Space Lab Technologies, LLC

Quantifying ECLSS Robustness for Deep Space Exploration

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OVERVIEW

I. The Need for Robust ECLSS Design

II. Robust Design Methodology for ECLSS

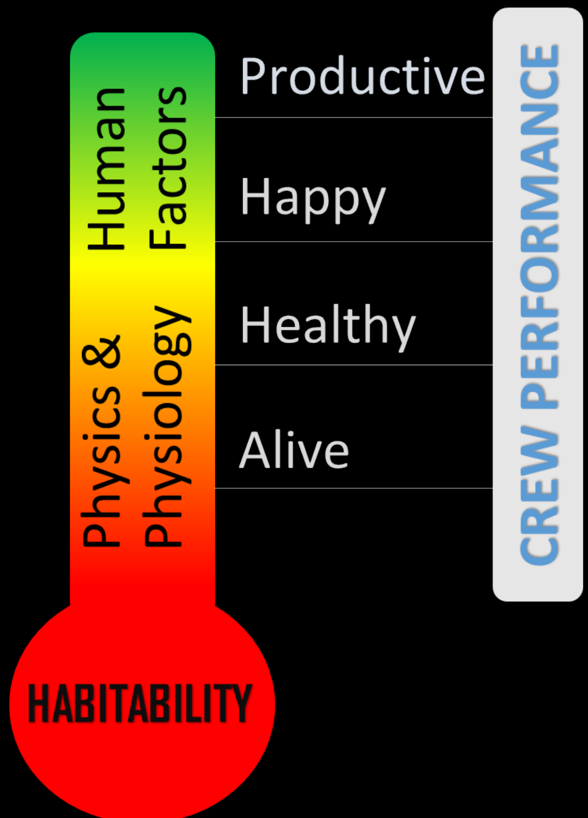
III. Quantifying ECLSS Robustness

IV. Improving ECLSS Robustness

NEED FOR ROBUST ECLSS DESIGN

ECLSS REQUIREMENTS

Mission Objectives ◆ Habitat Requirements ◆ ECLSS Requirements



Physics & Physiology

- Regulate the Atmosphere
- Provide Potable Water
- Remove Waste Hazards
- Food

Human Factors

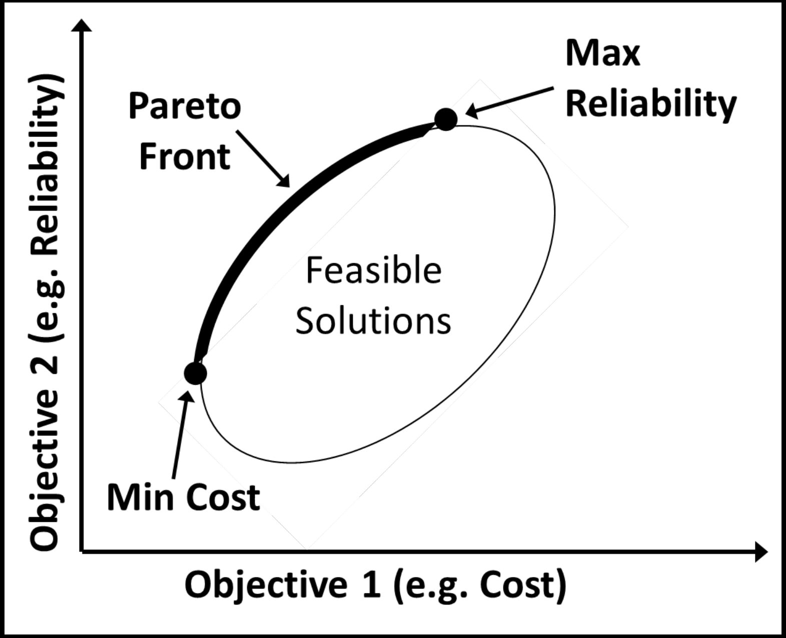
- Safety Infrastructure
- Health Countermeasures
- Crew Accommodations

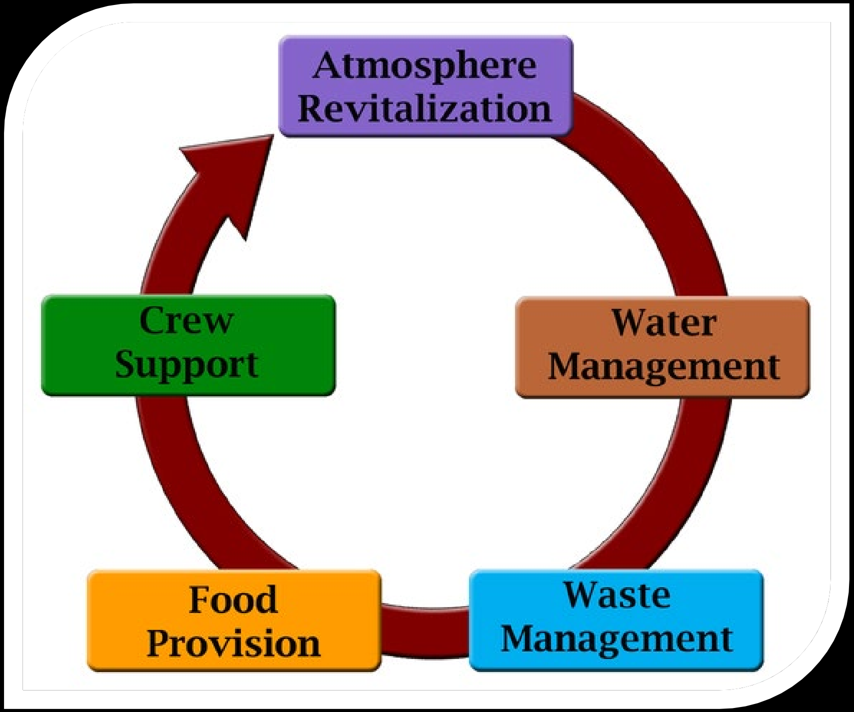
Design Drivers

- Human metabolic inputs & outputs
- Space environment
- Mission characteristics

ECLSS DESIGN OPTIMIZATION

Pareto Front for Multi-Objective Optimization





Optimization finds the best possible design solution amongst all available solutions

SOURCES OF UNCERTAINTY

Probable
- Frequent
- Foreseen
- Statistically Characterized

Possible
- Foreseeable
- Less Frequent
- Higher Impact

Plausible
- Unforeseeable
- Very High Impact
- Rare "Black Swan Events"

Aleatory (Irreducible Randomness) → Epistemic (Reducible Lack of Knowledge)

Complexity + Increased Life → Increased Variability

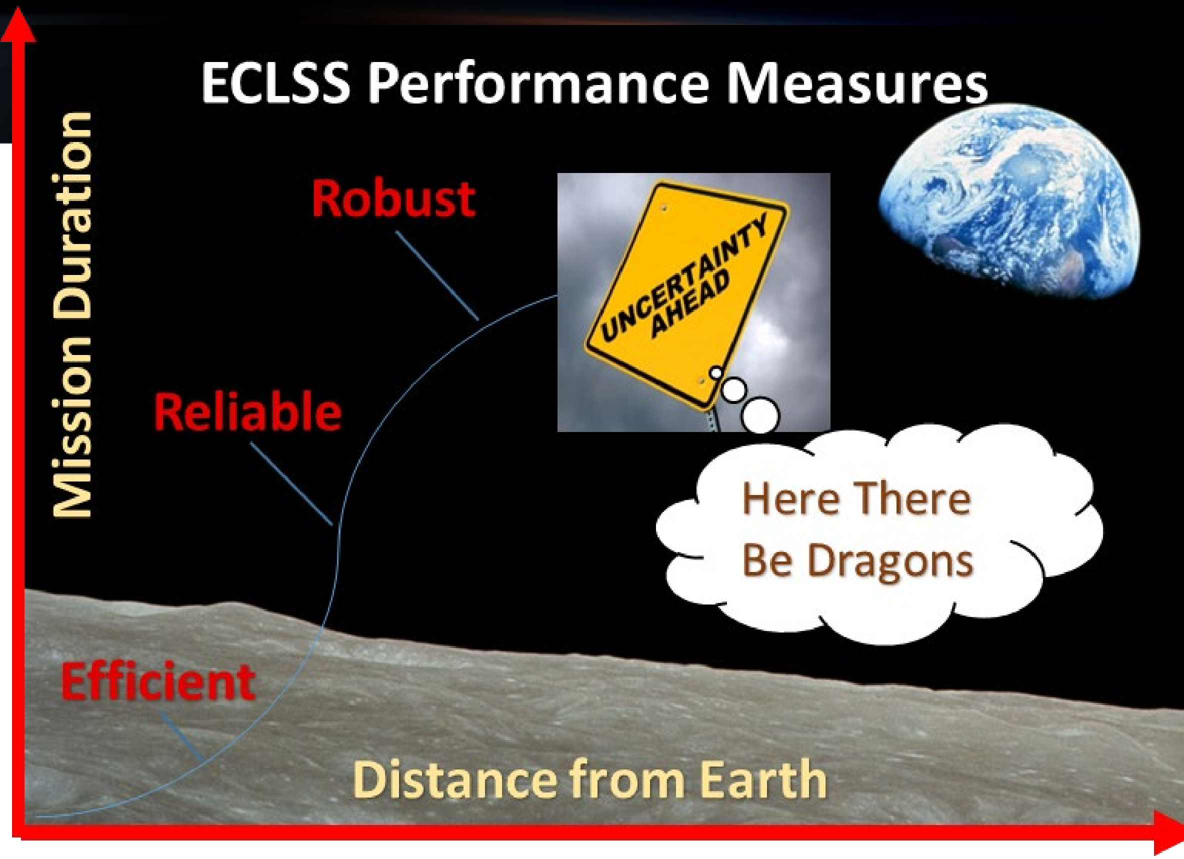
Sources of Uncertainty:

- **Component Performance**
- **System Dynamics**
- **Metric Uncertainty**
- **Operating Environment**
- **Mission Characteristics**

COST OF UNCERTAINTY

- **Failure Costs:** LoC, LoV, LoM
- **Cost of Prevention:** Redundancy, margin, etc.
- **Unanticipated system behavior in un-tested environments**
- **Increased Complexity:** Lower reliability & higher maintenance costs

"COST OF QUALITY"



Cost of uncertainty rises with mission duration & distance, increasing importance of **ROBUSTNESS** relative to other optimization criteria

A PROPOSED ROBUST DESIGN METHODOLOGY FOR ECLSS

DEFINING ECLSS ROBUSTNESS

"Capable of performing without failure under a wide range of conditions"

Merriam-Webster

"Often [spacecraft] systems are forced to operate under conditions which deviate significantly from ideal design conditions. A degree of how well a system performs with **no appreciable degradation** in performance **under such conditions** is measured by its **robustness**." *Miller et al. (2008)*

ECLSS robustness is its ability to **maintain habitable** conditions for crew survival and productivity over the mission lifetime under a **wide range of conditions**.

Escobar et al., 2017

- ➔ **Ordinary usage (Reliability)**
- ➔ **Temporary disturbances or disruptions (Robustness or Resilience)**
- ➔ **Long term system or mission changes (Resilience or Survivability)**

ROBUST CHARACTERISTICS

ROBUST SYSTEM CHARACTERSTICS

RELIABLE

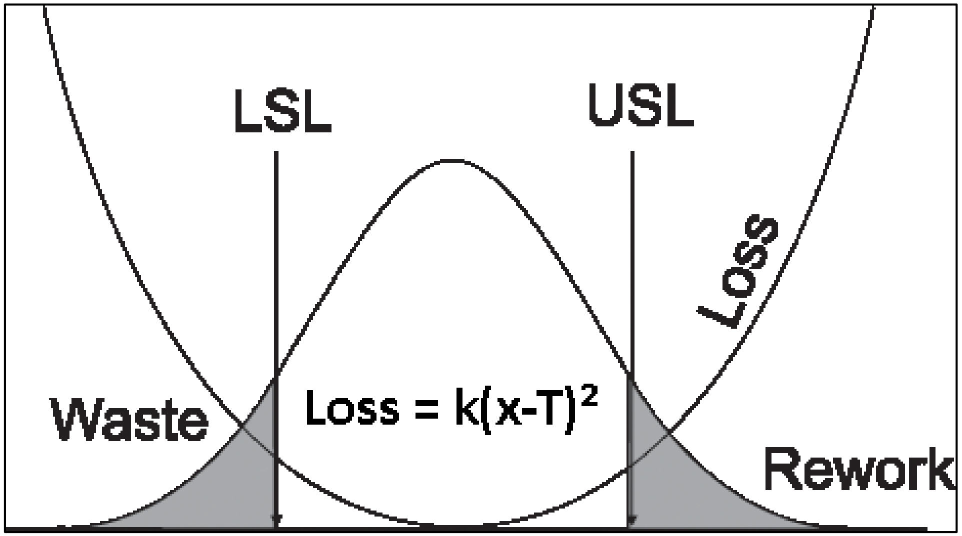
RESILIENT

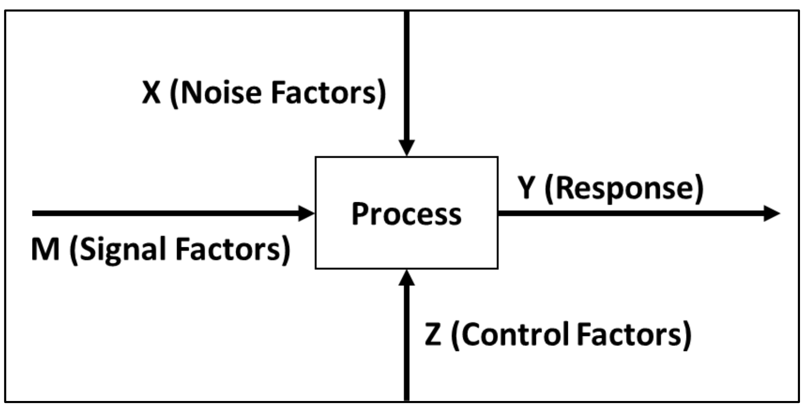
SURVIVABLE

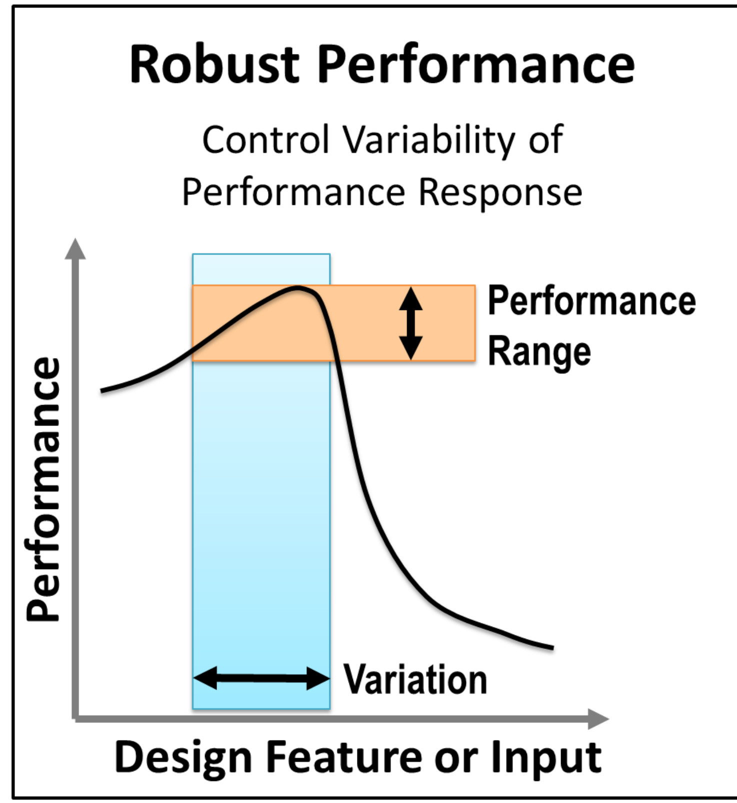
Insensitivity of performance (i.e. maintaining habitability) to

1) Random expected failures and conditions (reliability)
2) Foreseen but unexpected deviations in conditions or disturbances (resilience)
3) Unforeseen disturbances or adverse events (survivability)

ROBUST DESIGN DEFINITIONS AND CONCEPTS







EVOLUTION OF ROBUST DESIGN

Taguchi's Robust Design for Quality Engineering

↓

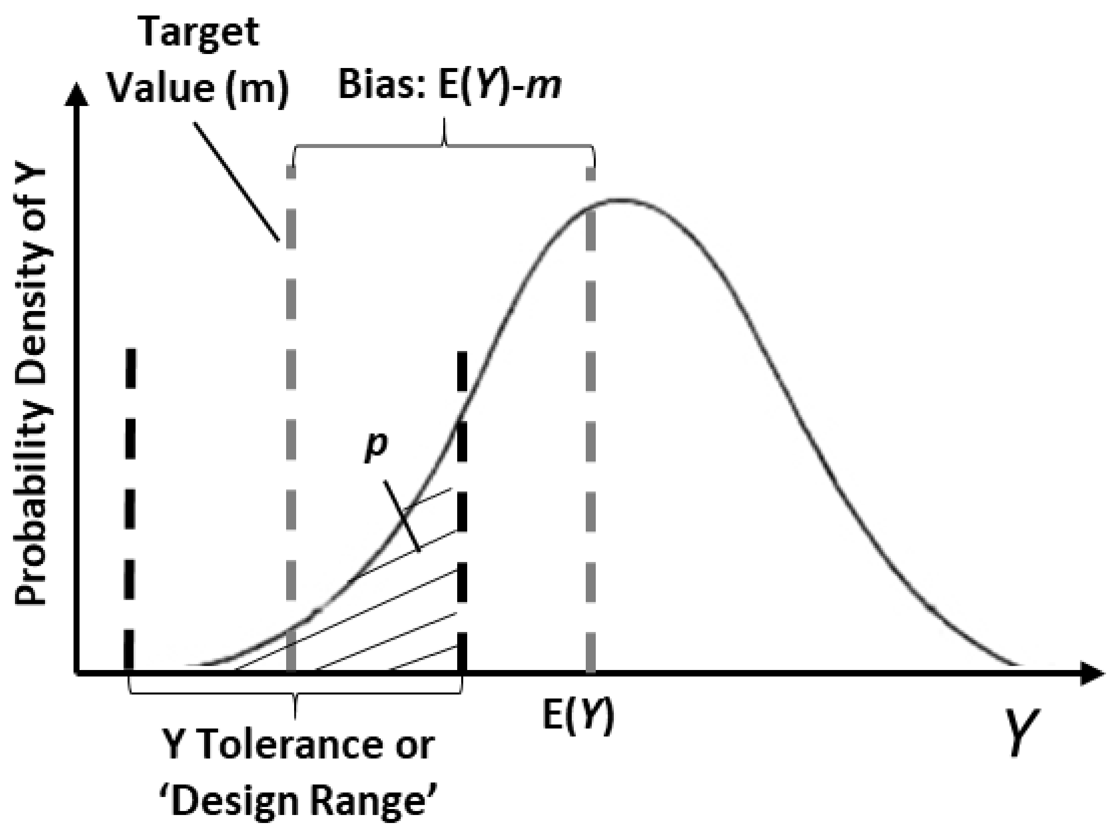
Statistical Process Control

↓

Robust Design Optimization

↓

Axiomatic Design



ROBUST DESIGN METHODOLOGY FOR ECLSS

General Methodology →	ECLSS Methodology
1. Define **key product characteristic** (KPC):	Need to define **"Habitability"**
2. Identify & characterize **variation sources**:	Need to characterize **ECLSS inputs, operating conditions, component reliability, etc.**
3. Define or **model system** behavior:	Need mathematical or physical **ECLSS model**
4. Quantify robustness of KPC given variation & system model:	Need an **ECLSS robustness metric**
5. Select or **improve design:**	Identify design features **contributing to habitability loss** w/ **minimum cost of quality**

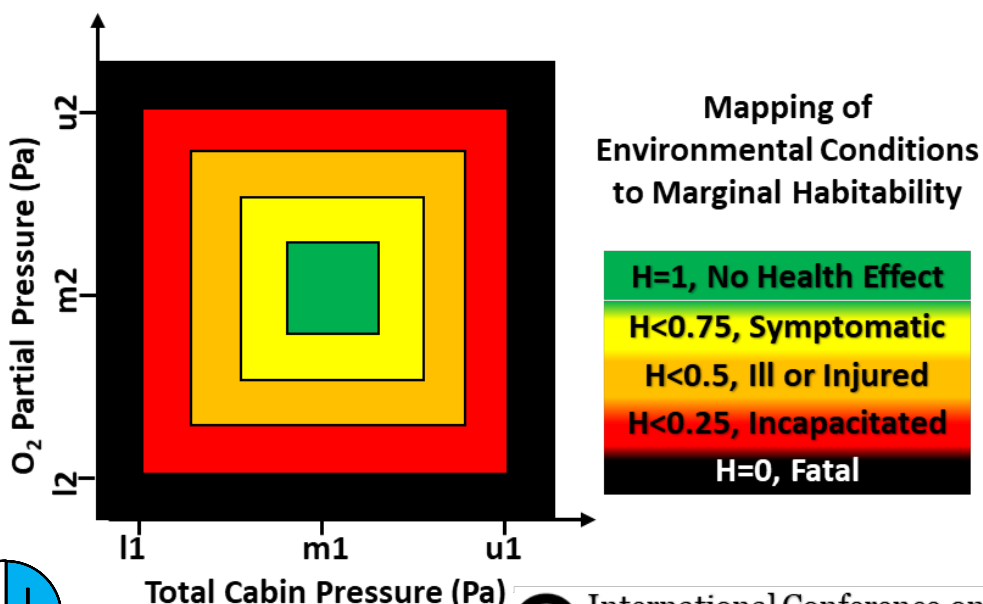
IV I
III II

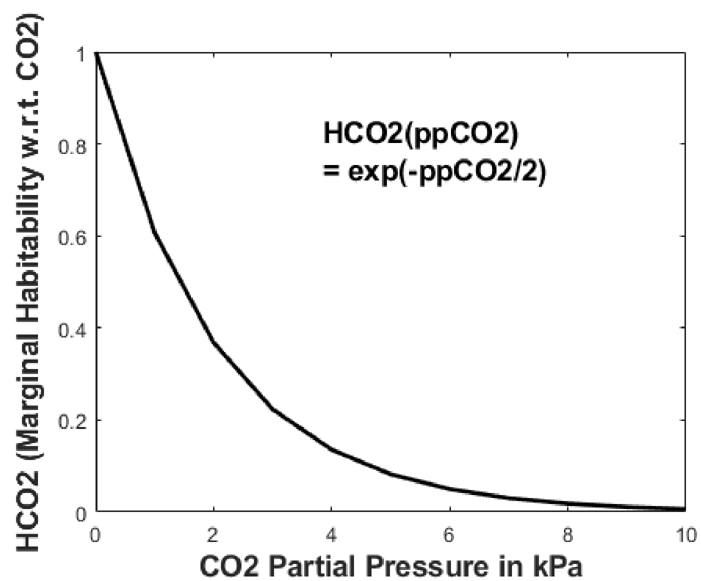
QUANTIFYING ECLSS ROBUSTNESS

HABITABILITY INDEX: ECLSS KPC

Potential Habitability Contributors (y_i) ➔ Map to Utility Functions, $H_i \in [0,1]$

1. O2 partial pressure in cabin air
2. CO2 partial pressure in cabin air
3. Total cabin pressure
4. Wet bulb temperature
5. Food quality (days of available acceptable food per CM)
6. Water quality (days/CM)
7. Presence of noxious substances



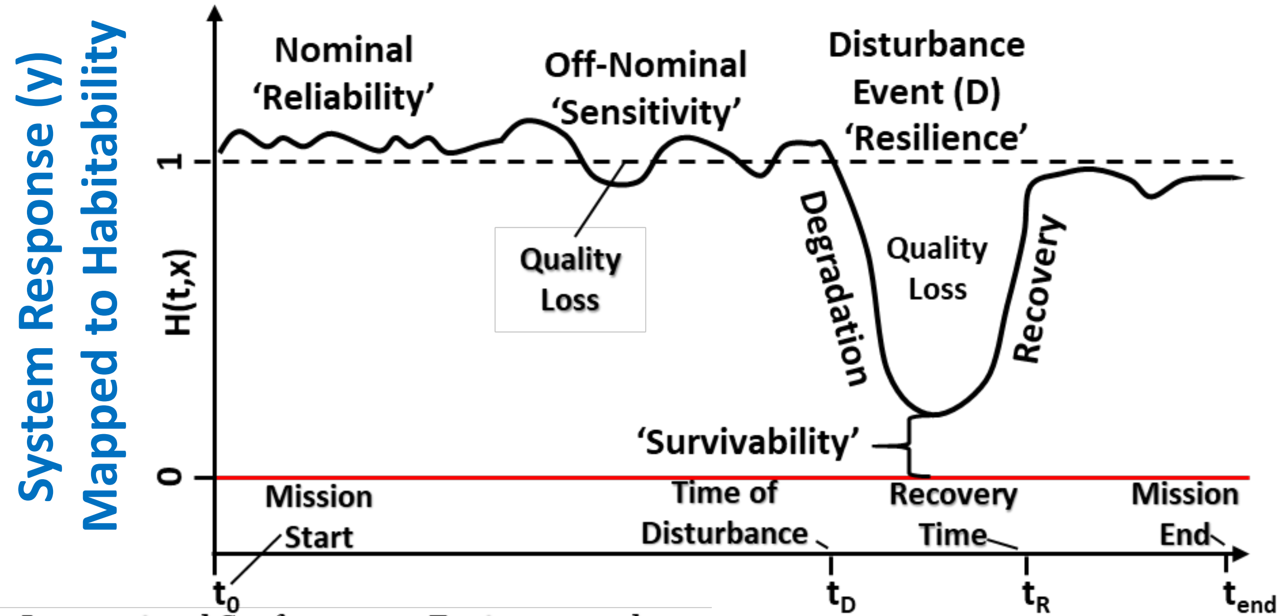


HABITABILITY INDEX

1. *H* must be 1 when crew performance capacity is full ➔ all *Hi* are equal to 1.
2. *H* must be 0 under any fatal conditions, i.e. when any *Hi* = 0.
3. *H* must be no better than any individual *Hi*, i.e. $H \leq \min(Hi)$
4. The impact of *Hi* on *H* is not independent. A reduction in one *Hi* increases the impact of another *Hi*.

$$H = \Pi Hi,$$
$$\text{for } i = 1,\ldots,n$$
$$\& \; Hi \in [0,1]$$

Habitability Over Mission Duration

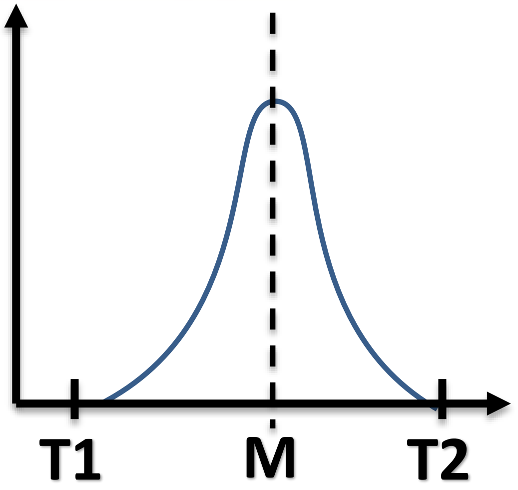


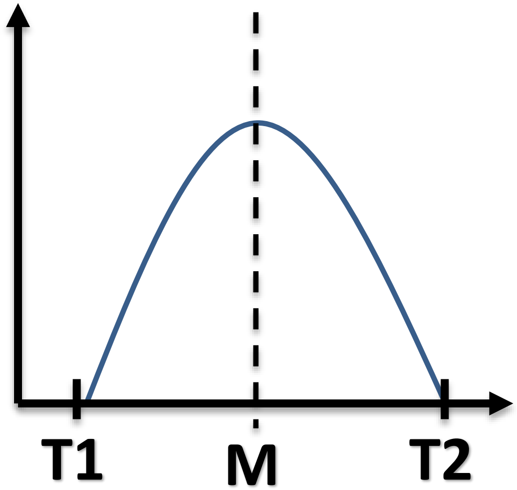
ROBUSTNESS METRICS

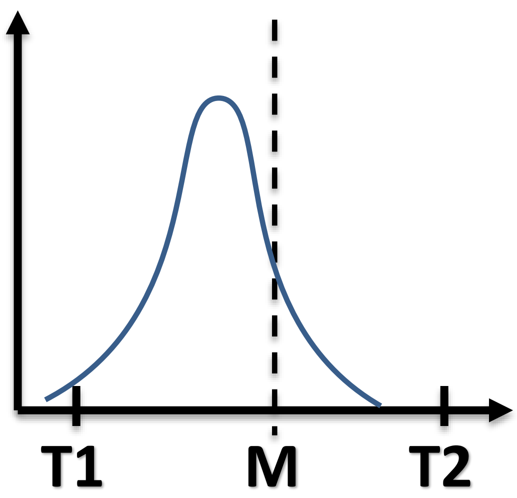
See Paper for Details

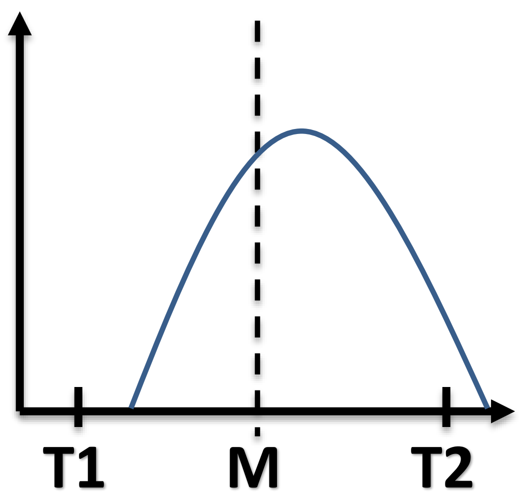
1. **Variance ➔** Min Var(Y|**x**)
2. **Effective Fitness ➔** Max E(Y|**x**)
3. **Minimax Optimization (Worst Case Philosophy) ➔**
   Choose design parameter that minimizes the worst case value of response Y, given variation in input X
4. **Process Capability Index ➔** Max $\Delta/6\sigma$
5. **Quality Loss:** Min $E(L) = E[k(y-m)^2] = k[(\mu-m)^2 + \sigma^2]$
6. **Sensitivity:** Min $\delta y/\delta x$ (sensitivity coefficients) a.k.a. Jacobian
7. **Signal to Noise (Taguchi):** Max $\eta = 10\log_{10}\mu^2/\sigma^2$
8. **Mean + Variance Weighted sum:** min $(1-\omega)E(y|x) + \omega Var(y|x)$
9. **Variation Risk Priority # ➔** Method to approximate Var(Y|**x**) when design fidelity is low
10. **Information Content (Axiomatic Design):** Min $I = \log_2(1/p)$

BIAS VS SPREAD: WHICH IS WORSE?









Я$_H$ - A PROPOSED METRIC FOR ECLSS ROBUSTNESS

- **Habitability Loss:**

  $L_H = (H-1)^2$

- **Expected Habitability Loss:**

  $E[L_H] = E[(H-1)^2] = [1-E(H)]^2 + Var(H)$

- **ECLSS Robustness:**

$$Я_H = 1 - \sqrt{E(L_H)} = 1 - \sqrt{[(1 - E(H))^2 + Var(H)]}$$

'bias' **'spread'**

IMPROVING ECLSS ROBUSTNESS

ROBUST DESIGN METHODOLOGY FOR ECLSS

General Methodology →	ECLSS Methodology
1. Define **key product characteristic** (KPC): ✓	Need to define **"Habitability"**
2. Identify & characterize **variation sources**: ✓	Need to characterize **ECLSS inputs, operating conditions, component reliability, etc.**
3. Define or **model system** behavior: ✓	Need mathematical or physical **ECLSS model**
4. Quantify robustness of KPC given variation & system model: ✓	Need an **ECLSS robustness metric**
5. Select or **improve design:**	Identify design features **contributing to habitability loss** w/ **minimum cost of quality**

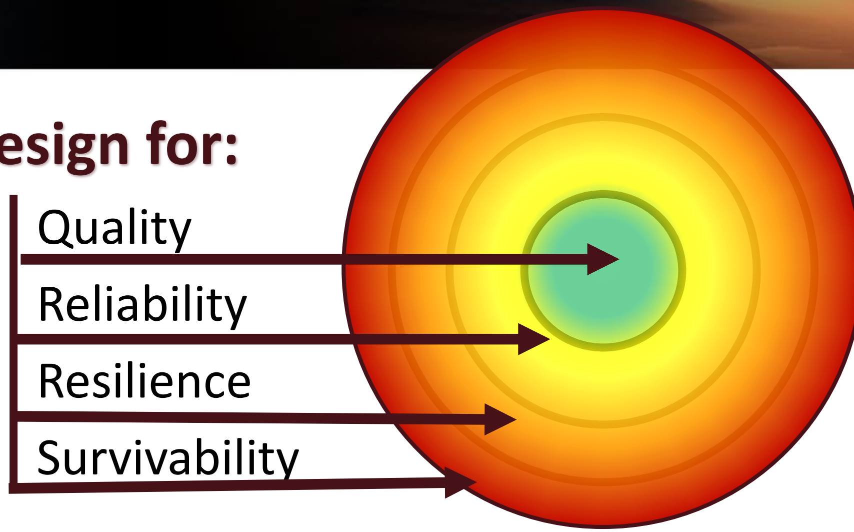
IV I III II

IMPROVING ROBUSTNESS: DEFENSE IN DEPTH STRATEGY

Many Design Options to Consider:

- Materials, technology choices
- Margin
- Tolerancing
- Redundancy (many types)
- Fault detection & isolation
- Repair/recovery
- Noise reduction through shielding, etc.
- Process changes
- Decrease complexity
- Decrease coupling (controllability)

Design for:

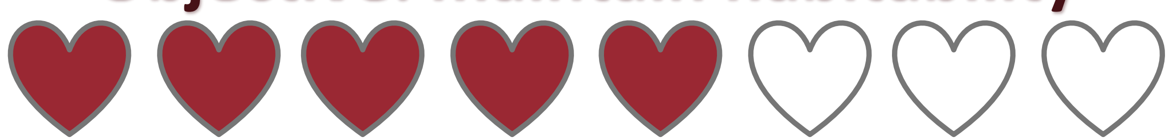


Good day → Not so good day → Bad Day

Probable→Possible→Plausible

Fail Safe →→→ Safe to Fail

Objective: maintain habitability



IMPROVING ROBUSTNESS: MINIMIZE COST OF QUALITY

Robustness Normalized ESM (?)

Equivalent mass required to achieve equivalent robustness

$$ESM_{Я} = ESM/Я_{H}$$

NEXT STEPS

- **Development of Marginal Habitability Functions for ECLSS sub-systems**

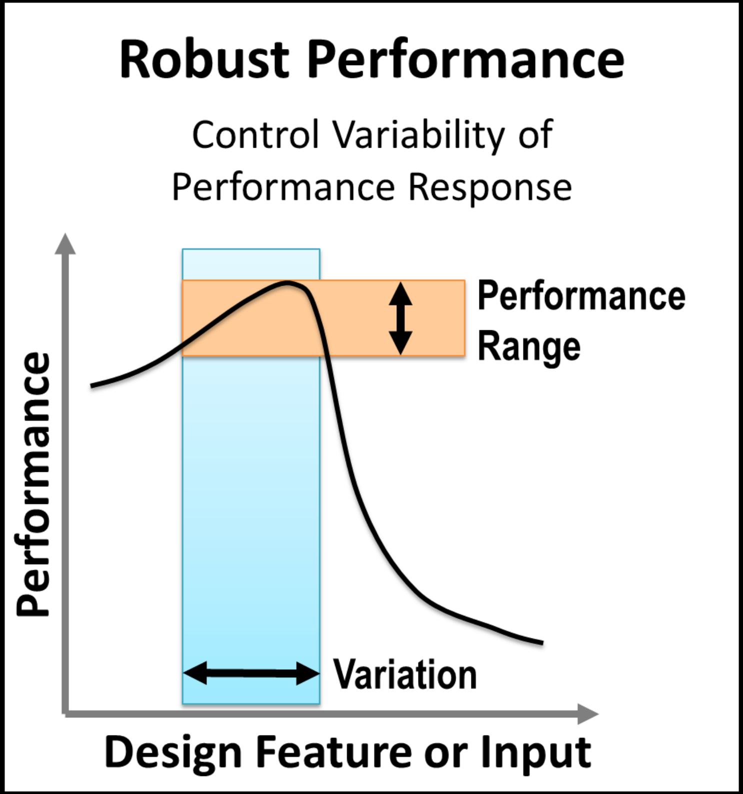
  Requires cooperative research amongst subject matter experts!

- **Demonstrate ECLSS robustness analysis with historical data (ISS, etc.)**

- **Demonstrate robust design methodology**

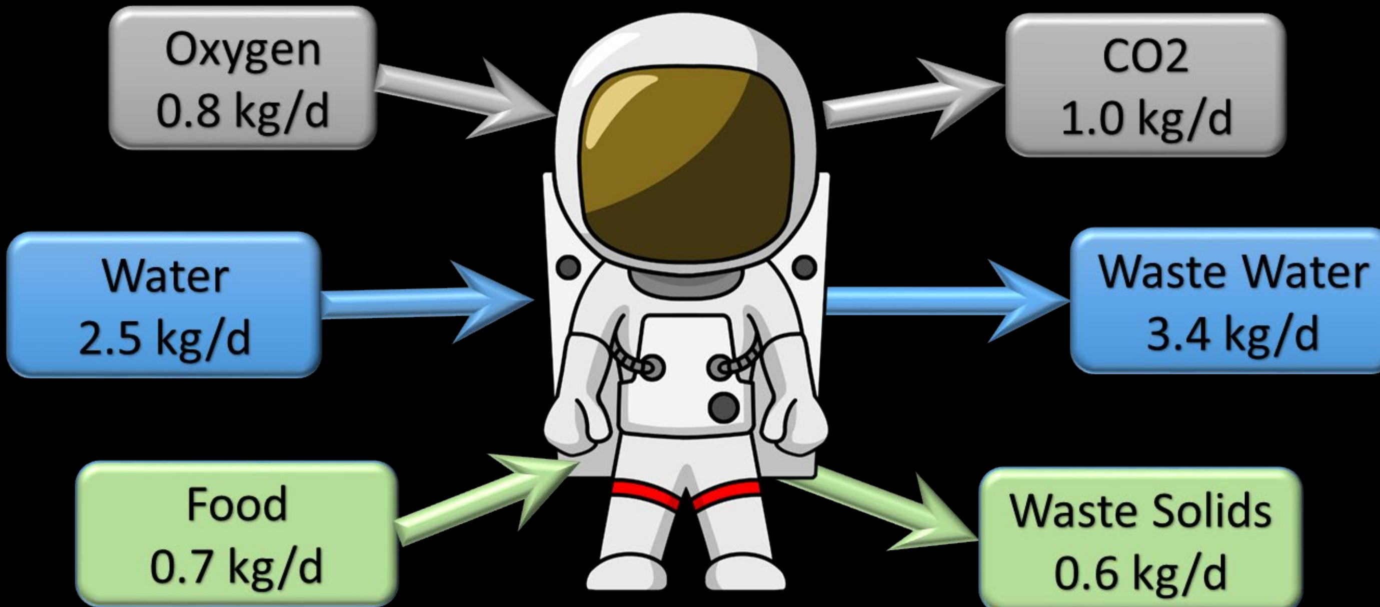
Reaching consensus on marginal utility functions contributing to habitability will be challenging, but instrumental in improving ECLSS design

QUESTIONS?


Robust Performance
Control Variability of
Performance Response
Performance Range
Performance
Variation
Design Feature or Input

ECLSS DESIGN DRIVERS

Human Metabolic Inputs & Outputs



Control Temperature | Maintain Pressure | Maintain Relative Humidity

BVAD 2015 (pp 50, 53, 64, & 106)

ECLSS DESIGN DRIVERS

Interplanetary Environment

Earth's Moon
-233 to 123°C

-270°C
'Cosmic Background'

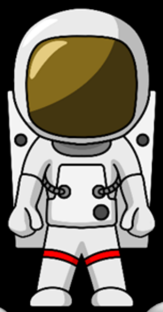
Extreme Temp Swings

High Vacuum ($\sim 10^{-14}$ Pa)

'Nutritional Wasteland'
(Rothschild, 2001)

Micro-meteoroids

Fast Particles
<0.05 mm



Reduced Gravity ($<10^{-6}$g)

Not Lethal, Not Well Understood

Radiation Exposure

Energy in Transit

ECLSS DESIGN DRIVERS

Mission Characteristics

- Mass & Volume Constraints
- EVA Activity
- Crew Workload
- Surface Operations
- Distance from Earth

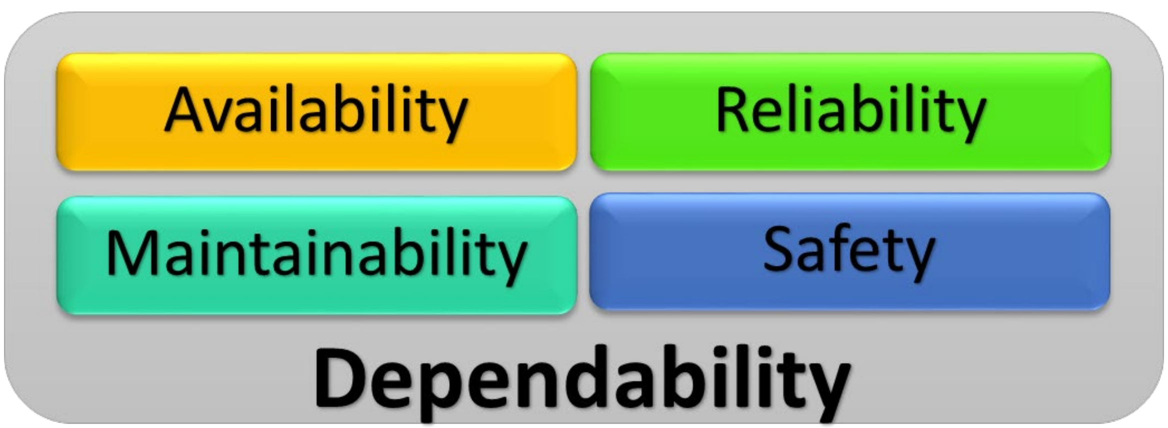
NASA Exploration Systems Architecture Study

https://www.nasa.gov/pdf/140649main_ESAS_full.pdf

Reliability Definition

"The probability of a system or system element performing its intended function under stated conditions without failure for a given period of time."

Adcock, 2016



Resilience Definition

"The capacity to recover quickly from difficulties; toughness"

"The ability of a substance or object to spring back into shape; elasticity" *Oxfrd Dictionary*

Engineering definitions vary widely:

- Ability to adapt to changing conditions and prepare for, withstand, and rapidly recover from disruption (DHS)
- Attributes include flexibility, recovery, and adaptation

Defining Survivability

Ability of a system to **minimize the impact of a finite disturbance on value delivery**, achieved through either the satisfaction of a minimally acceptable level of value delivery during and after a finite disturbance or the reduction of the likelihood or magnitude of a disturbance

Castet et al., 2008