fire and Toxic Exposure



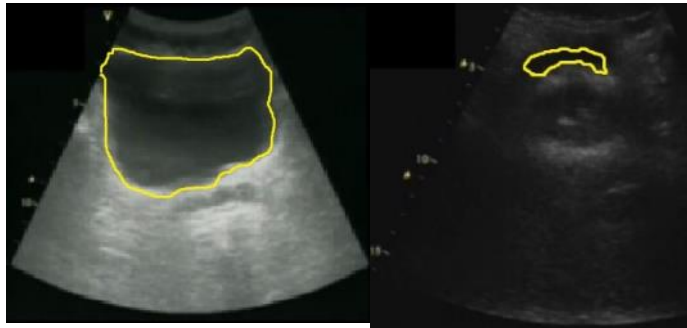
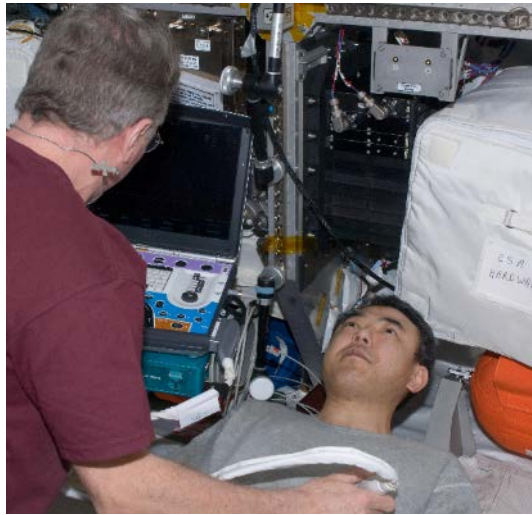
Near Drowning in EVA



SANS – adaptation or pathology?



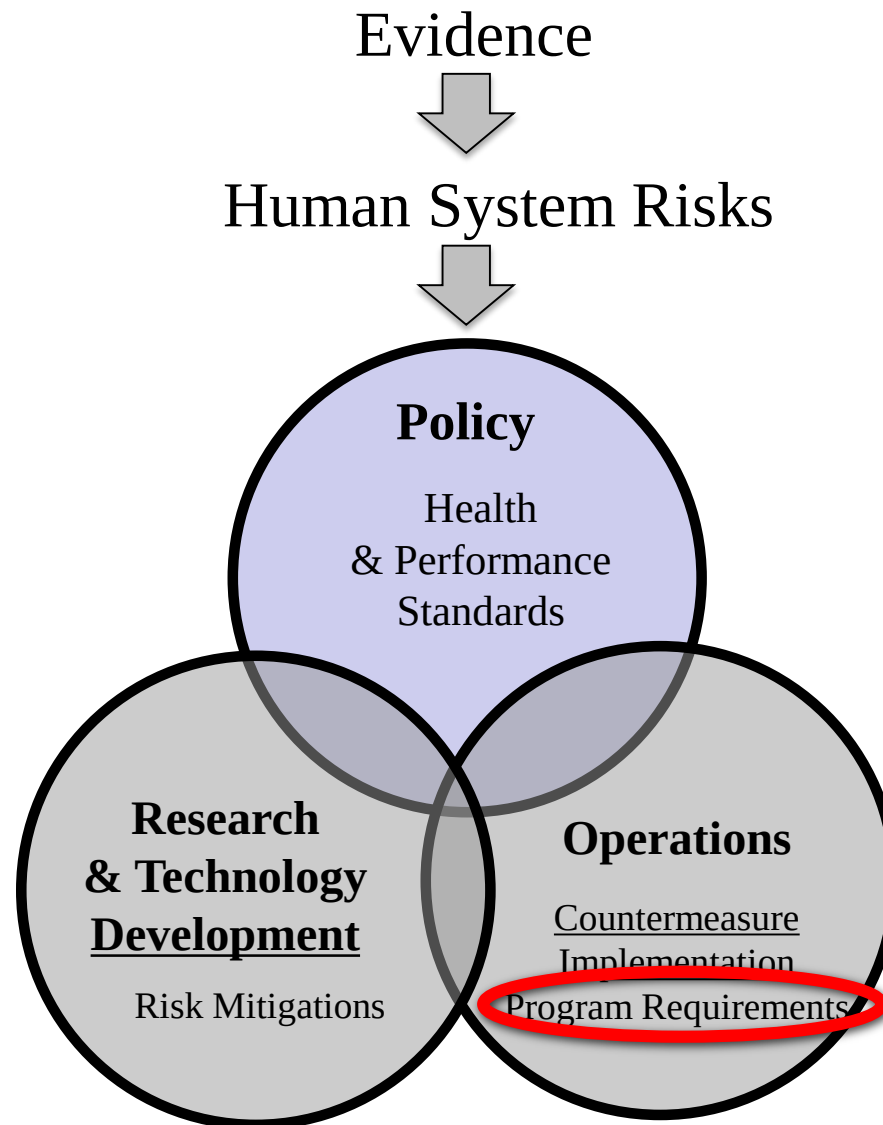
Urinary Tract Infections and Sepsis



In-flight Post-void
Ultrasound

Ground Post-void
Ultrasound

Risk Mitigation Framework



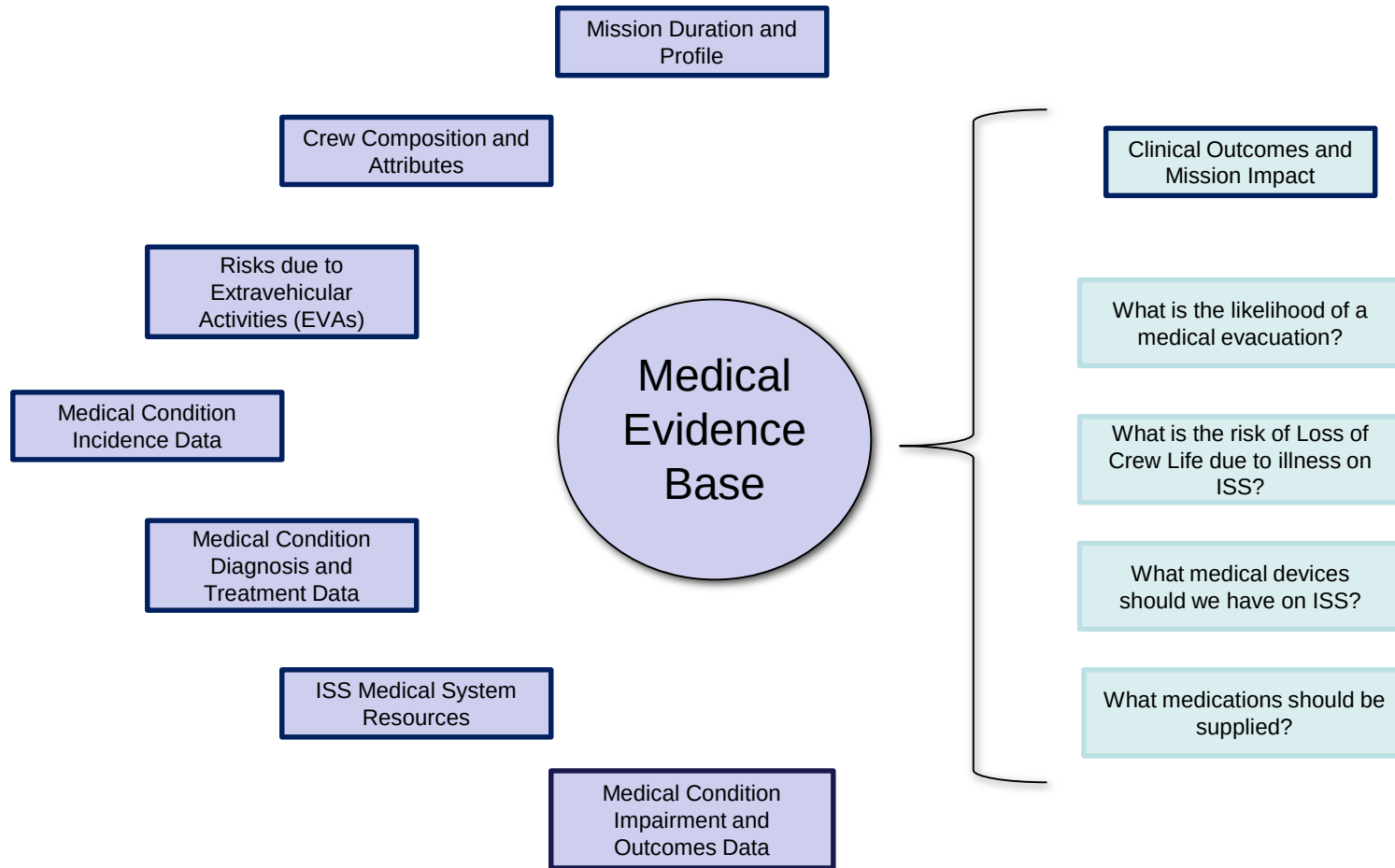
How do we calculate Risk?

Human Spaceflight functions at the Intersection of Engineering and Medicine

- Medical Operations needs quantitative techniques to optimize mission planning and medical resources – inform Requirements
- Engineering and design teams need quantitative medical information to balance medical risk with resource limitations
- Medical SMEs have not historically had the capability to provide this

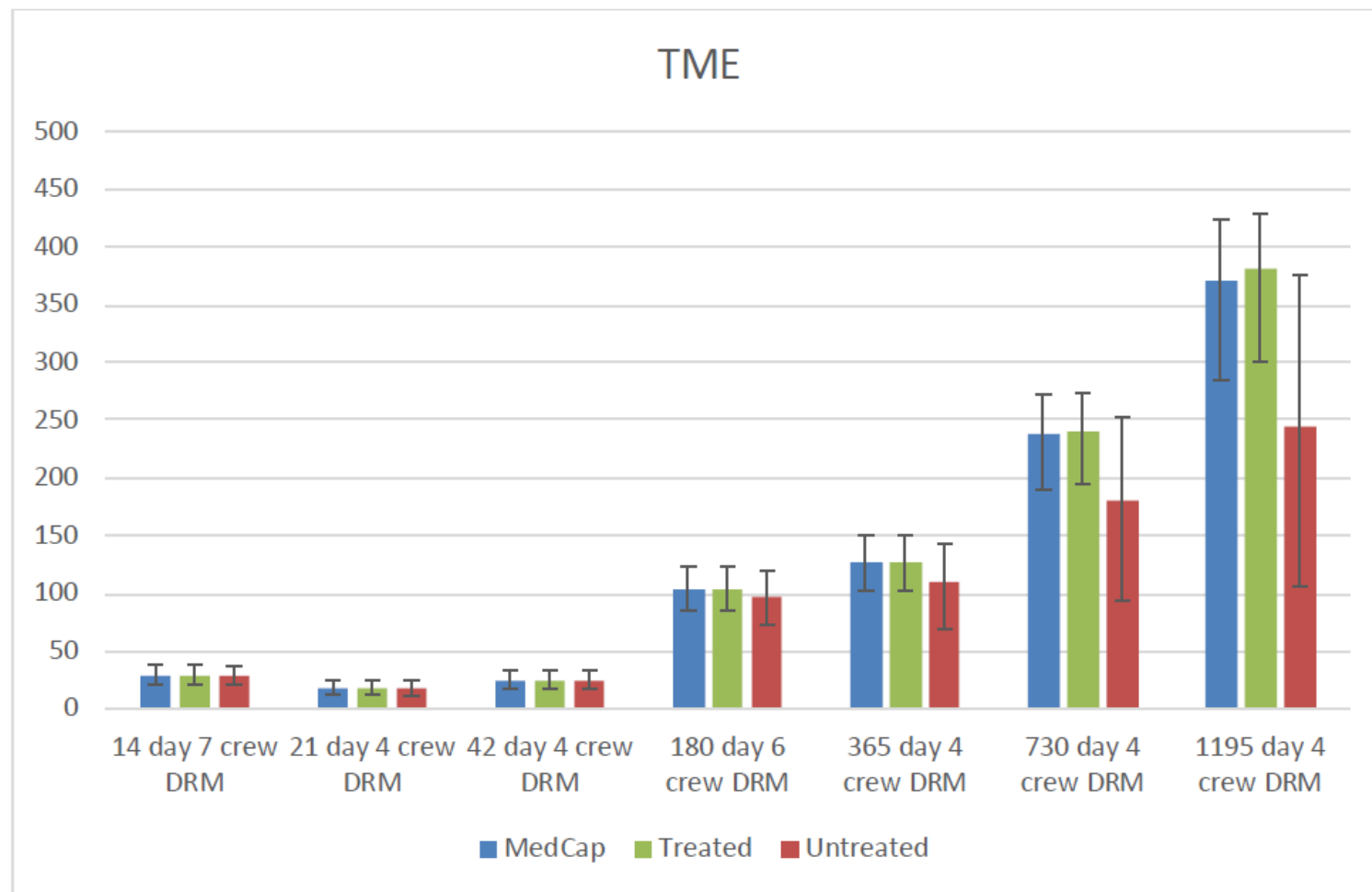
Enter Probabilistic Risk Assessment

Translating between Medicine and Engineering

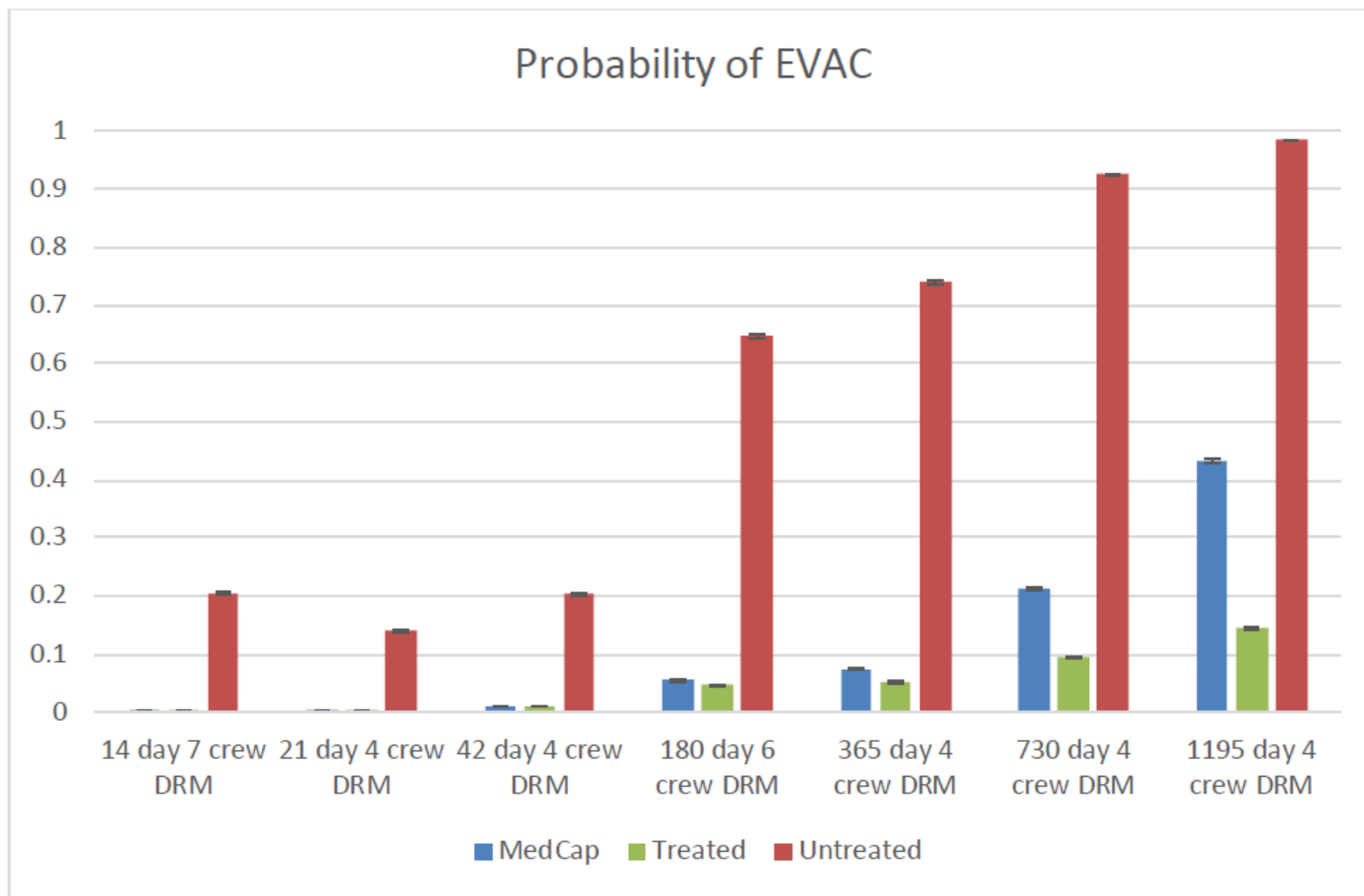


The Integrated Medical Model

IMM Example Output - Total Medical Events



Considering Evacuation



How do models compare to real life?

IMM Simulation Data

- Medical Illness
 - VIIP/SANS
 - Dental Abscess
 - Kidney Stone
 - Sepsis
 - Stroke
 - Angina/ MI
 - Afib/Aflutter
- Environmental
 - Smoke/Toxic Exposure
- Injury/Trauma
 - Hypovolemic Shock
 - Wrist Fracture
 - Back Injury

Actual Russian Flight Data*

- EVAC
 - Urosepsis
 - Cardiac Arrhythmia
 - Smoke Inhalation
- Close Call EVAC
 - Kidney Stone
 - Dental Abscess
 - Toxic Exposure

* Russian medical data not used in IMM

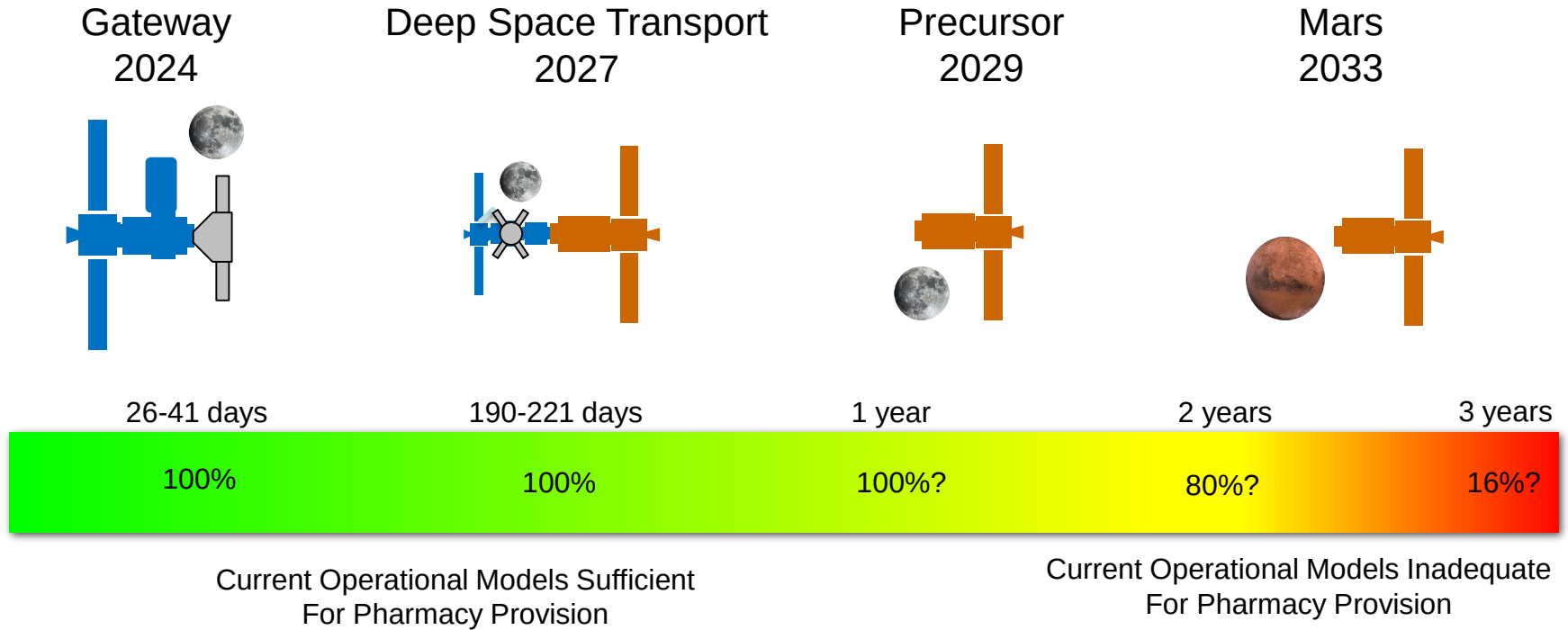
Spaceflight Medical Risk

Medical Risk

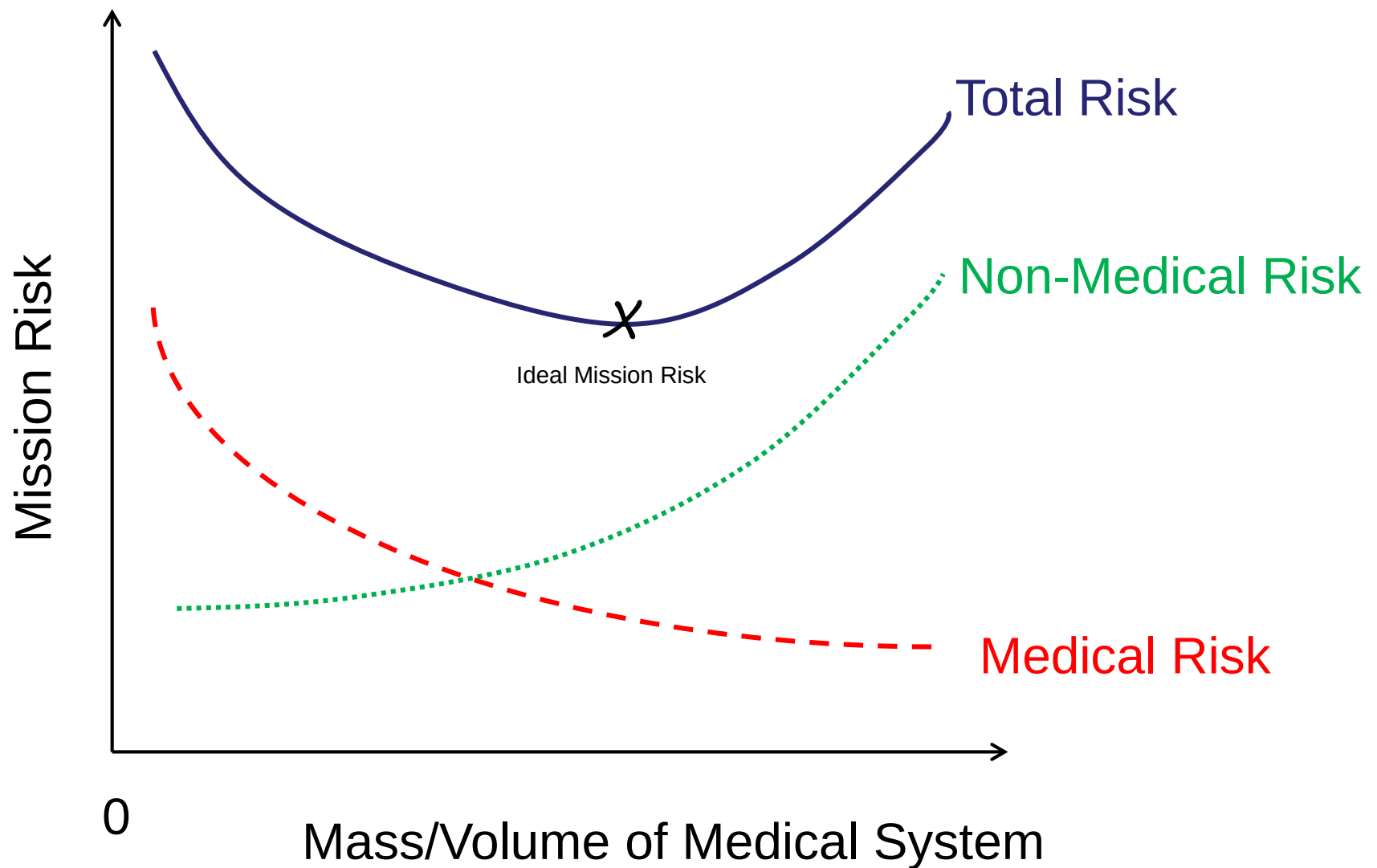
~100 Medical Conditions

Medical Conditions for which we have not planned.

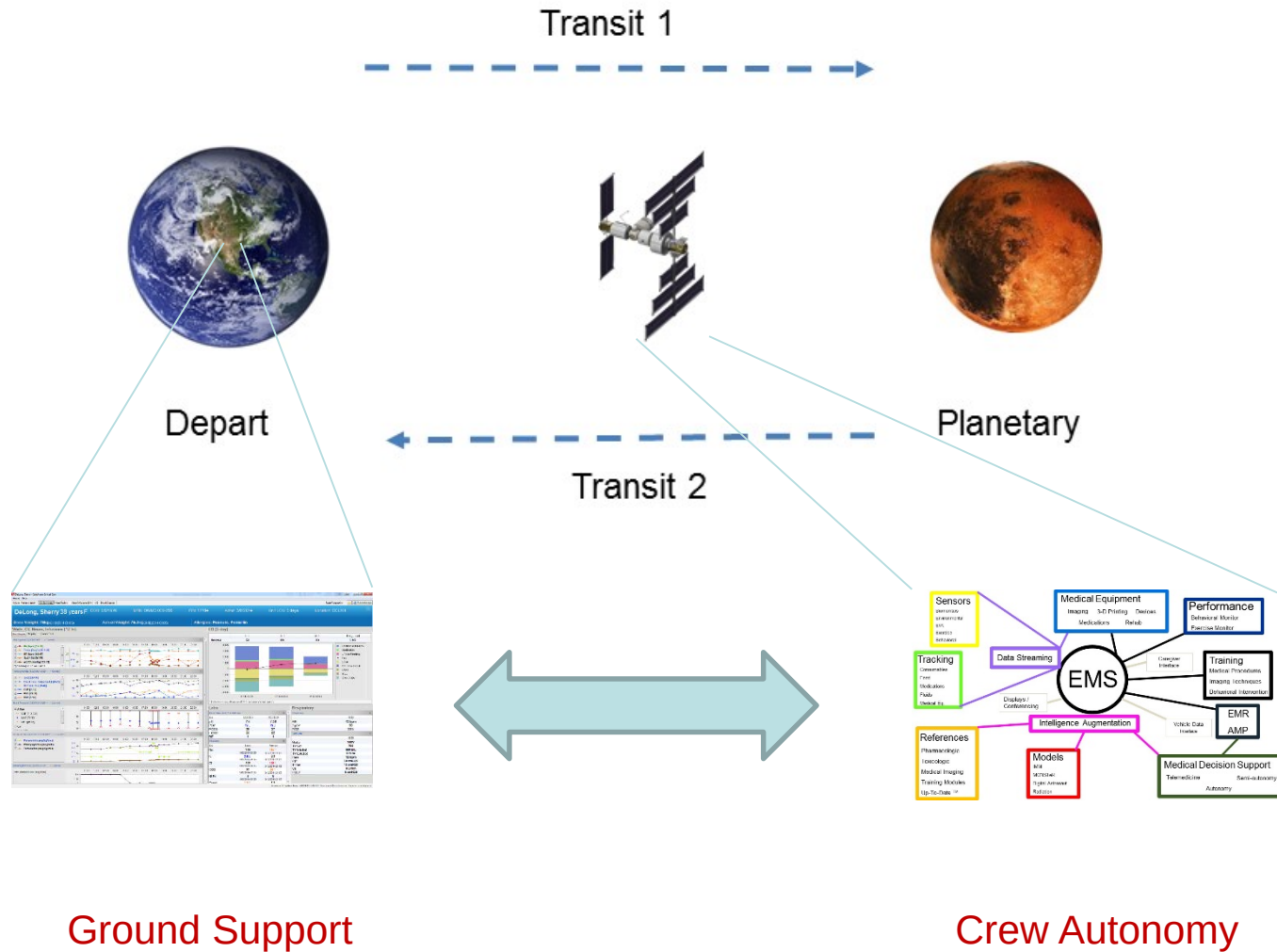
Consumables Resupply



Understanding the Trade Space



Implementation requires a Health and Performance System



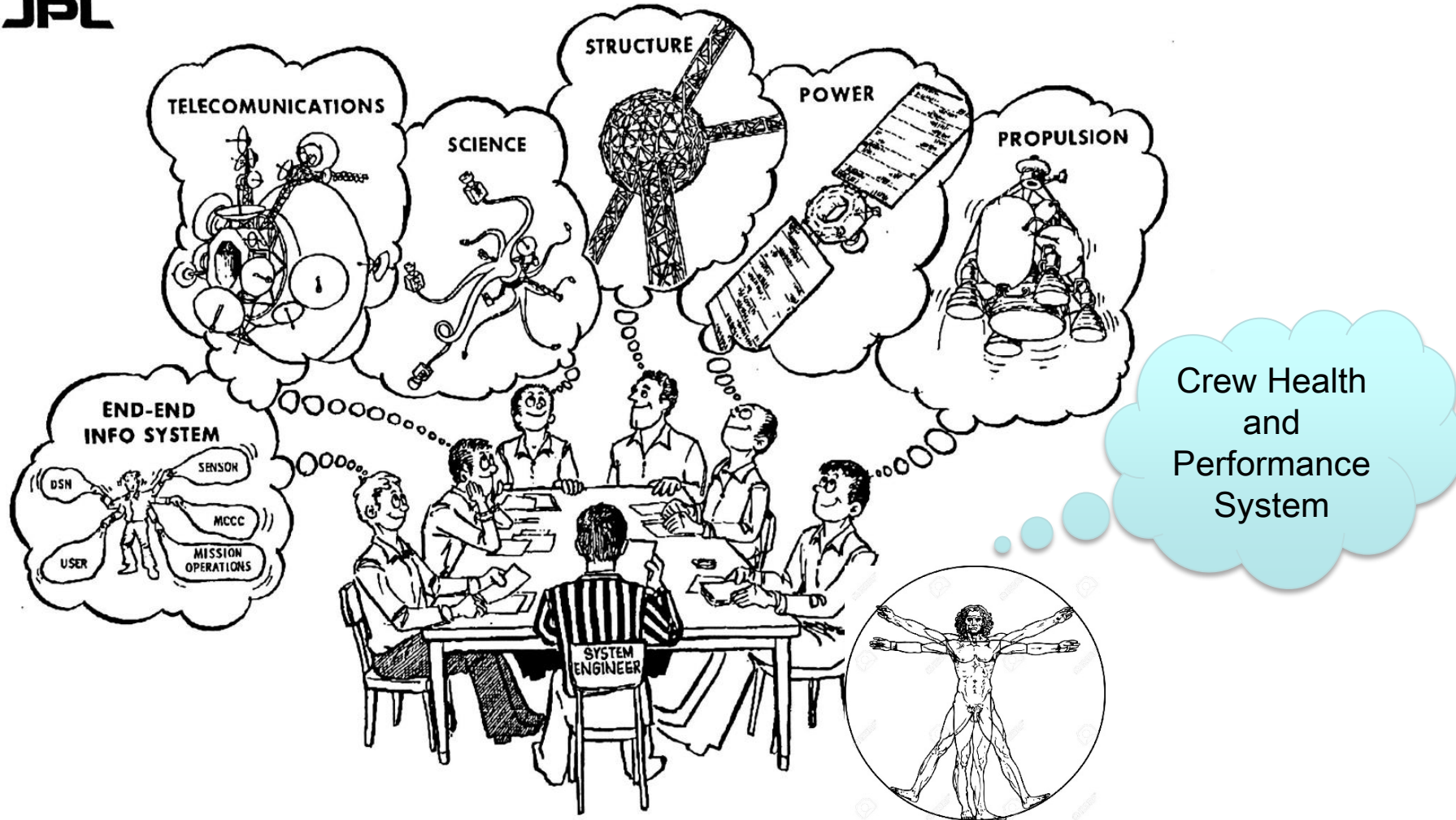


GETTING THE MEDICINE INTO THE ENGINEERING SYSTEM

Medical Systems Engineering

DESIGN TEAM OPERATIONS

JPL



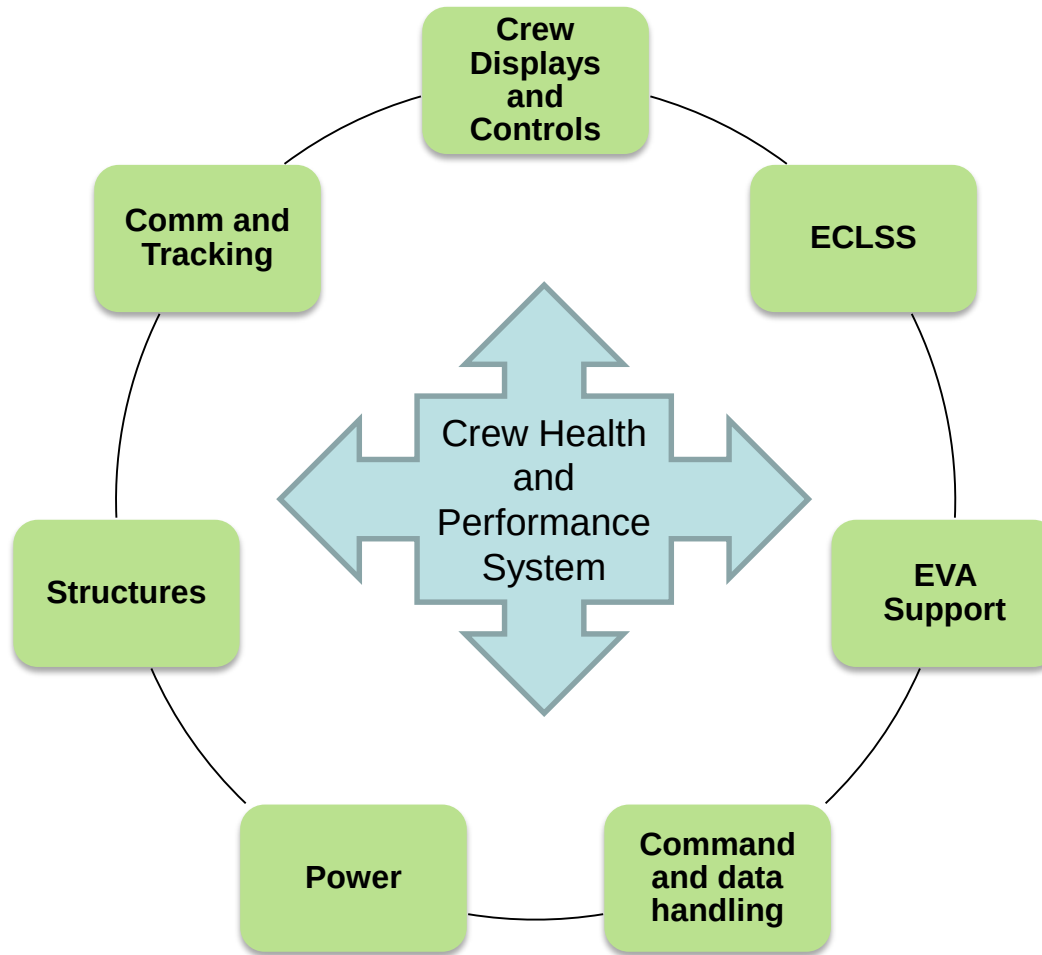
SYSTEM ENGINEERING AT JPL

06/14/91

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From "System Engineering at JPL" training course material, June 1991

System Interfaces with the Flight System



Example: Mars Telecommunication - Three Main Challenges

- Three major challenges face all communication with deep space (CLA):
 - Capacity:** The link data rate or average daily volume
 - Latency:** Speed of light delay between the planets
 - Availability:** The percentage of time (over a day/Sol, week, month or year) that an asset has access to a link
- Deep Space Network CLA needs to be considered for the case of crew support needs
- What data rates are acceptable for Store-and-Forward type crew support? Emergency medical support? Behavioral health support?
- What if emergencies occur during planned daily link outages (due to Mars occultation)?

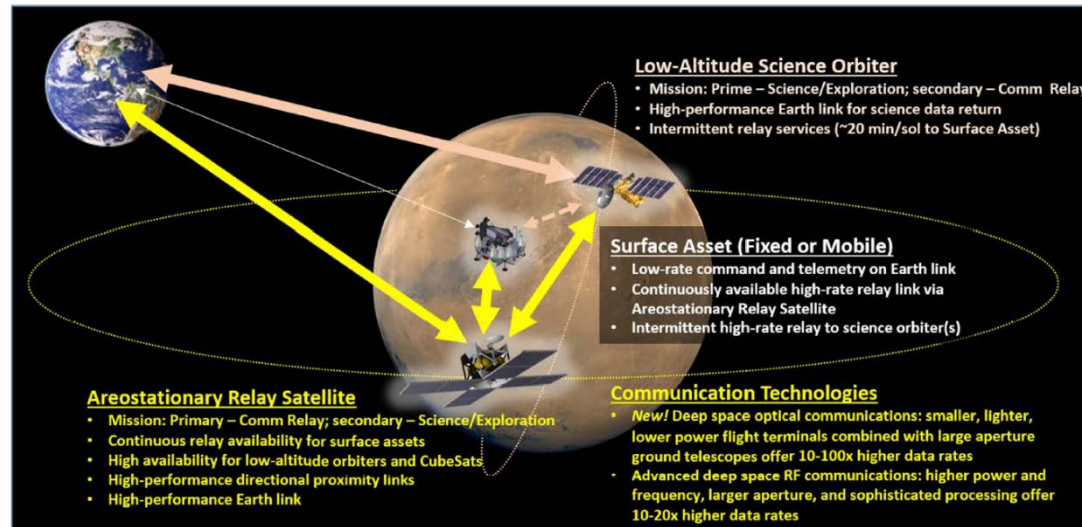


Figure 1. Advanced RF and optical communications technologies combined with using the areostationary orbit offer 100-1000x greater data return from Mars and nearly continuous availability.

	Frequency Band	Maturity	S/C Aperture	S/C Tx Power	Ground Rx / Tx	Data Rate @2AU (Megabits/sec)
LEO: ISS	Ku-band	TRL 10 / Operational	2 m	>2 W N/A	TDRSS Relay	Return: 90-110 (1/19: 517)* Forward: 25 (1/19: 50)*
MARS Current State-of-the-art (MRO SDST)	X-band	TRL 10 / Operational	3 m	100 W	1x34 m DSN Station	Return: 1-2
		TRL 10 / Operational		N/A	1x34 m DSN Station	Forward: 0.5
	Ka-band	TRL 10 / Operational	None	35 W	1x34 m DSN Station	Return: 6
		TRL 4		N/A	N/A	Forward: 0
Next Generation Mars Trunks (Future human missions)	Ka-band / DSRC	TRL 3-4	5 m	1kW	1x34 m DSN Station	Return: EST 250
					1x34 m DSN Station	Forward: EST 125
	Optical / Lasercomm / DSOC	TRL 6	22 cm	4 W N/A	5 m ground telescope	Return: >5.2 Forward: >0.1
		TRL 3	50 cm	40 W N/A	12+ m ground telescope	Return: >600 Forward: >25

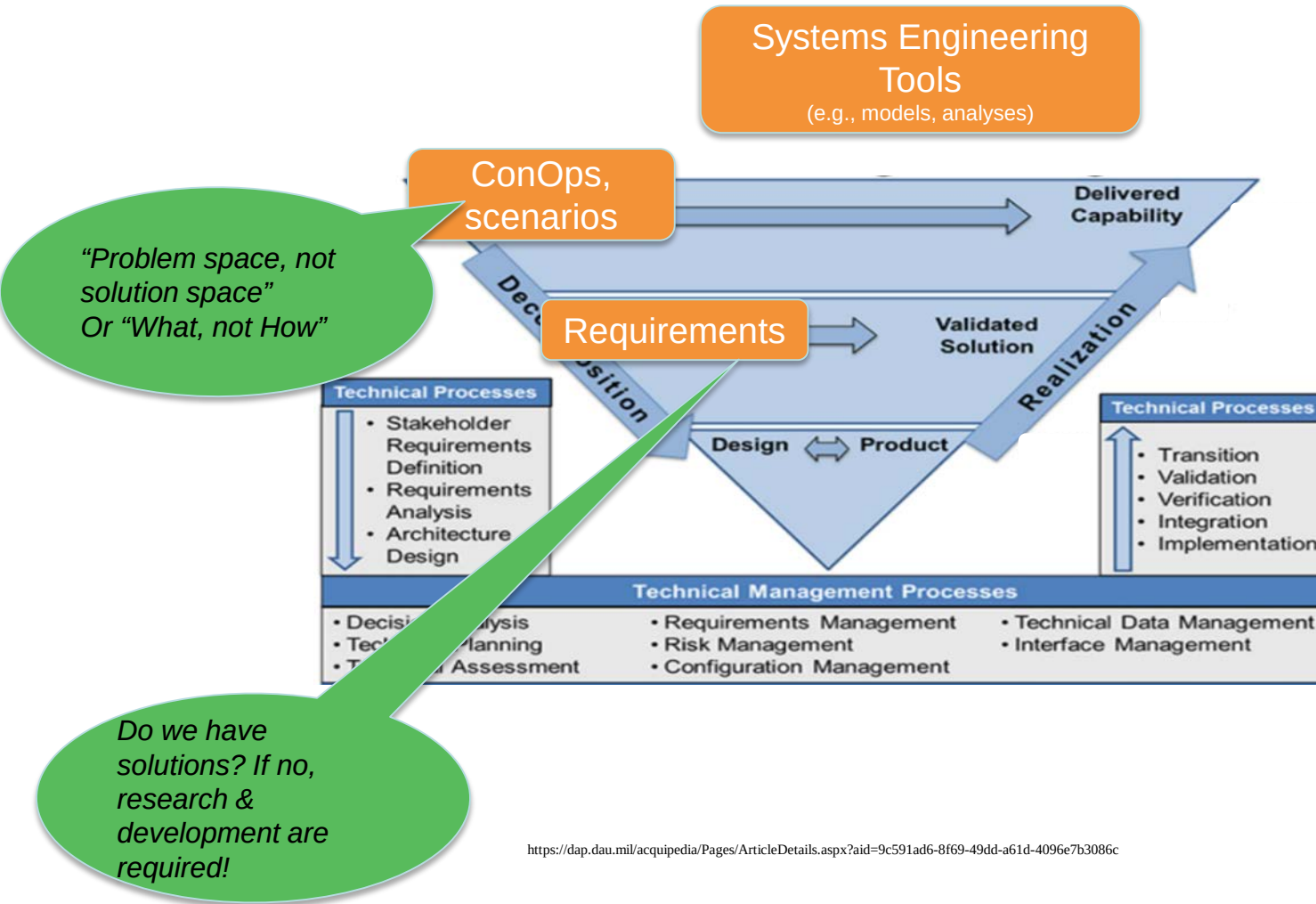
* - Expected performance after Jan 2019 upgrade

NASA Engineering Life Cycle

NASA Life-Cycle Phases	<u>Approval for Formulation</u>		<u>Approval for Implementation</u>		<u>Implementation</u>		
Project Life-Cycle Phases	<u>Pre-Phase A:</u> Concept Studies	<u>Phase A:</u> Concept & Technology Development	<u>Phase B:</u> Preliminary Design & Technology Completion	<u>Phase C:</u> Final Design & Fabrication	<u>Phase D:</u> System Assembly, Integration & Test, Launch & Checkout	<u>Phase E:</u> Operations & Sustainment	<u>Phase F:</u> Closeout
Project Life-Cycle Gates & Reviews	KDP A ▼ Δ MCR	KDP B ▼ ▲ ▲ SRISDR	KDP C ▼ ▲ PDR	KDP D ▼ ▲ ▲ CDR SIR	KDP E ▼ ▲ Δ ORR FRR	KDP F ▼	

Why Systems Engineering?

Improved communication with exploration mission development activities



<https://dap.dau.mil/acquipedia/Pages/ArticleDetails.aspx?aid=9c591ad6-8f69-49dd-a61d-4096e7b3086c>

Crew Health and Performance System Goal

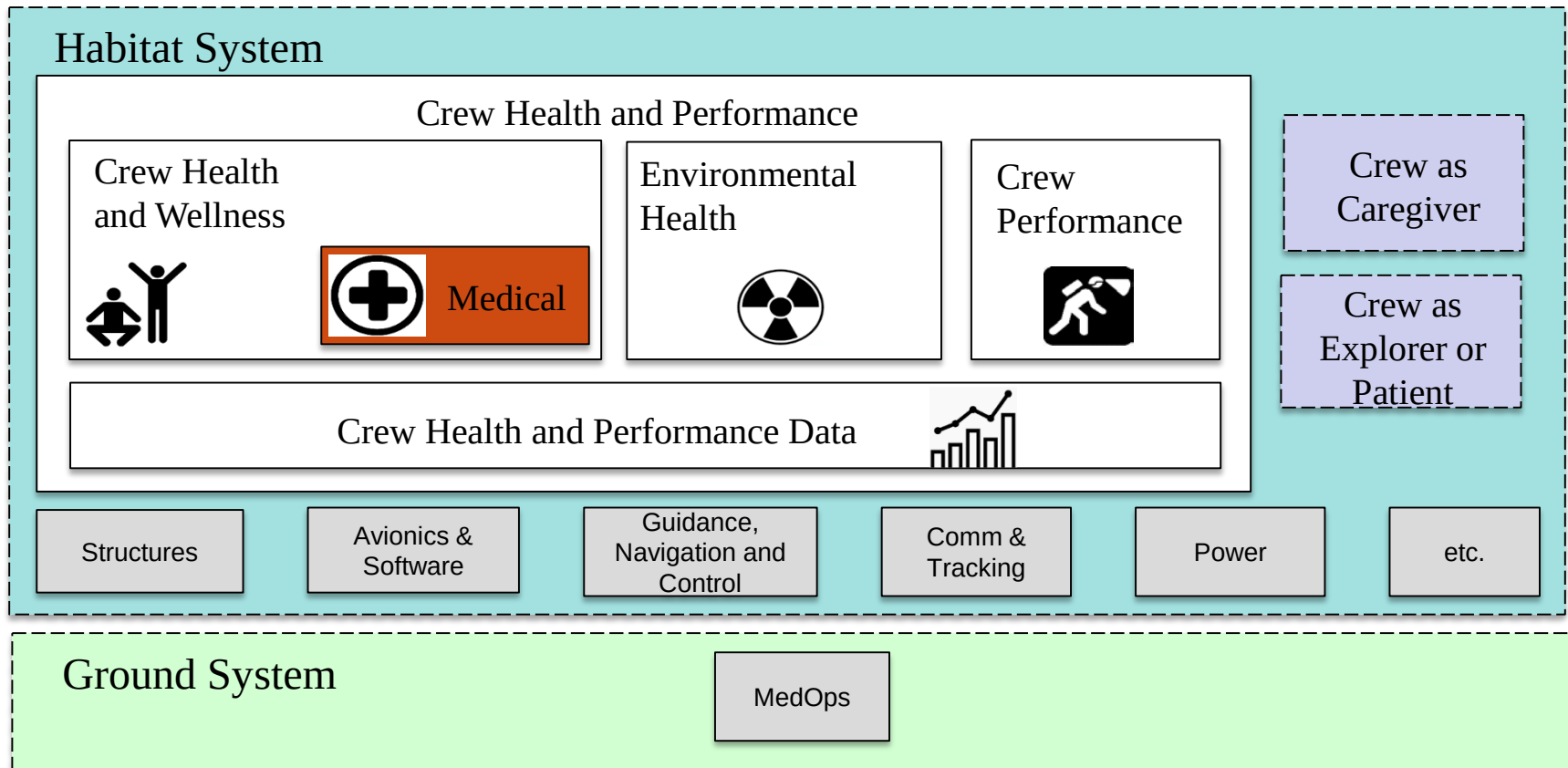
Provide a crew that is fit for duty when the mission calls.

Crew Health and Performance System Must...

- **Protect from environmental hazards**
 - Radiation protection
 - Noise, vibration, CO₂, etc.
- **Keep healthy crew well**
 - Exercise
 - Other physiological countermeasures
 - Food
 - Behavioral health
- **Prevent, diagnose, treat, manage long-term health care**
 - Data system
 - Medical Data Capture
 - Medical Training
 - Medical devices
 - Medical supplies
- **Support crew to accomplish mission tasks**
 - Procedures
 - Training
 - User interfaces

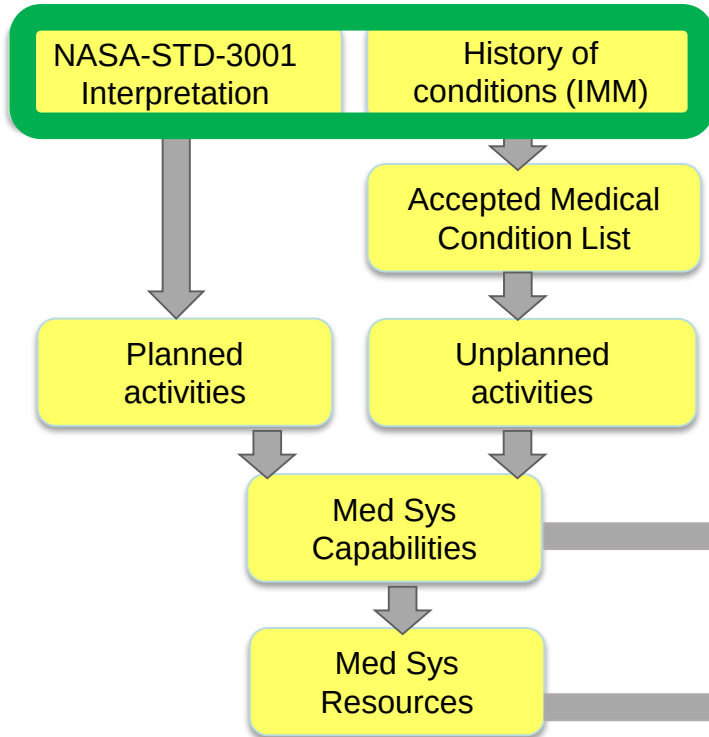


Applying Systems Engineering to Integrate CHP

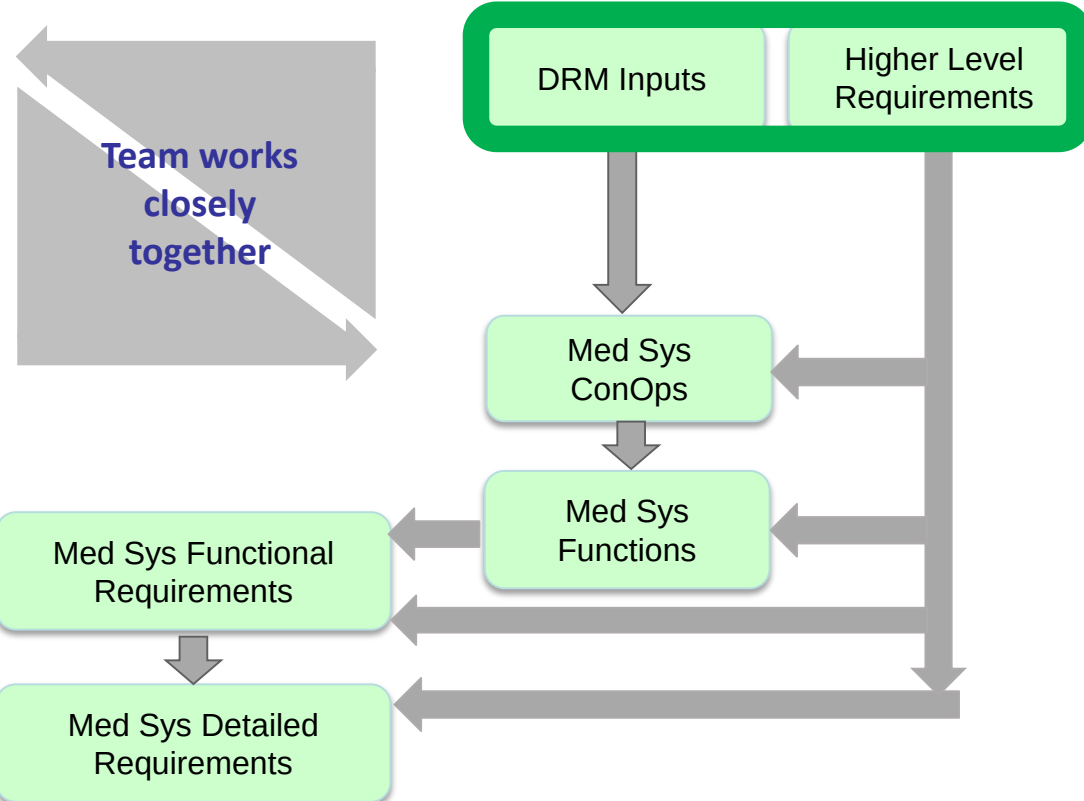


Getting from Medical Need to Requirements

Medical Domain Activities



Sys Eng Activities

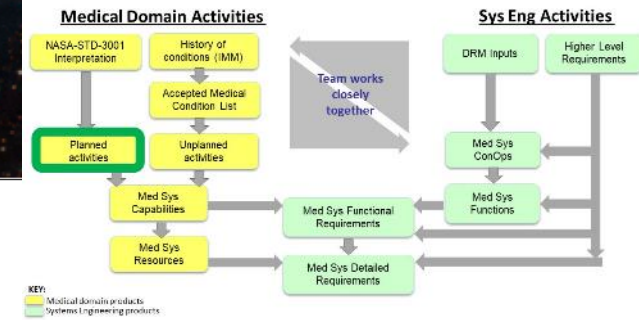


KEY:

- Medical domain products
- Systems Engineering products

Do we have the capabilities to meet the needs?
Do we need altered allocations?

Planned Activities



Scheduled medical care that is expected or required to occur

- Maintain crew health
- Monitor for potential contingency medical events
- Provide a test bed for future exploration missions

Examples

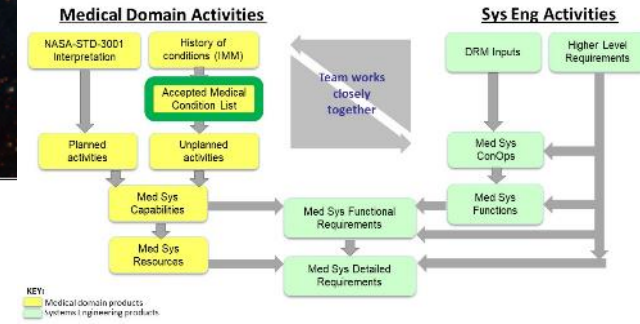
Planned Activities

- Private Medical Conference
- Periodic Eye Exam

Testbed Planned Activities

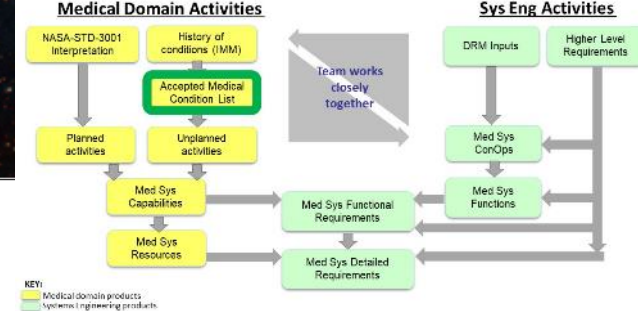
- Periodic Dental Exam
- Bone Health Evaluation

Accepted Medical Condition List



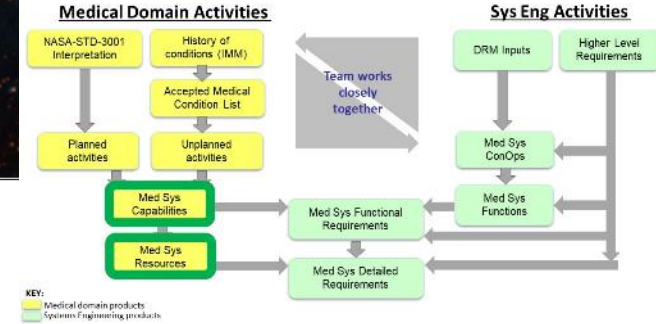
- **Process uses list of conditions that influence mission planning**
- **Start with the IMM Conditions List**
 - Has evidence base and metrics that support the likelihood of occurrence
 - Each condition as defined by best case and worst case
- **Decide what is realistic to diagnose and treat (based on your mission)**
 - Probability of occurrence
 - Complexity score – Large # resources or difficult management
 - Futility score – likely to result in death or disability despite treatment

Accepted Medical Condition List - Example



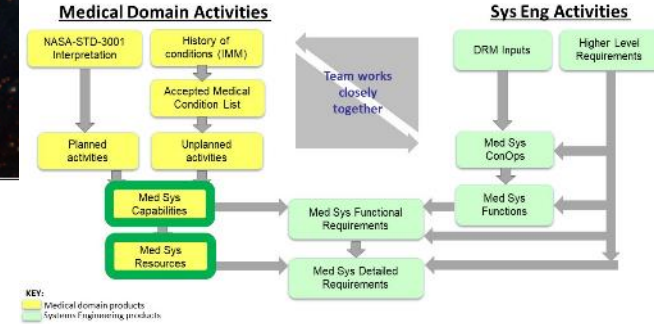
Medical Condition	Best / Worst	Definition	Plan to Treat	Characterization
SKIN RASH	Best	The best case scenario is defined as mild to moderate and uncomplicated skin rash that responds to treatment.	Plan to Treat	N/A
SKIN RASH	Worst	The worst case scenario is defined as a moderate to severe skin rash, covering an extensive area and that might be refractory to treatment.	Plan to Treat with Conditions	Treat to best case only
SMALL BOWEL OBSTRUCTION	Best	The best case scenario is defined as an uncomplicated course of small bowel obstruction which responds to conservative medical treatment (antibiotics and symptomatic treatment) and involves relatively minor functional impairment.	Plan to Treat	N/A
SMALL BOWEL OBSTRUCTION	Worst	The worst case scenario is defined as having a complicated course of small bowel obstruction that is not responsive to conservative treatment and involves significant systemic symptoms, such as severe pain, such as fever, leukocytosis, tachycardia, elevated BUN, serum amylase or alkaline phosphatase, metabolic acidosis and a major functional impairment.	Plan to Treat with Conditions	Treat to best case, add antipyretics/pain control, IV fluids; consider medical evac

Clinical Capabilities & Resources



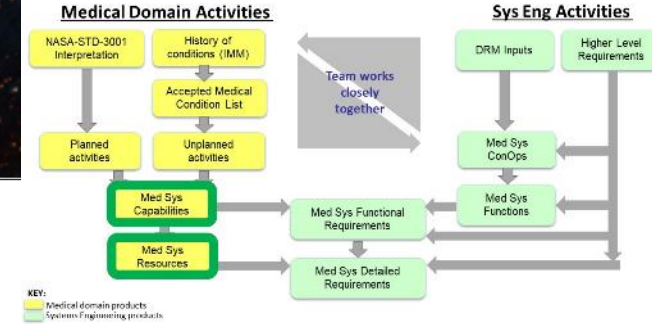
- **What clinical capabilities are included?**
 - Action(s) provided by a caregiver to address a condition or planned activity
 - 18 categories of capabilities, 165 unique capabilities
- **What resources are needed to realize those capabilities?**
 - Tangible and intangible assets used for a planned activity or condition

Capabilities / Resources - Examples



Condition	Capability Category	Capability	Resources
DENTAL AVULSION (TOOTH LOSS)	Administer and Manage Medications	Medication - Injectable (IV, IO, SQ, Intraarticular)	EMR interface, Refrigerator, Needle (23G) 1.5", Needle [25g] 1.5", Syringe (3cc), Syringe (10cc), Syringe (5cc), Intraosseous Injection device, Bandaid (2x3), Bandaid Dot, Bandaid strip (1x3), Syringe (1cc Insulin syringe with SQ needle), PPE - Nitrile gloves (multiple sizes, pair), Sharps container, Biohazard Trash Bag, BZK wipes
DENTAL AVULSION (TOOTH LOSS)	Administer and Manage Medications	Medication - Oral	EMR interface, Potable water
DENTAL AVULSION (TOOTH LOSS)	Administer and Manage Medications	Medication - Topical	EMR interface, Refrigerator, Cotton swabs - sterile, Cotton swabs - clean, Cotton balls, PPE - Nitrile gloves (multiple sizes, pair), Biohazard Trash Bag

Capabilities / Resources - Examples



Resource

Capability

Syringe (10cc)

Airway - Endotracheal Intubation,
 Medication - Injectable (IV, IO, SQ, Intraarticular),
 Breathing - Needle Thoracostomy,
 Circulation - IO Access,
 Circulation - IV Access,
 GI/GU/Chest - Percutaneous drainage
 Bladder/Gallbladder/Appendix/Chest,
 Nose - Nasal Packing (Anterior + Posterior),
 GI/GU - Urinary Catheterization,
 Screening Exam/Test - Intracranial pressure,
 Wound Care - Repair, multiple layer,
 Wound Care - Repair, Single layer

Syringe (1cc Insulin syringe with SQ needle)

Medication - Injectable (IV, IO, SQ, Intraarticular)

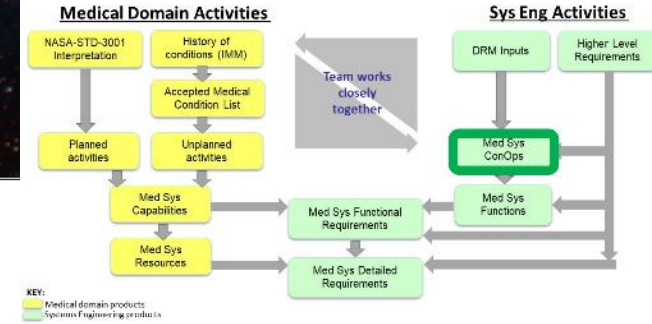
Syringe (3cc)

Medication - Injectable (IV, IO, SQ, Intraarticular)

Syringe (5cc)

Medication - Injectable (IV, IO, SQ, Intraarticular)

Concept of Operations: Outline



Purpose

1. Provides a **vision** for the design reference mission of interest (Gateway)
2. Defines the problem space, not solution
3. Informs the ExMC systems engineering effort, providing a foundation on which human-centered activities should be developed and eventually used to derive system functions & requirement for the medical system.

Stakeholder Need

• Maintain Crew Health

Stakeholders need a medical system that maintains crew health.

Scope

1. Medical system for Gateway
2. Integration of the medical system with other vehicle systems
3. Integration of the medical system with ground

System Goals

1. Health Management
2. Crew Autonomy
3. Continual Information Application & Learning
4. System Flexibility and Extensibility
5. System, Habitat, and Mission Systems Integration
6. Crew and Medical System Integration
7. Ground Awareness
8. Crew Performance
9. Crew Health Privacy Protection
10. Research Support
11. Future Capabilities Test Bed

1. Purpose

2. Scope

3. Stakeholder Need

4. System Goals

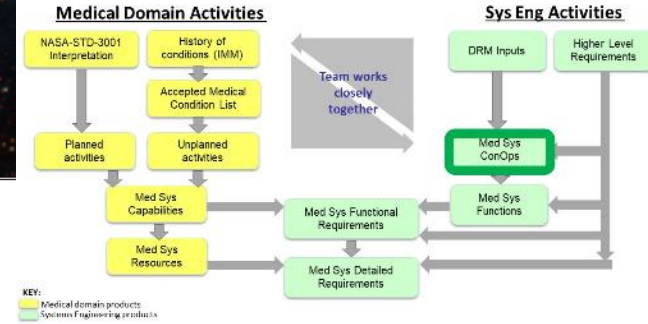
5. Architecture/System Description

6. Mission Description

7. Scenarios

- Context
- Assumptions
- Functionality
- Narratives
- Activity Diagrams

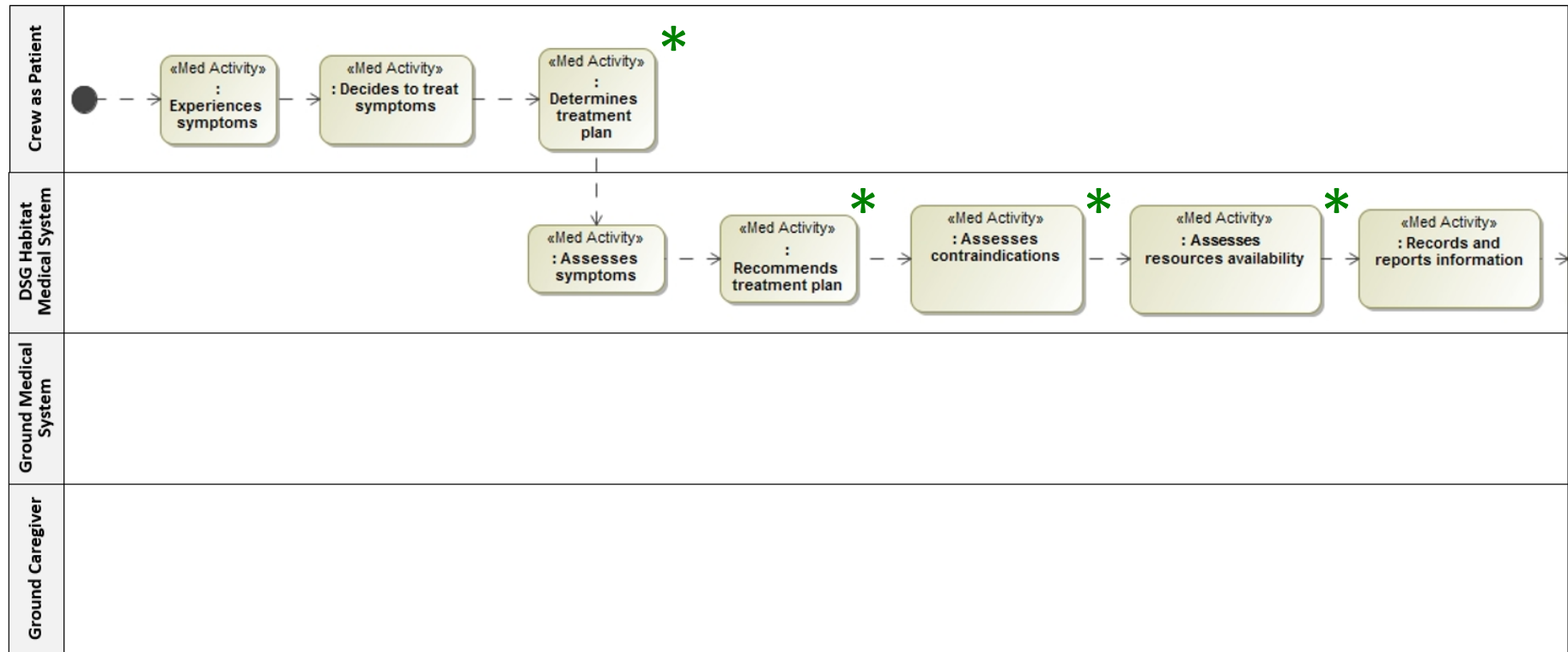
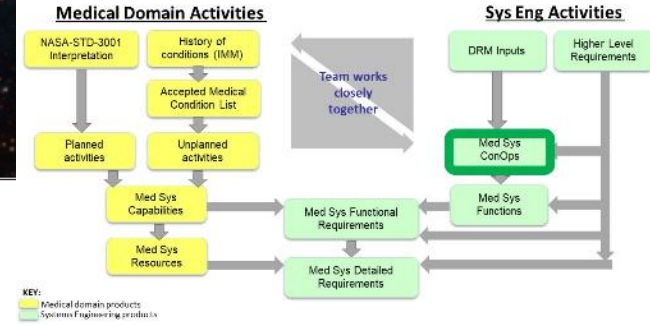
Example Scenario - Headache



This scenario shows that the medical system can:

- Prompt and facilitate data collection for unplanned medical events.
- Receive data entry from the patient about the patient.
- Provide limited decision support for self-care conditions.
- Assess known inventory and report stowage locations to crew via the Gateway Habitat Medical System interface.
- Automatically report inventory status to the Ground Medical System.
- Generate alerts for the Ground Medical System based upon inflight interactions with the system.
- Record and transmit medically oriented, attributable information to ground clinicians.
- Retrieve reports in the Ground System that can be reviewed by the Gateway Habitat Medical System

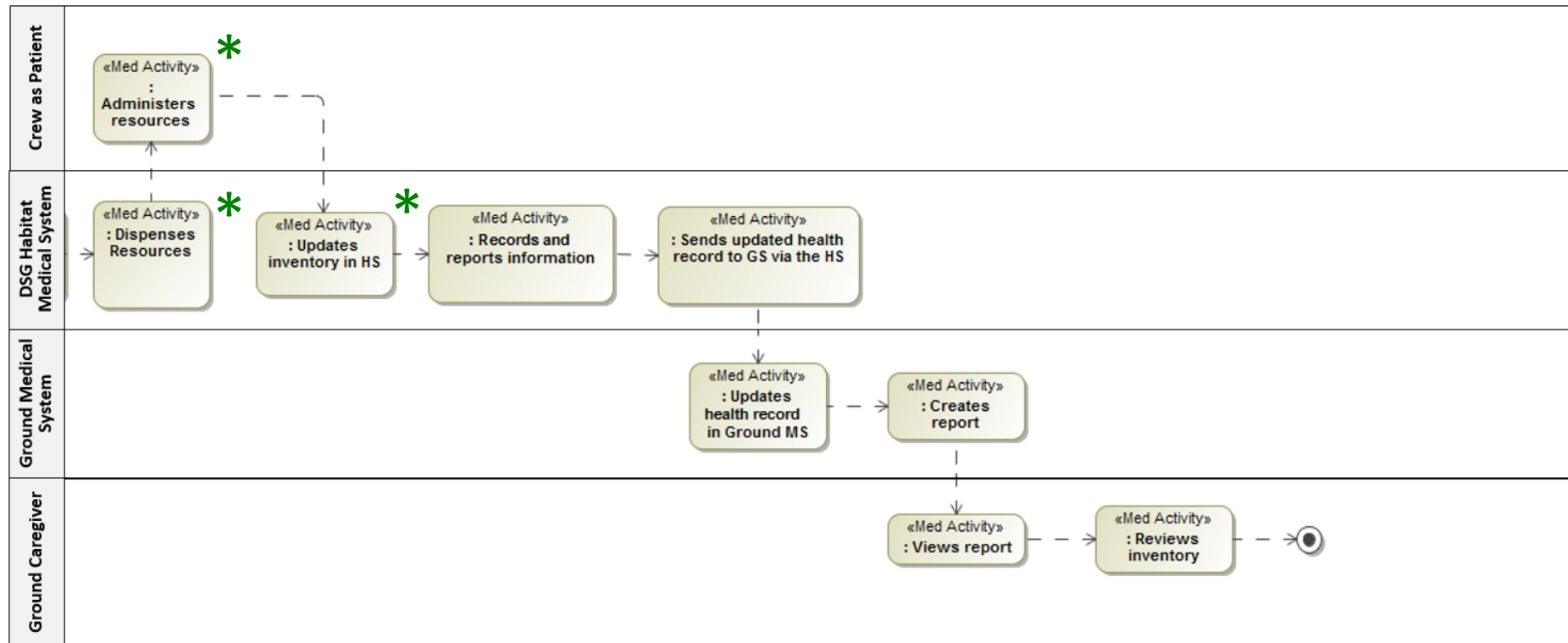
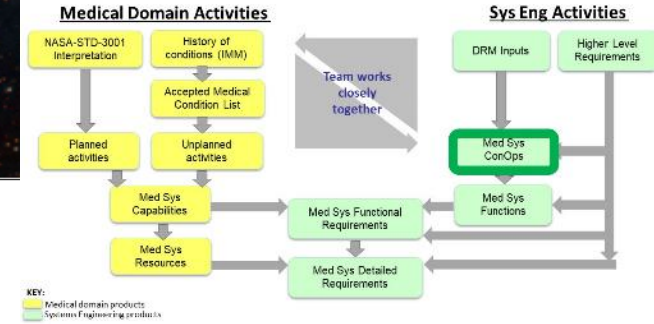
ConOps scenarios in model - Headache (1 of 2)



* = relevant to a pharmacy need

- Team converges on same understanding of behavior and terminology
- Analysis of scenarios supports identification of needed functions

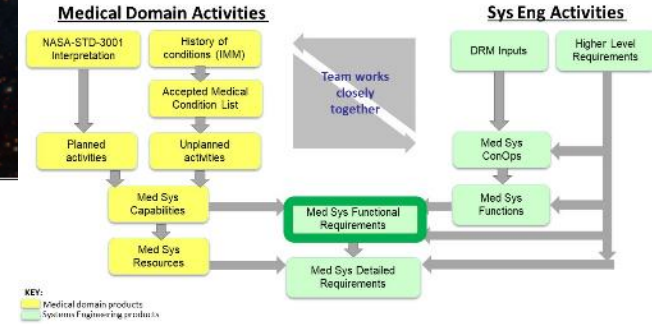
ConOps scenarios in model - Headache (2 of 2)



* = relevant to a pharmacy need

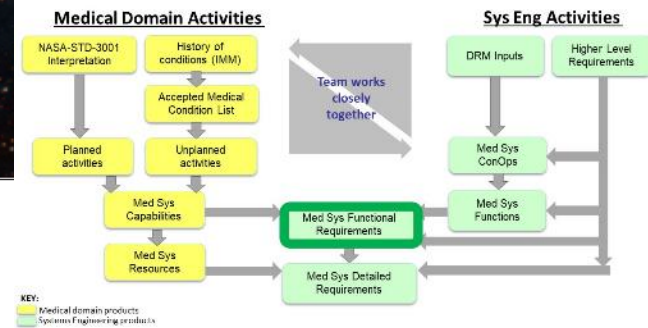
- Team converges on same understanding of behavior and terminology
- Analysis of scenarios supports identification of needed functions

Requirement Examples



ID	Name	Text	Rationale
Hab-MedSys-0024	Provide pharmacy	The Habitat Medical System shall provide an in-flight pharmacy to the crew members.	Pharmaceutical intervention and prevention, as provided by the in-flight pharmacy, is an essential component of risk management planning for crew healthcare during spaceflight. This includes prepare, administer, document, monitoring, inventory, analyze efficacy of med, titrate, or choose new medication if needed. Pharmaceuticals assist crewmembers with adaptation to the spaceflight environment as well as help manage unexpected medical events that could occur, such as illness or injury. Types of medications needed are specified at Level 5.
Hab-MedSys-0005	Track medical inventory	The Habitat Medical System shall track medical inventory.	Ensure that medical inventory (supplies, equipment, and medications) is tracked at all times including when inventory is dispensed. Specific medical inventories, including quantities, availability, track history, etc., are specified at Level 5.
Hab-MedSys-0204	Perform genitourinary procedures	The Habitat Medical System shall enable caregivers to perform genitourinary procedures.	The medical system needs to provide capabilities (e.g., tools, technology, skills, medications) to perform genitourinary (GU) procedures (such as decompression of bladder). These procedures are needed for treatment of conditions such as urinary retention. Types of GU procedures are specified at Level 5.

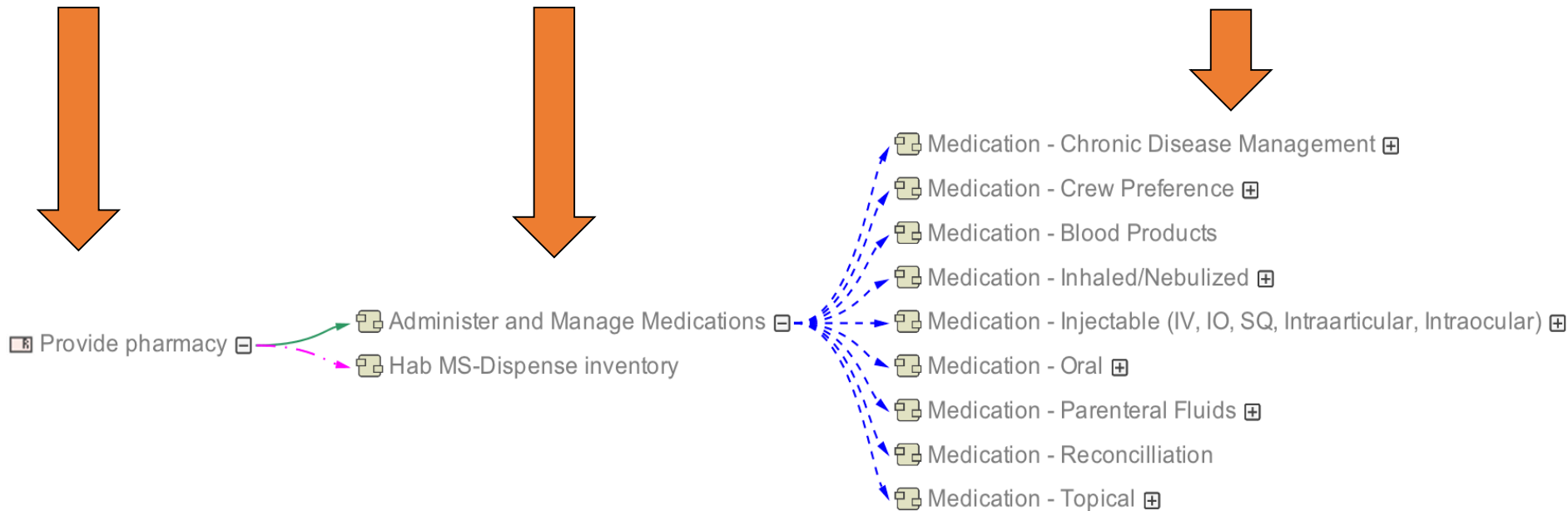
Model output: Visualizing the requirement “legs to stand on”



Level 4 rqmt name

Rationale supported by clinical capability category (green) inputs and ConOps-derived functions (pink)

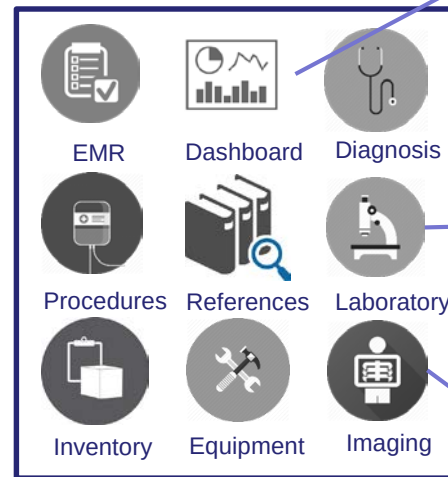
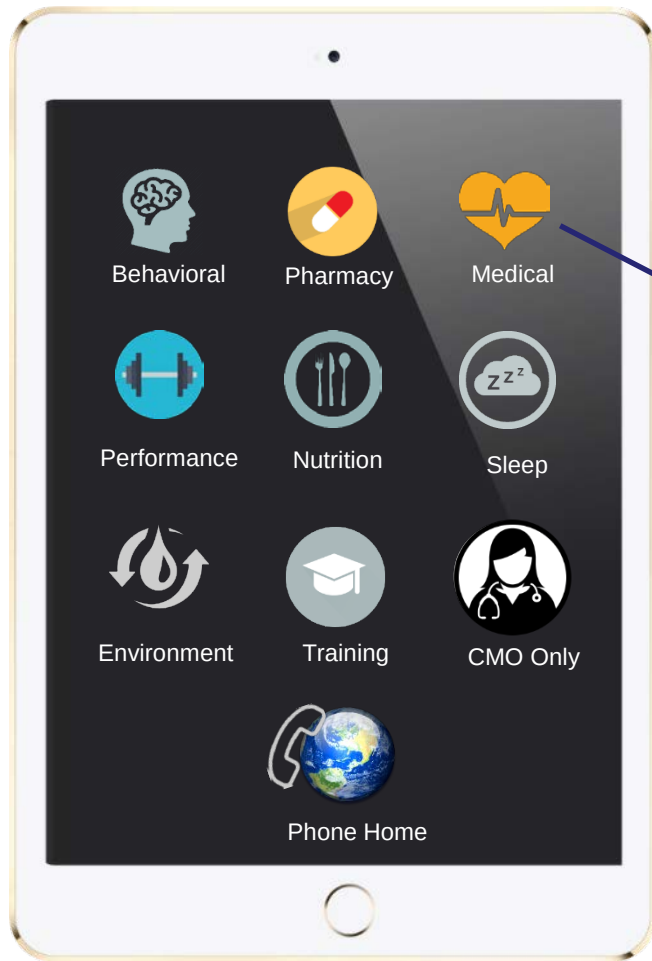
Child rqmts will be based on more detailed input (e.g., clinical capabilities) (blue)



We're not bringing an Intensive Care Unit

Crew Health and Performance System

These technologies exist today

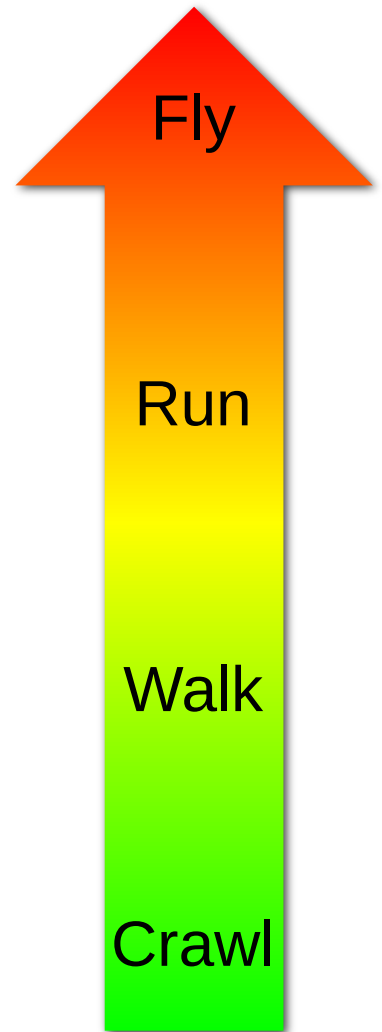


Medical

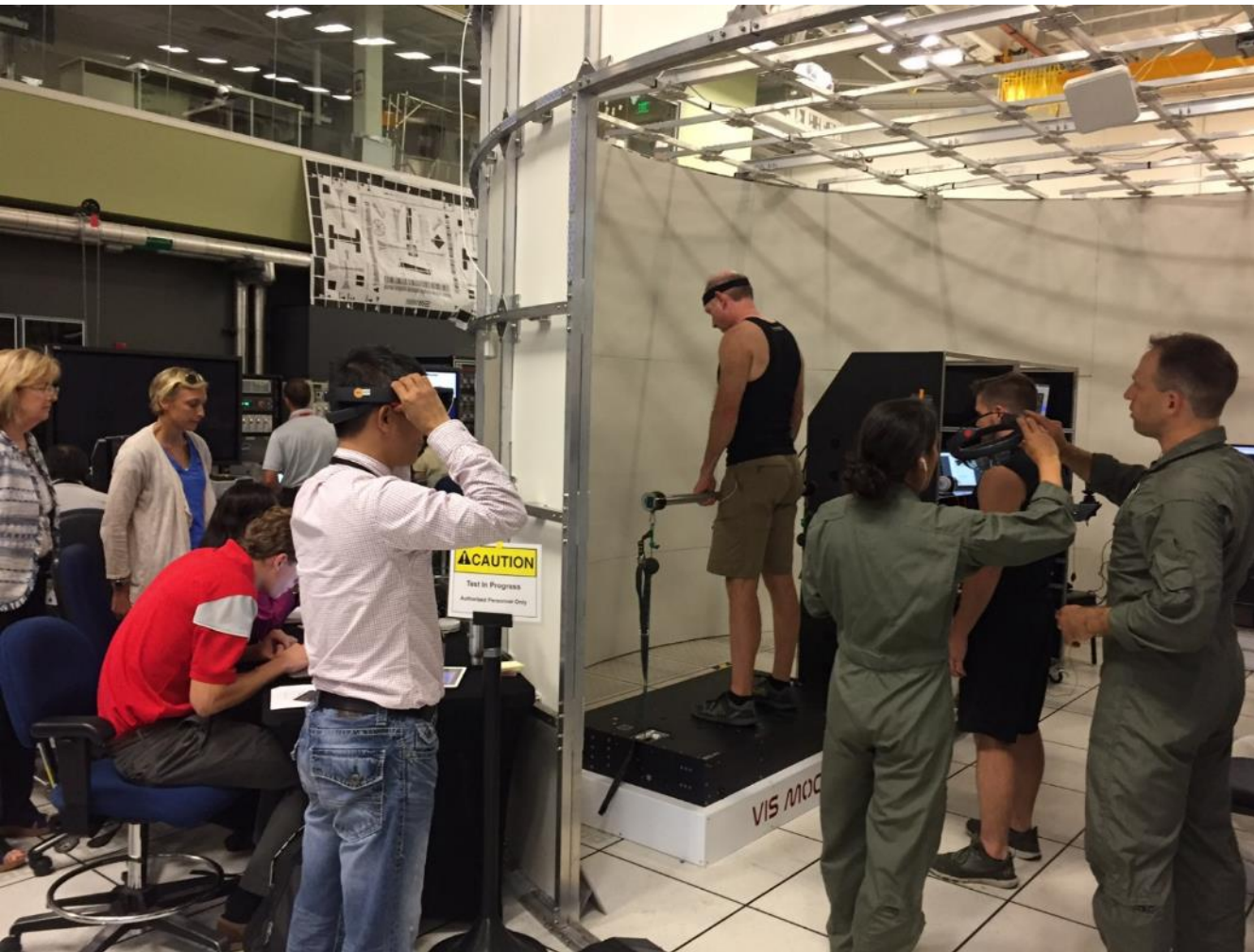


Can we replace the doctor?

- Full Artificial Intelligence
- Integrative Health and Performance Prediction
- Condition Specific Guidance
- Differential Diagnosis Generation
- Automated Image/Data Analysis
- Knowledge Support/Known Algorithm Provision
- Preventive Care Strategies



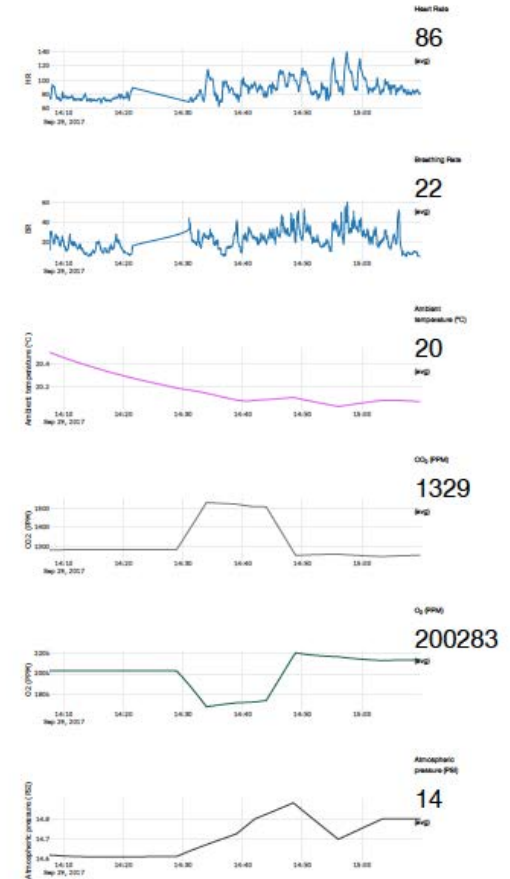
Where are we today?



L24, F75 telemetry report.

Choose Date Time Month Day September 8 14 5 2017 5 15 5 4 5 43 5 PM

Start: 2017-09-08 14:07:28 Crc: 2017-09-08 18:08:47 Interval: 2000



Data Sent/Collective by MDA System via Telemetry with CFS (CCSDS Protocol)

Summary

- **Medical system design for human spaceflight faces many challenges**
 - Evidence base is small
 - Lots of competing interests just to get vehicle flying
- **Methods to quantify medical risk are improving.**
 - No person can calculate this in their head
 - These get us in the ballpark, must be vetted by people
 - These are critical to getting insight into what should be included and what can safely be excluded
- **Marrying medical need and evidence base with systems engineering processes**
 - provide a starting point for medical doctors to evaluate and work from
 - provides a defensible and traceable set of capabilities that can be shown to reduce risk

Backup Slides

How is medical care example

- Live remote guidance



- Live monitoring



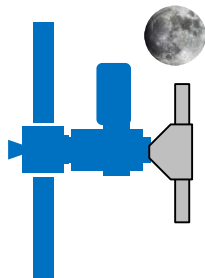
- Store and forward



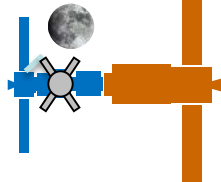
- Autonomous?

Stepwise Progression

Gateway
2024



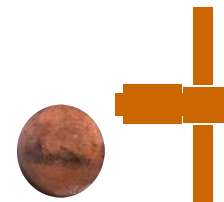
Deep Space Transport
2027



Precursor
2029



Mars
2033



Human System
Requirements

Test System Data
Management

Ground Optimize for 42
Day Mission

Deploy System Data
Handling

Initial Ground Operations
Changes

Exercise Deep Space
Comm, Autonomy, and
Decision Paths

Deploy Revised Ground
Ops

Optimally Autonomous
Crew

Redefined Ground
Operations Paradigm

Ground System
Requirements

Increasing Crew Self-Reliance

27Apr17 crew note from HMS-ULTRSND-SCAN-CMO:

You know what would really help us? If we had pictures of a "perfect case" for each type of image. Given the time lag between ground and ISS - and the minute adjustments we are making for the correct image- the ground is like "3 seconds ago". If we had a picture of what we should make each image look like, we will print it out and have it above the machine so we can more quickly get to what you want and then stabilize for the ground to catch up. I think it will also help cosmonauts considerably given the high amount of commanding/translation. Just a thought - but I think it would help us be more efficient.

Provision of Training and Crew Support

[MENU](#)

COMFORT

Baseline

Date: 2/9/2017

ID: 9201

[NOTES](#)

[EXIT](#)

 **FUNDOSCOPY**

[OBJECTIVE](#)

[FOUNDATION](#)

[SETUP](#)

[EXAM PROCEDURE](#)

[QUIZ](#)

[REFERENCE](#)

[Eye Anatomy](#)

[CellScope Use](#)

[Taking Images](#)

[Eye Pathology](#)

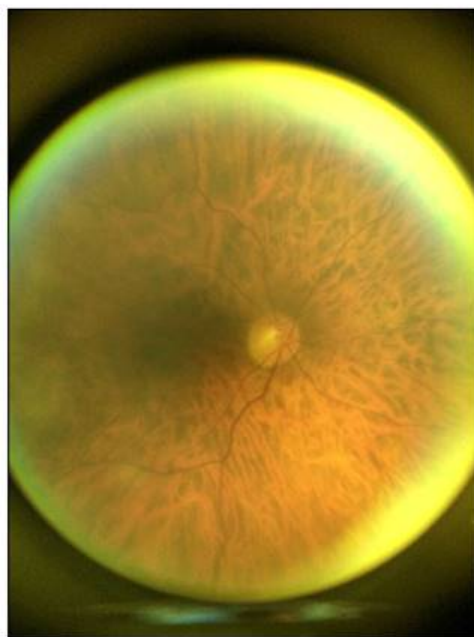
TAKING A GOOD IMAGE: COMPOSITION

Tips for good composition:

To move the optic disc down the subject needs to look up.

To move the optic disc right the subject needs to look right.

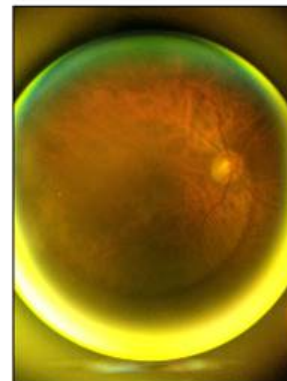
In a good composition the optic disc is centered.



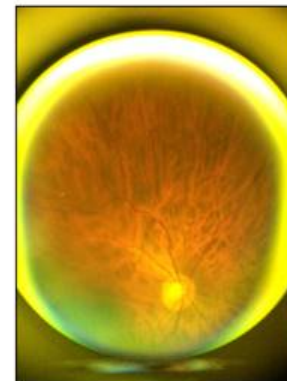
Good composition

Bad composition

In poor composition, the optic disc is not centered or not visible.



Bad composition
Optic disc is too far right



Bad composition
Optic disc is too low

[PREVIOUS](#)

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36

[NEXT](#)

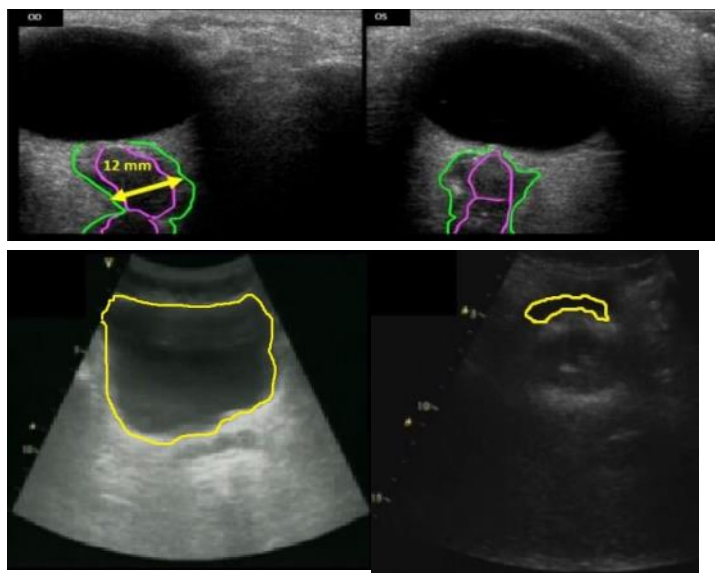
but I think it would help us be more efficient.

Remote -> Autonomy

**Augmented
Reality
Training
Tietronix**



Sensor Technology



In-flight Post-void
Ultrasound

Ground Post-void
Ultrasound



Return to Earth gravity

