Spacecraft Design for Habitability (part 1)

- Lecture #13 – October 10, 2023
- Required crew volumes
- Interior layouts
- Workstation design
- Habitat optimization

Designing for Living in Space

- How much room do you need?
- How do you design the habitat shape?
- How do you design the habitat interior?
- Where do you put everything?
- How do you make it livable?
- How do you make it functional?
- How do you make it comfortable?

How Much Room Do You Need?

- How do we define “room”?
  - Floor area (in appreciable gravity)
  - Volume (in microgravity)
- How do we define “need”?
  - Survival
  - Critical functionality
  - Comfort
- How does the mission affect the answers?

Bounding the Problem

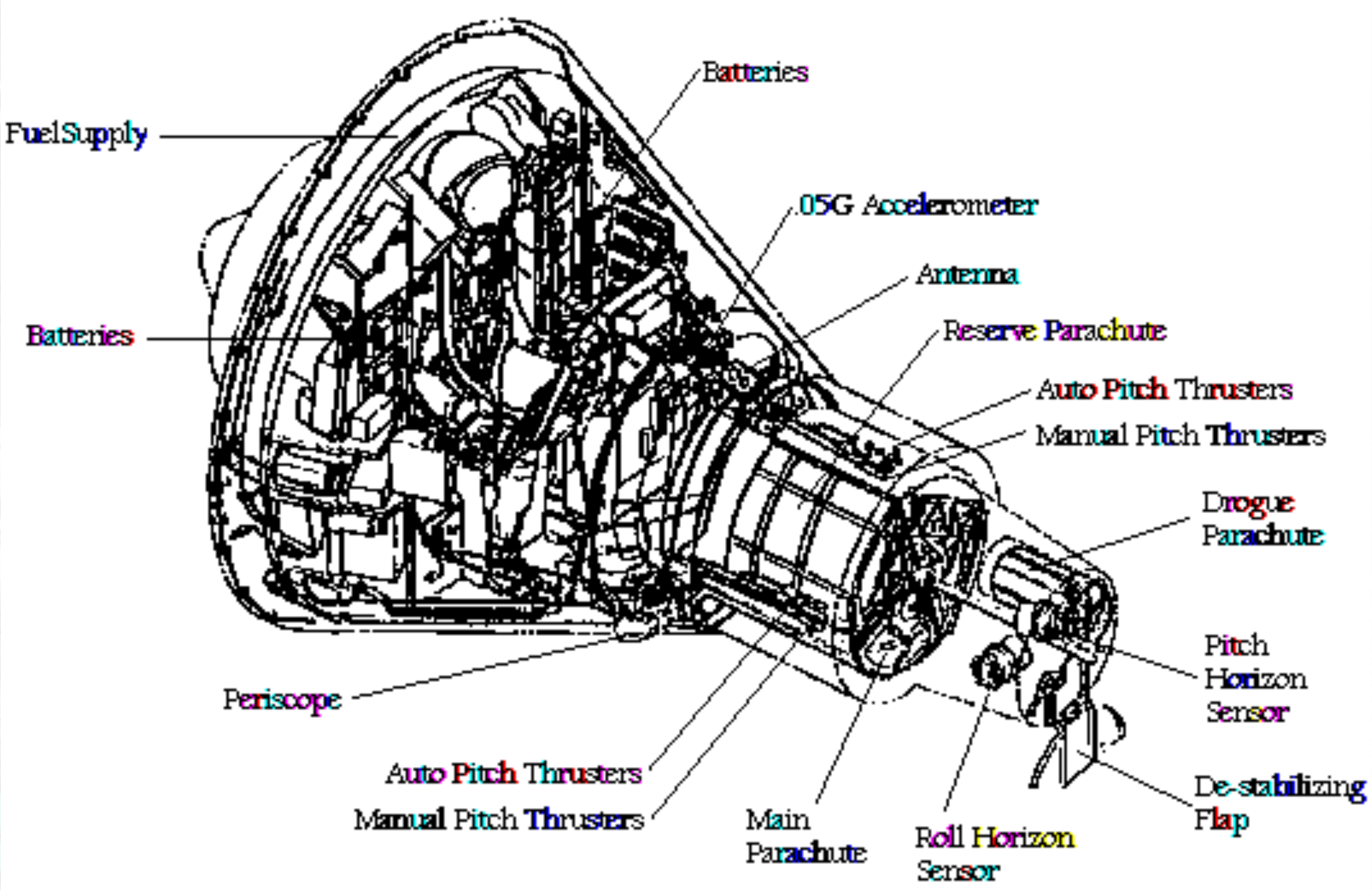
Environment	Relative Gravity
Earth	1
Mars	0.38
Moon	0.16
Minor Bodies	$10^{-2} – 10^{-4}$
Orbit	$10^{-5} – 10^{-6}$

Macrogravity (Earth to Moon)

Partial Gravity (Mars to Moon)

Microgravity (Minor Bodies to Orbit)

Mercury Spacecraft Interior Layout



Habitat Design Size

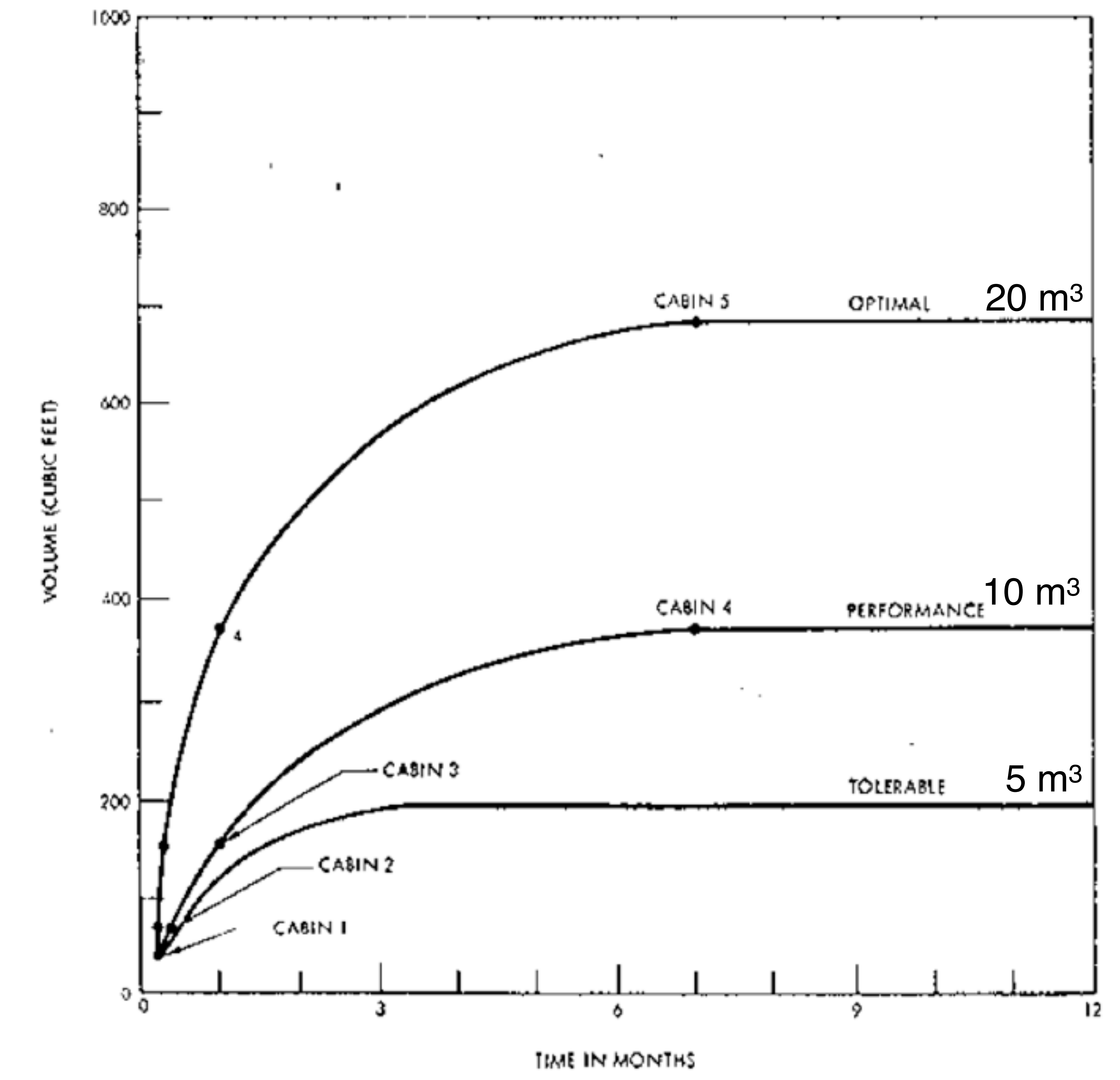
- Typically estimated per crew member
  - Microgravity habitat figure of merit m^3/crew
  - Partial gravity habitat figure of merit m^2/crew
- Historical analysis
  - Most available habitat data is for partial gravity missions
  - Classic parametric function: “Celentano curves”

$$\frac{volume}{crew\ member} = A\left(1 - e^{-\frac{duration}{B}}\right)$$

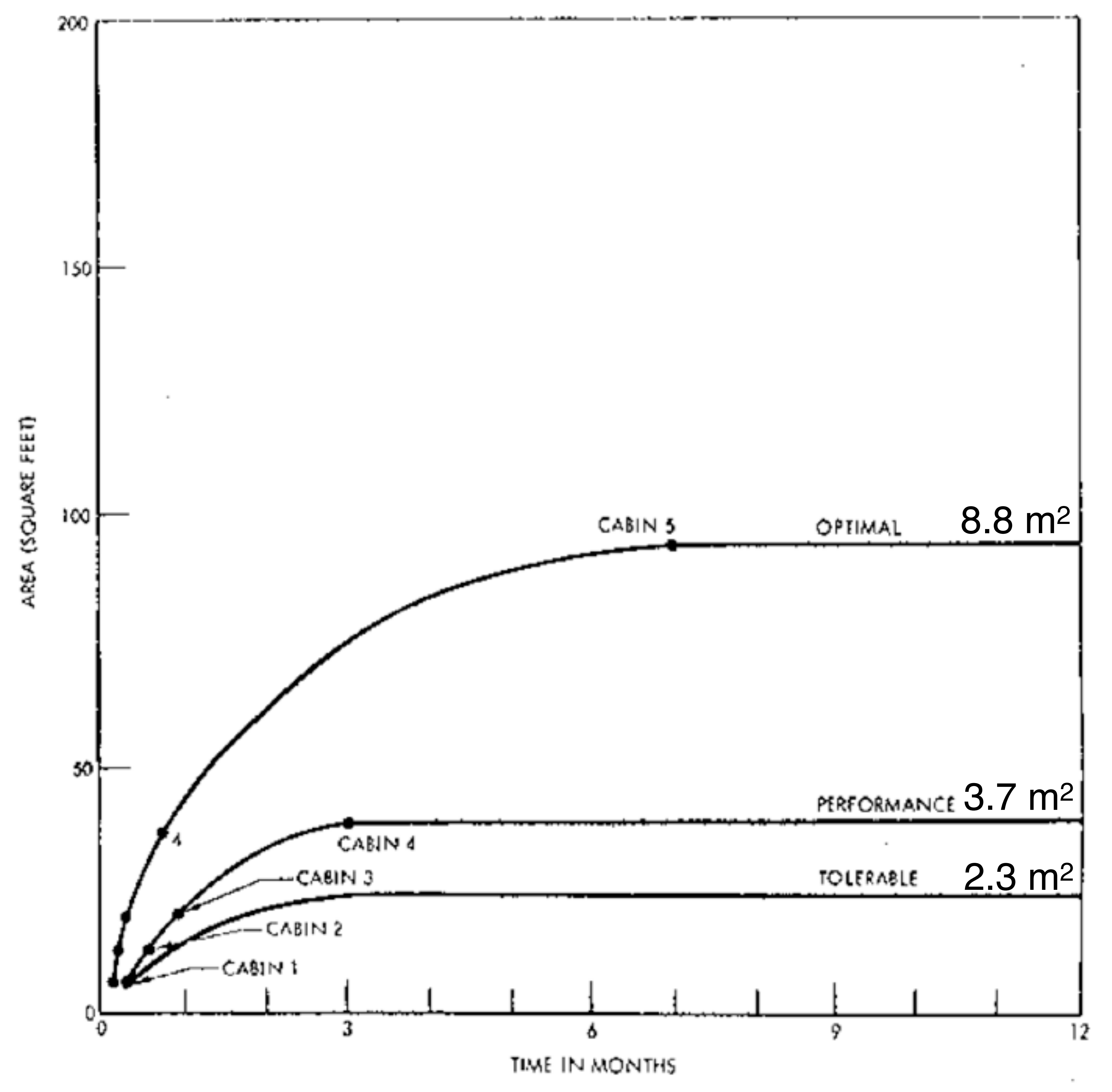
  - Standard form uses A=5 (“tolerable”), 10 (“performance”), 20 (“optimum”) m^3/crew; B=20 days

Required Space per Crew Member

Volume

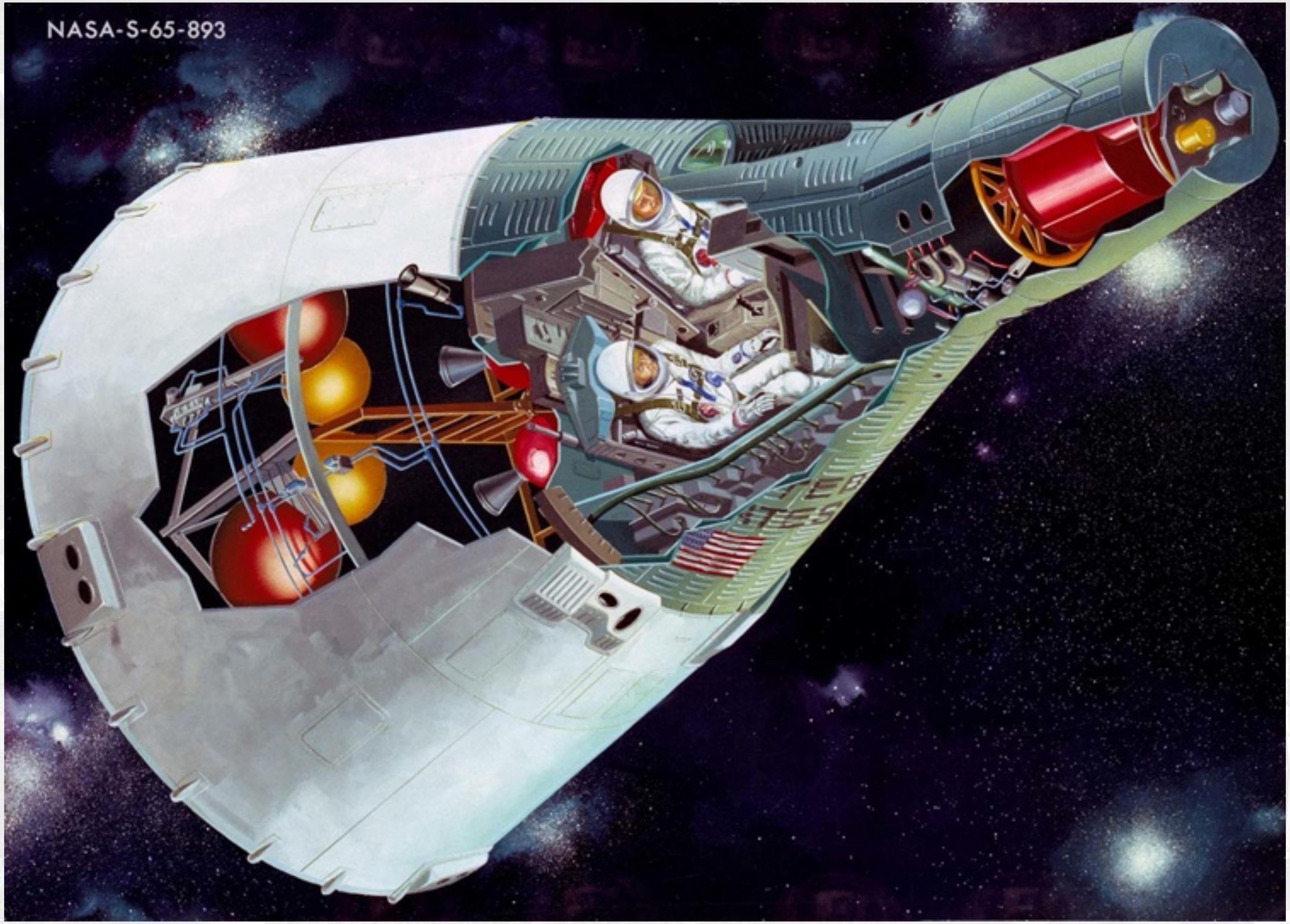


Area



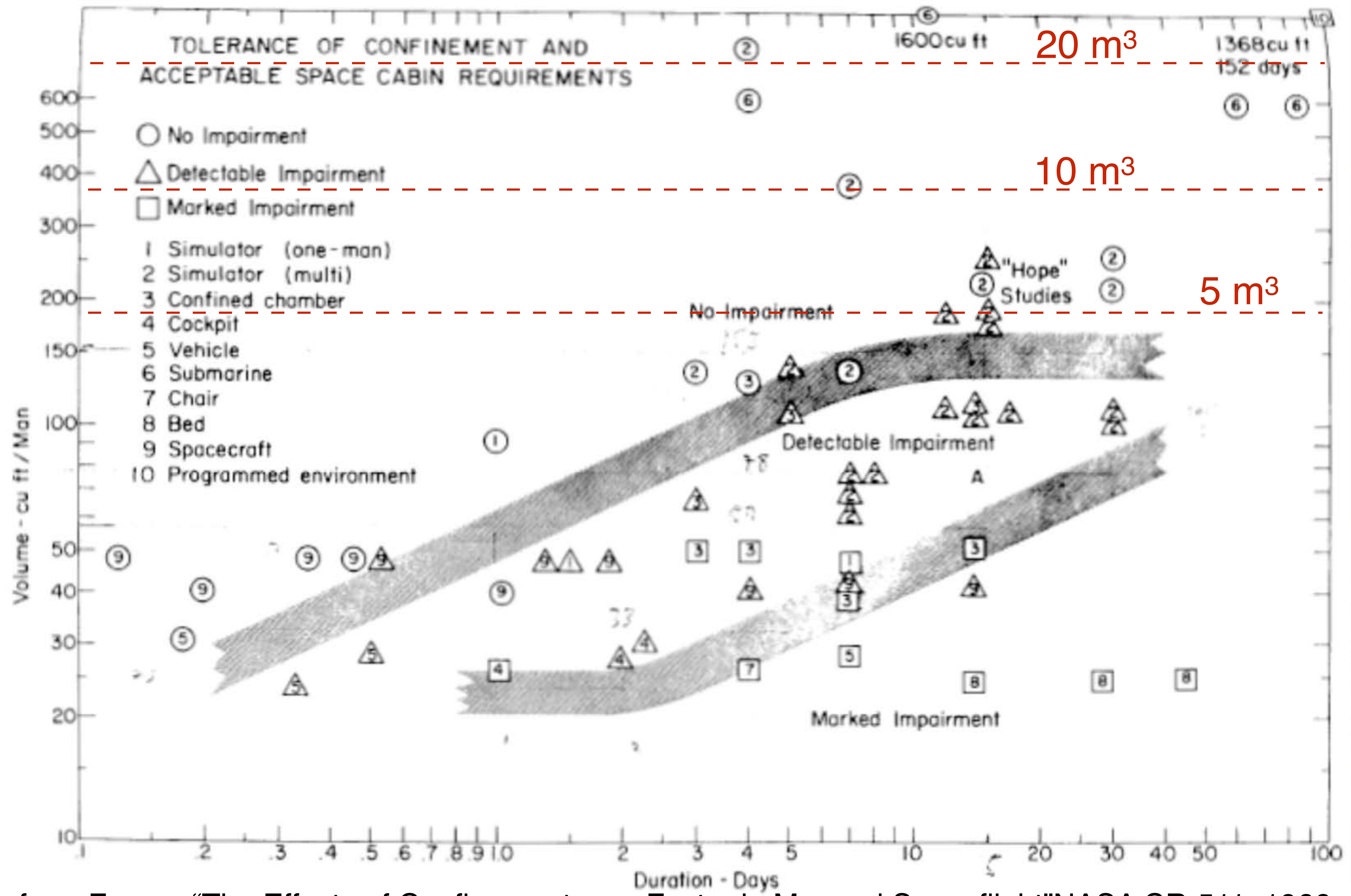
from Celentano, Amorelli, and Freeman, "Establishing a Habitability Index for Space Stations and Planetary Bases"
AIAA 63-139, AIAA/ASMA Manned Space Laboratory Conference, Los Angeles, California, May 2, 1963

Gemini Spacecraft Cutaway



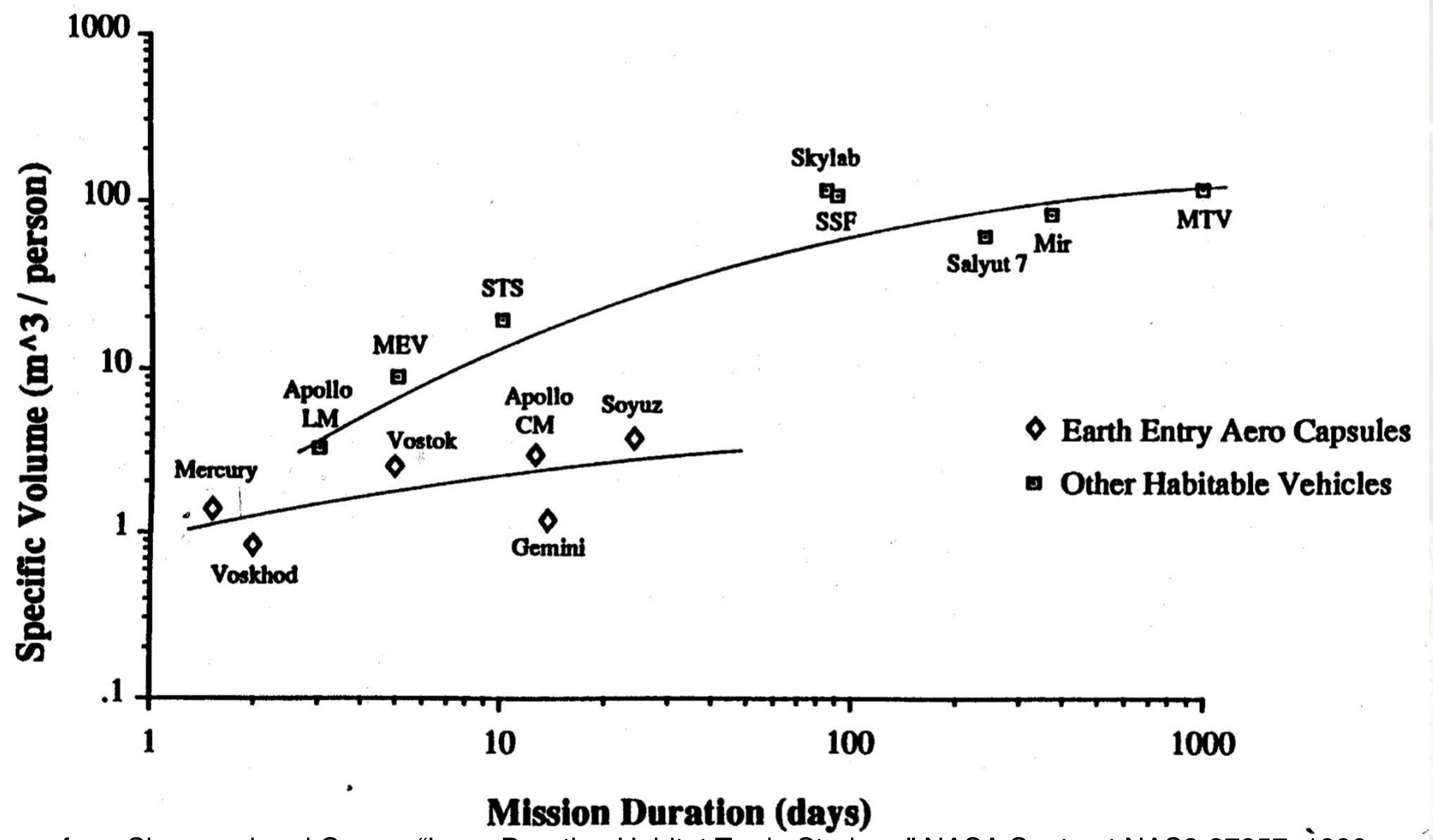
Gemini 4 Crew Cabin

Early Looks at Performance Data



from Fraser, "The Effects of Confinement as a Factor in Manned Spaceflight" NASA CR-511, 1966

Total S/C Pressurized Volume Data



from Sherwood and Capps, “Long-Duration Habitat Trade Study:…” NASA Contract NAS8-37857, 1990

A Closer Look at Volume Rqmnts

SAE TECHNICAL PAPER SERIES

2008-01-2027

Testing the Celentano Curve: An Empirical Survey of Predictions for Human Spacecraft Pressurized Volume

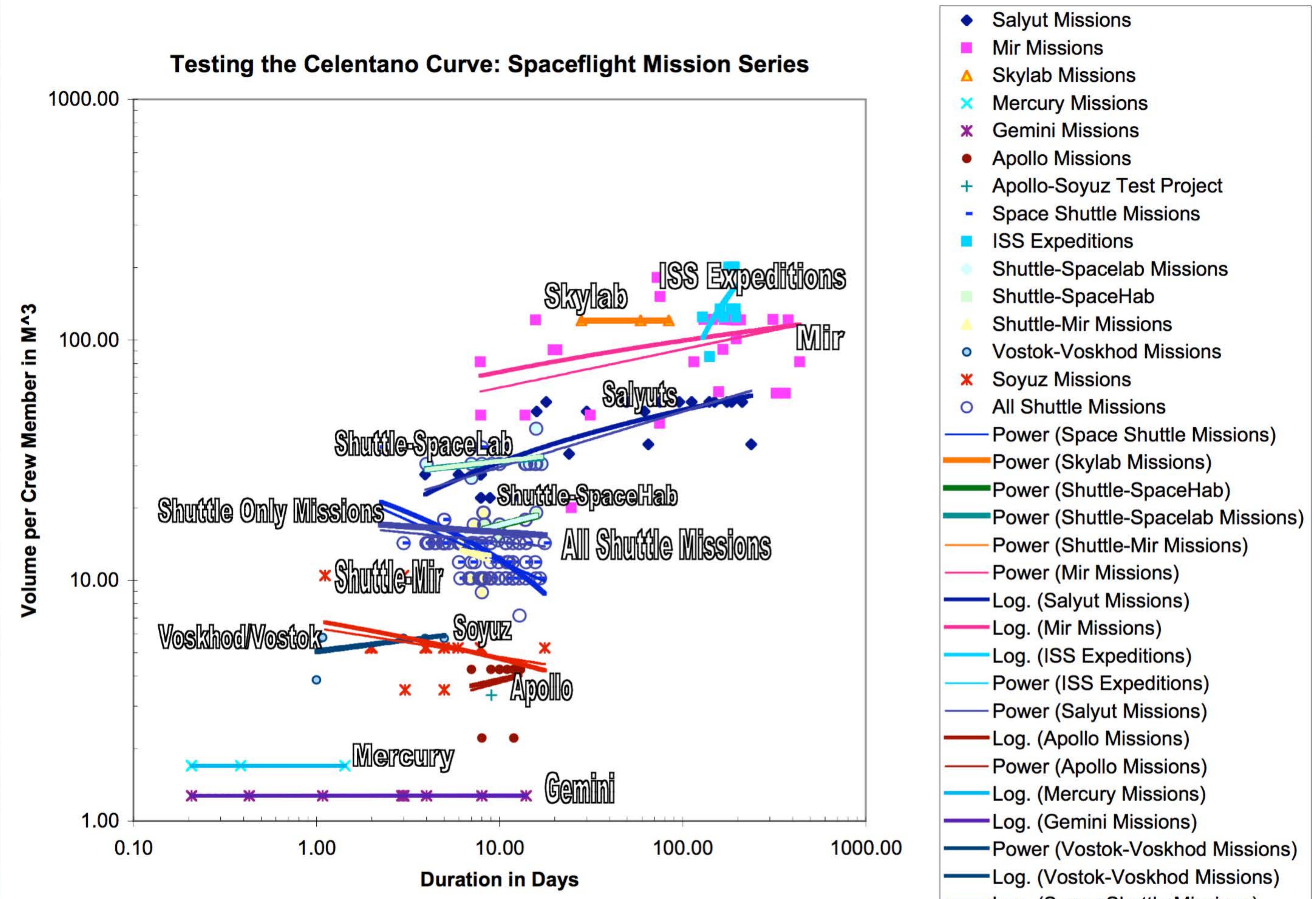
Marc M. Cohen
Northrop Grumman Corporation

Data from Space Flight Experience

Spacecraft Type	Category	Number of missions	Max. Mission Duration Days	Min. Mission Duration Days	Max. Volume Per Crew m^3	Min. Volume Per Crew m^3	Max. Crew	Min. Crew
Mercury	Capsule	6	1.43	0.02	1.70	1.70	1	1
Gemini	Capsule	10	14.00	0.21	1.28	1.28	2	1
Apollo CM with and w/o LM	Capsule	11	12.75	6.00	4.27	2.22	3	3
Apollo LM	Lander	7	3.21	1.00	3.33	3.33	2	2
Apollo-Soyuz	Capsule	1	9.04	9.04	3.33	3.33	5	5
Vostok	Capsule	6	5.00	0.07	5.73	5.73	1	1
Voskhod	Capsule	2	1.08	1.00	2.87	1.91	3	2
Soyuz	Capsule	42	14.00	0.43	1.28	1.28	2	2
Shenzhou	Capsule	2	5.00	1.00	17.00	8.50	2	1
Space Shuttle	Shuttle	89	17.67	2.25	35.75	8.94	8	2
Shuttle-Spacelab/SpaceHab	Shuttle	25	16.90	4.00	42.70	14.66	8	5
Skylab	Station	3	84.00	28.00	120.33	120.33	3	3
Salyut	Station	17	237.00	16.00	55.25	33.50	3	2
Mir	Station	25	437.75	72.82	181.35	45.00	3	2
ISS	Station	12	195.82	128.86	201.13	85.17	3	2

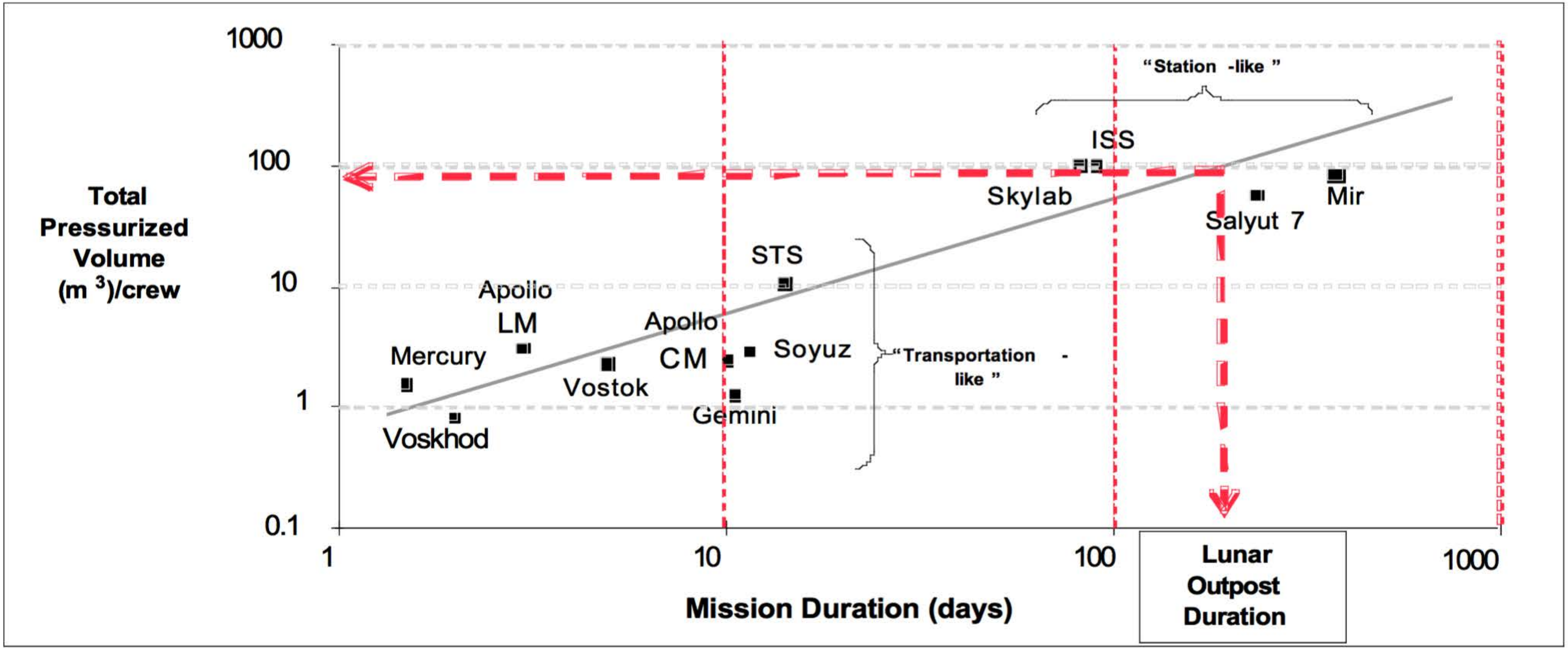
from Cohen, “Testing the Celentano Curve:…”SAE 2008-01-2027

Correlation to Space Flight Experience



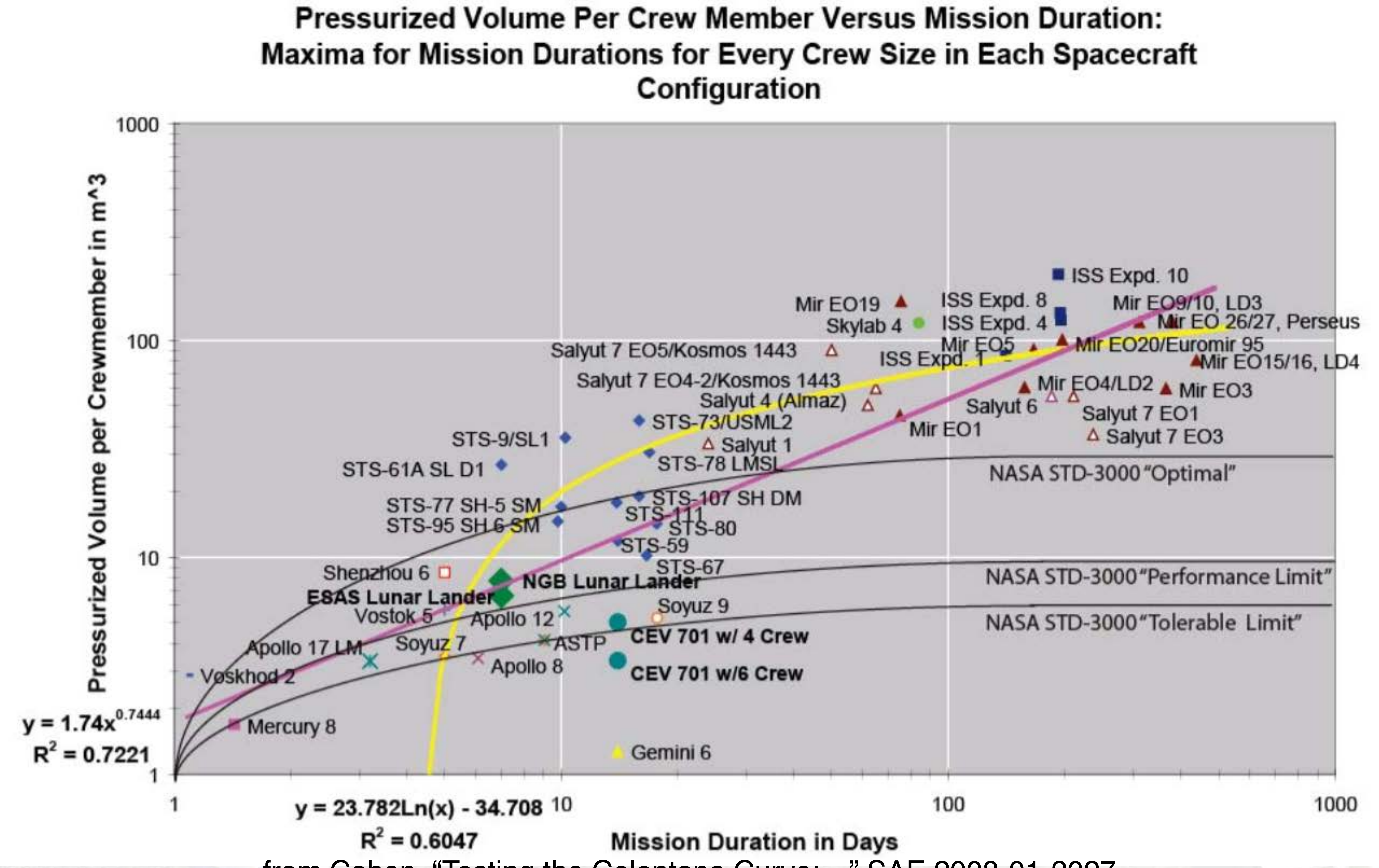
from Cohen, “Testing the Celentano Curve:…”SAE 2008-01-2027

Straight Power-Law Curve Fit (2008)



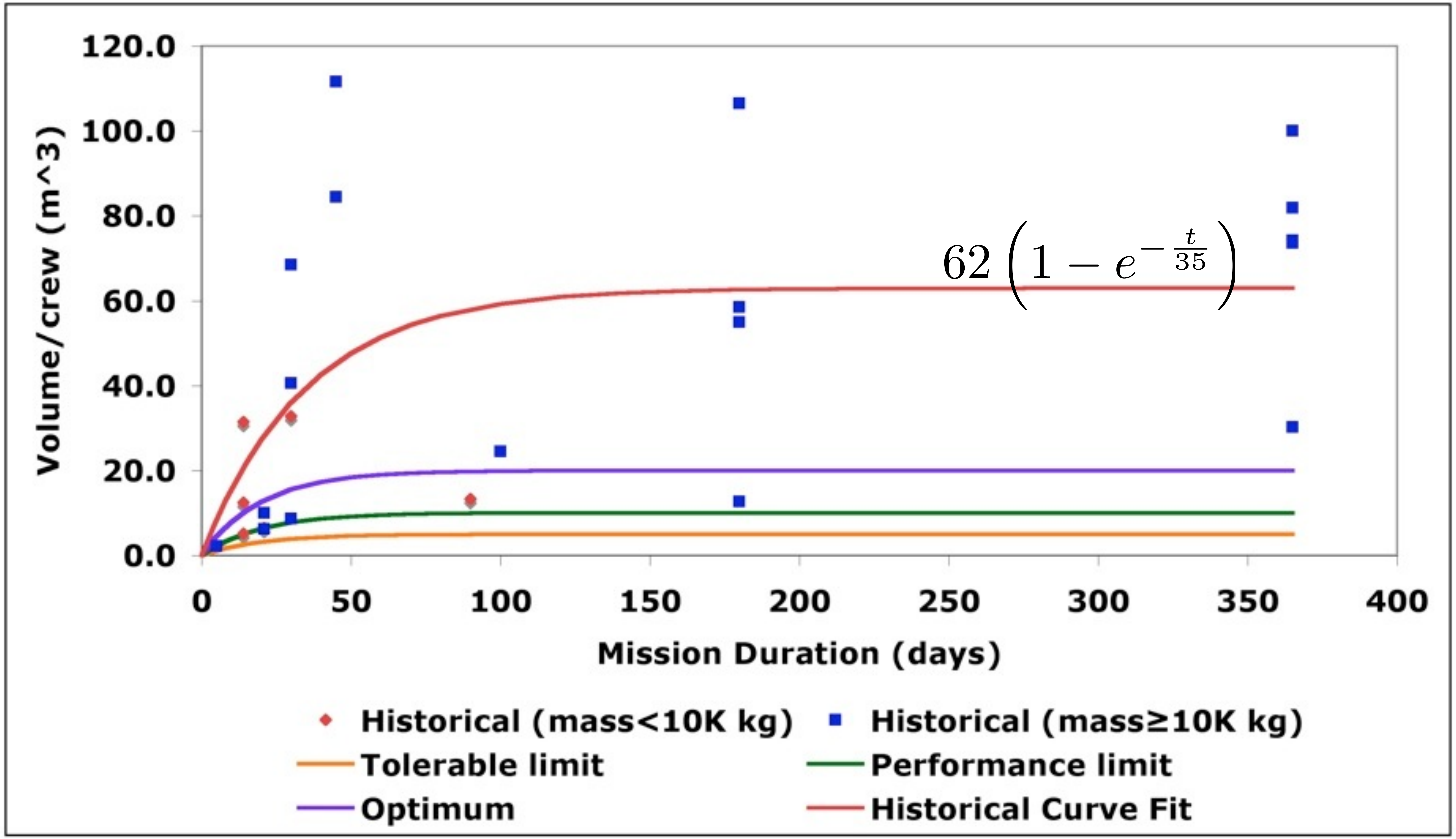
from Cohen, "Testing the Celentano Curve:…" SAE 2008-01-2027

Cohen's Fit to Data Maxima

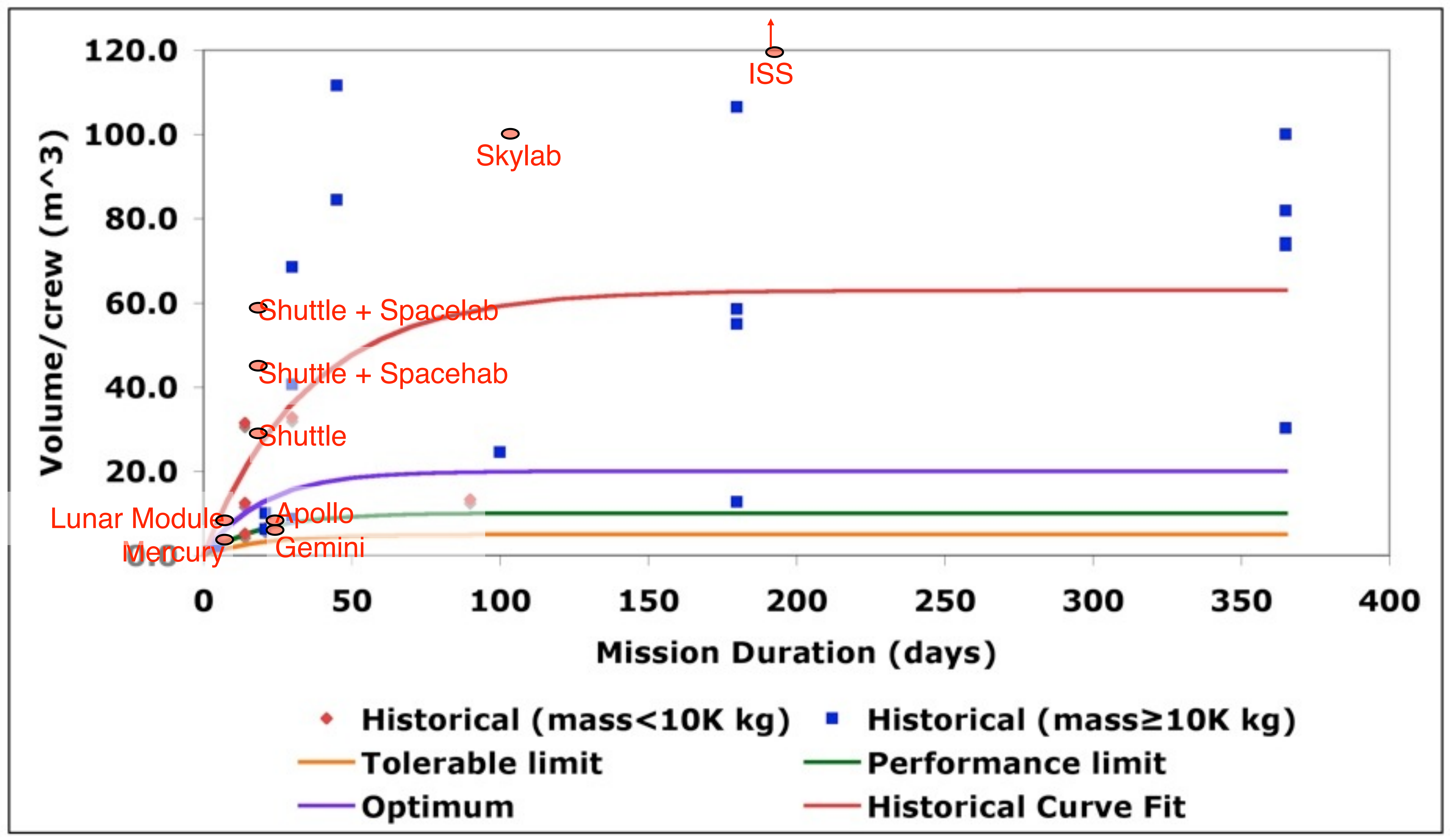


from Cohen, "Testing the Celentano Curve:..." SAE 2008-01-2027

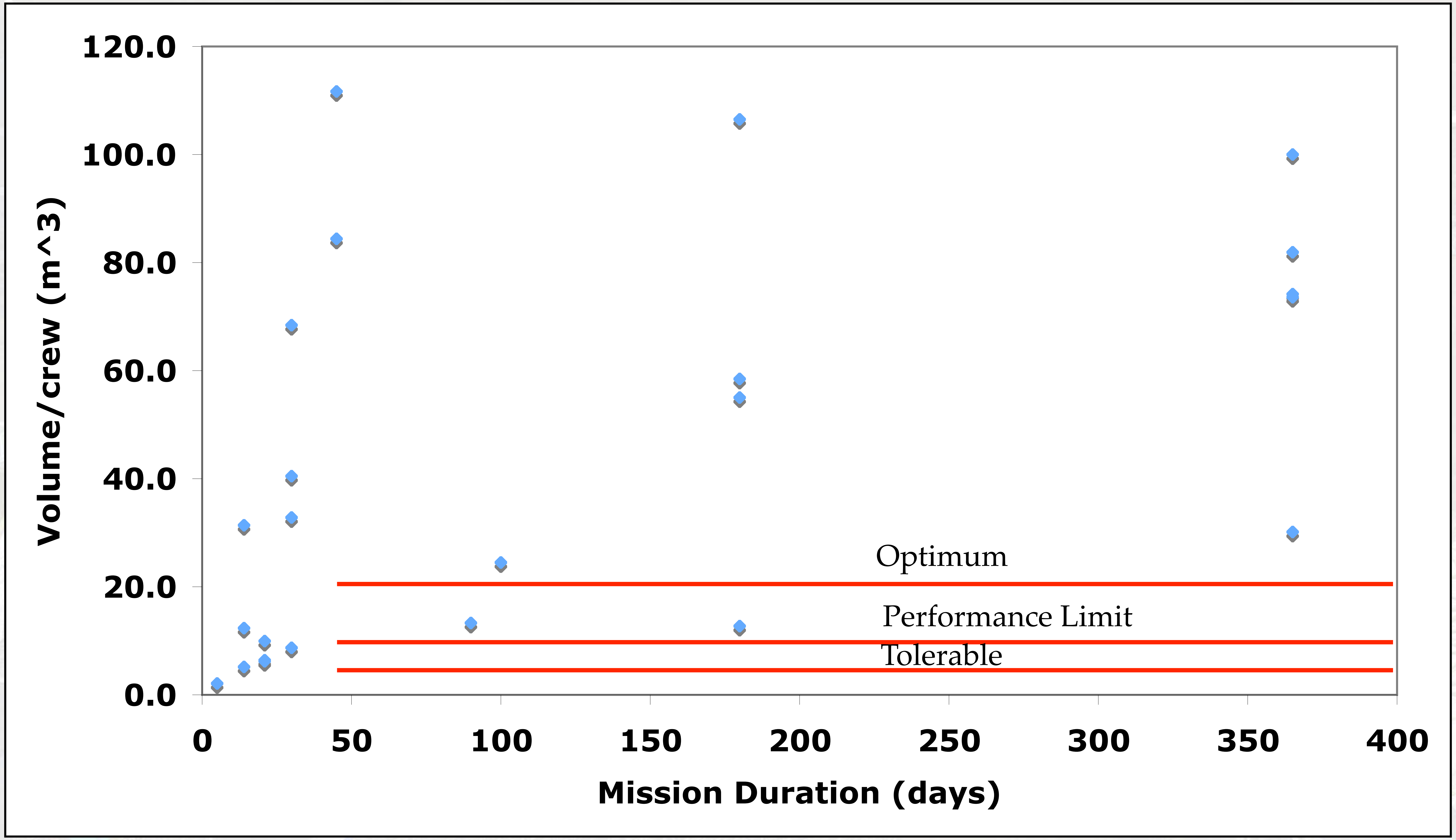
Historical Data Fitted to Celentano Curves



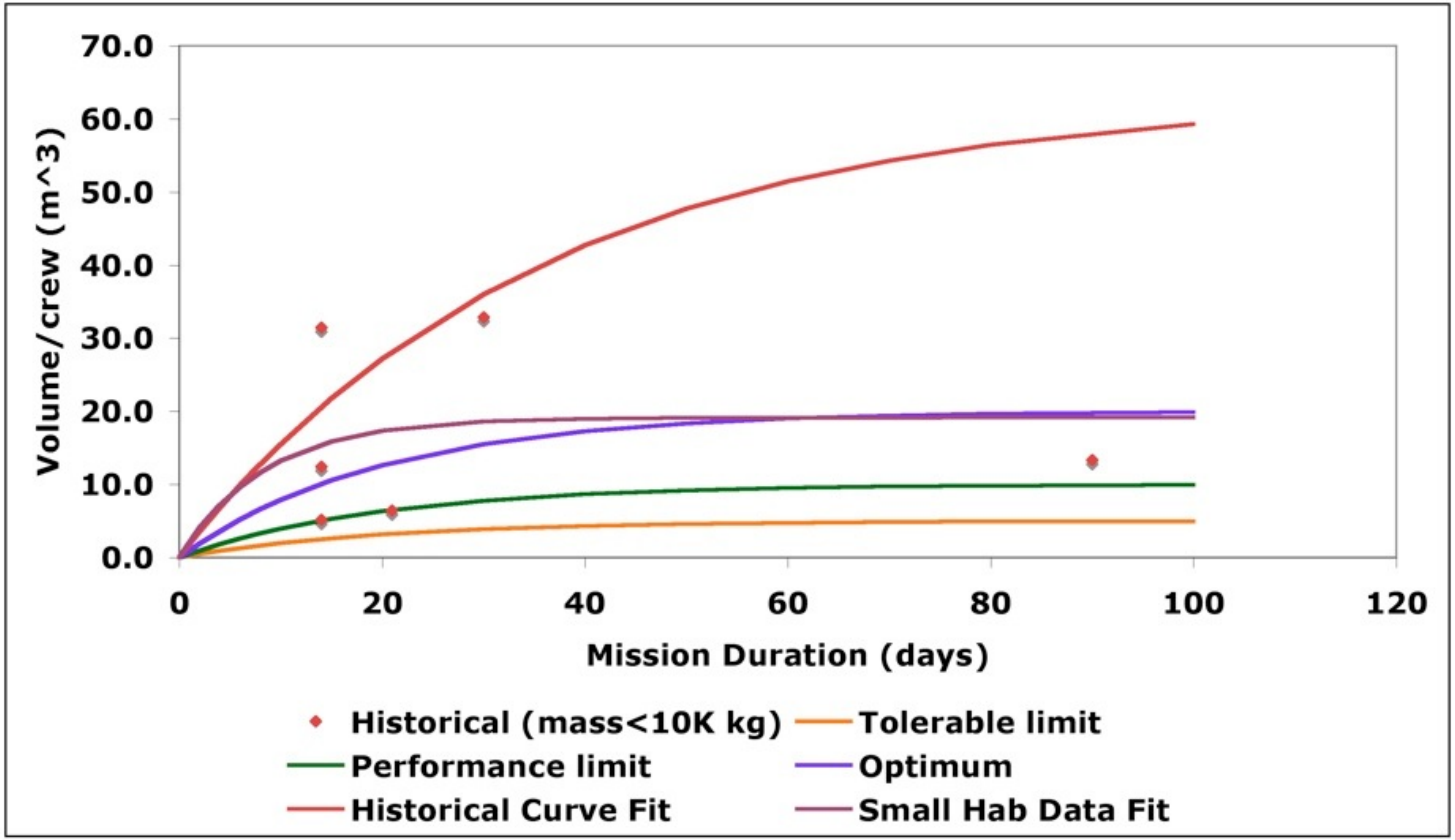
Historical Trends – Habitat Volume



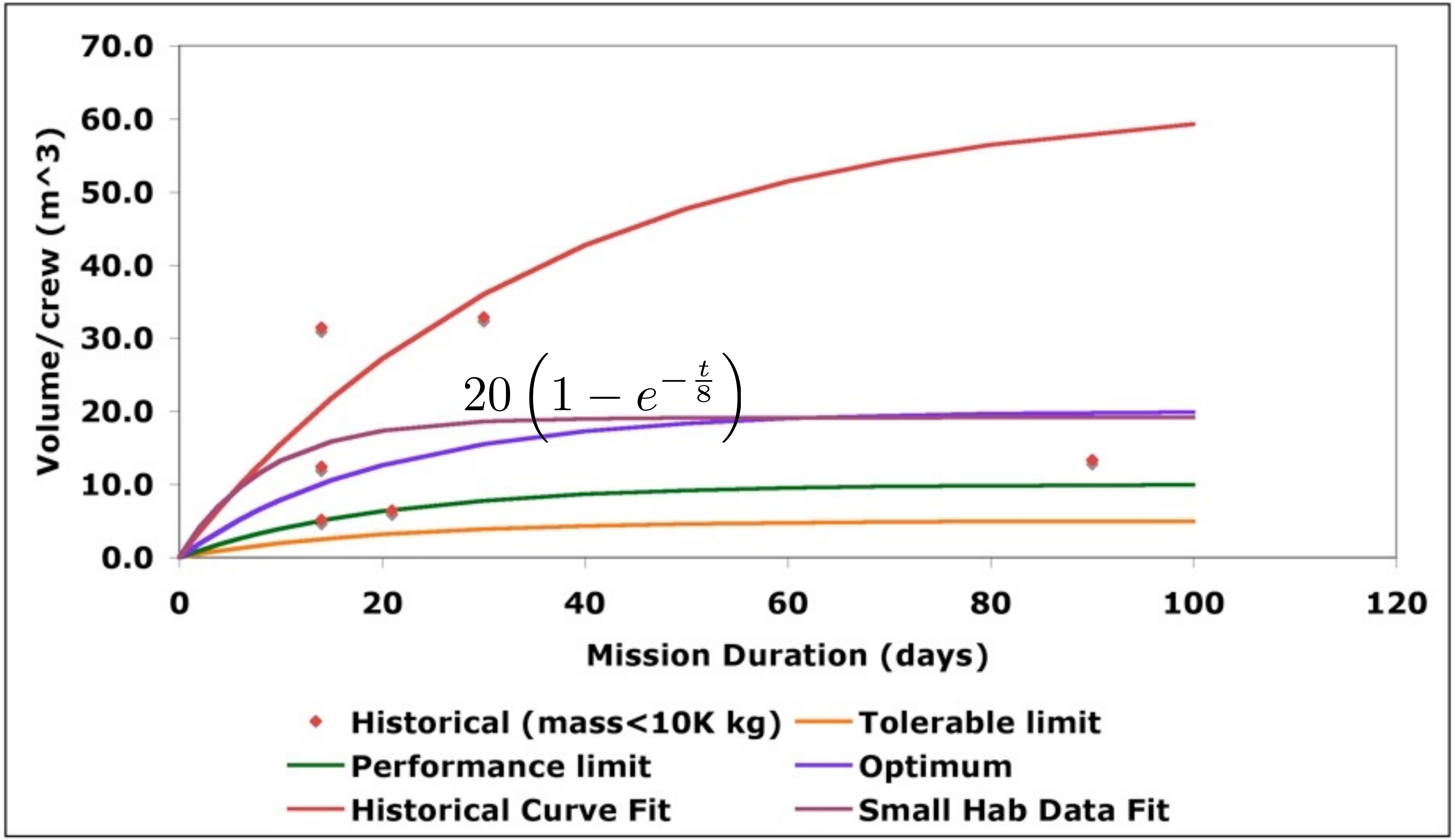
Data from 24 Lunar Mission Concepts



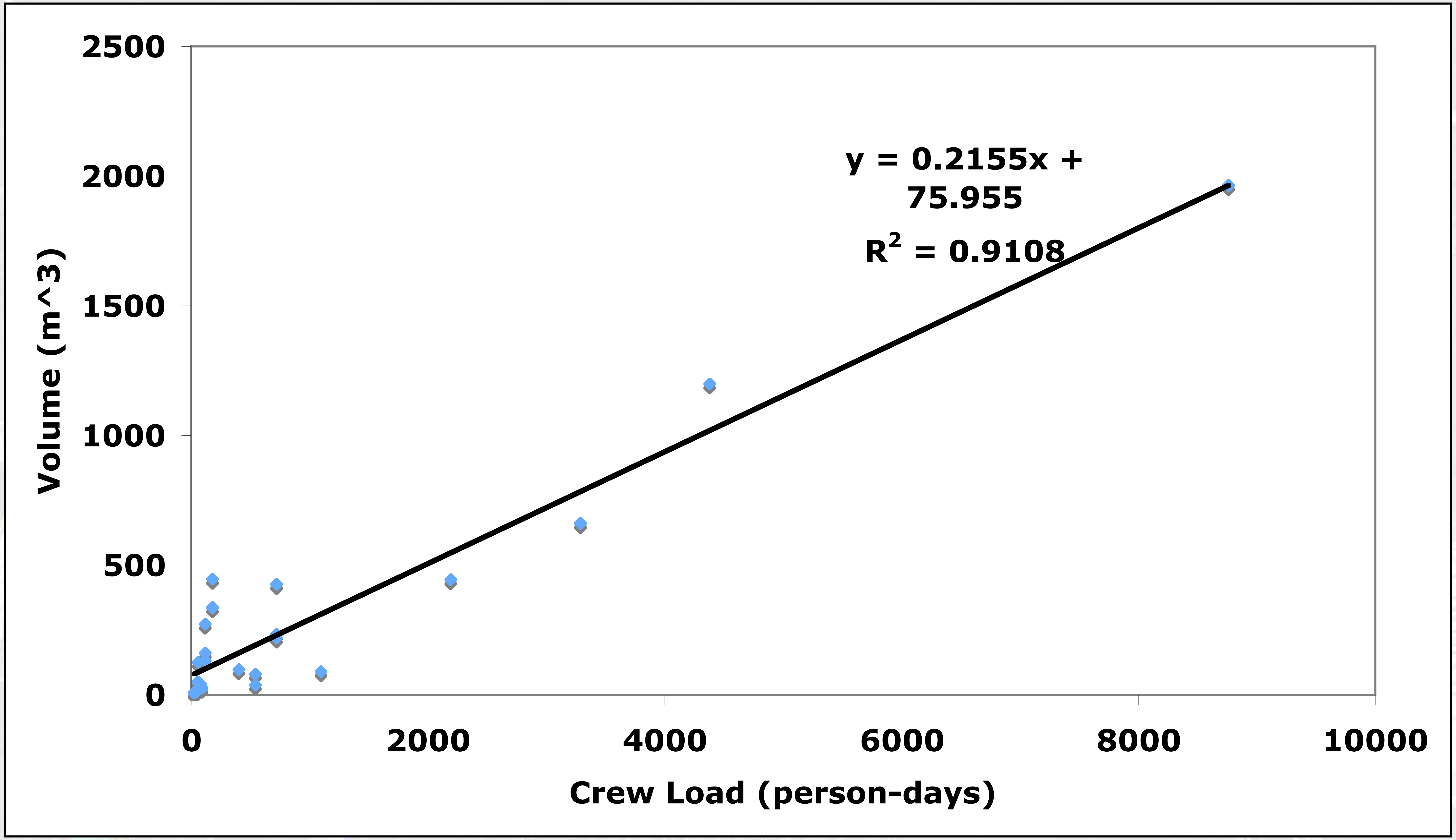
Focusing on Smaller Habitats



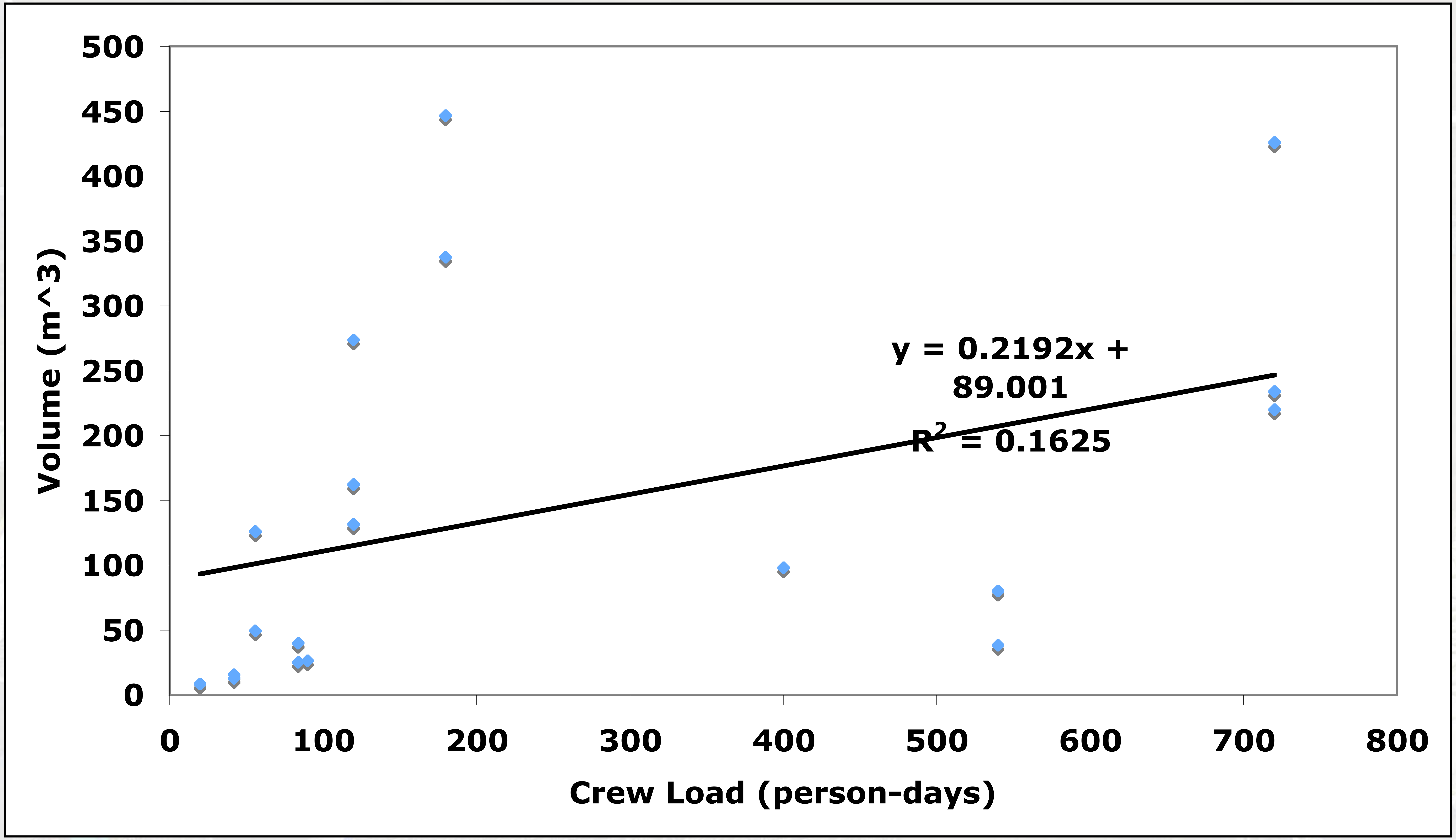
Curve Fit to Small Hab Data Only



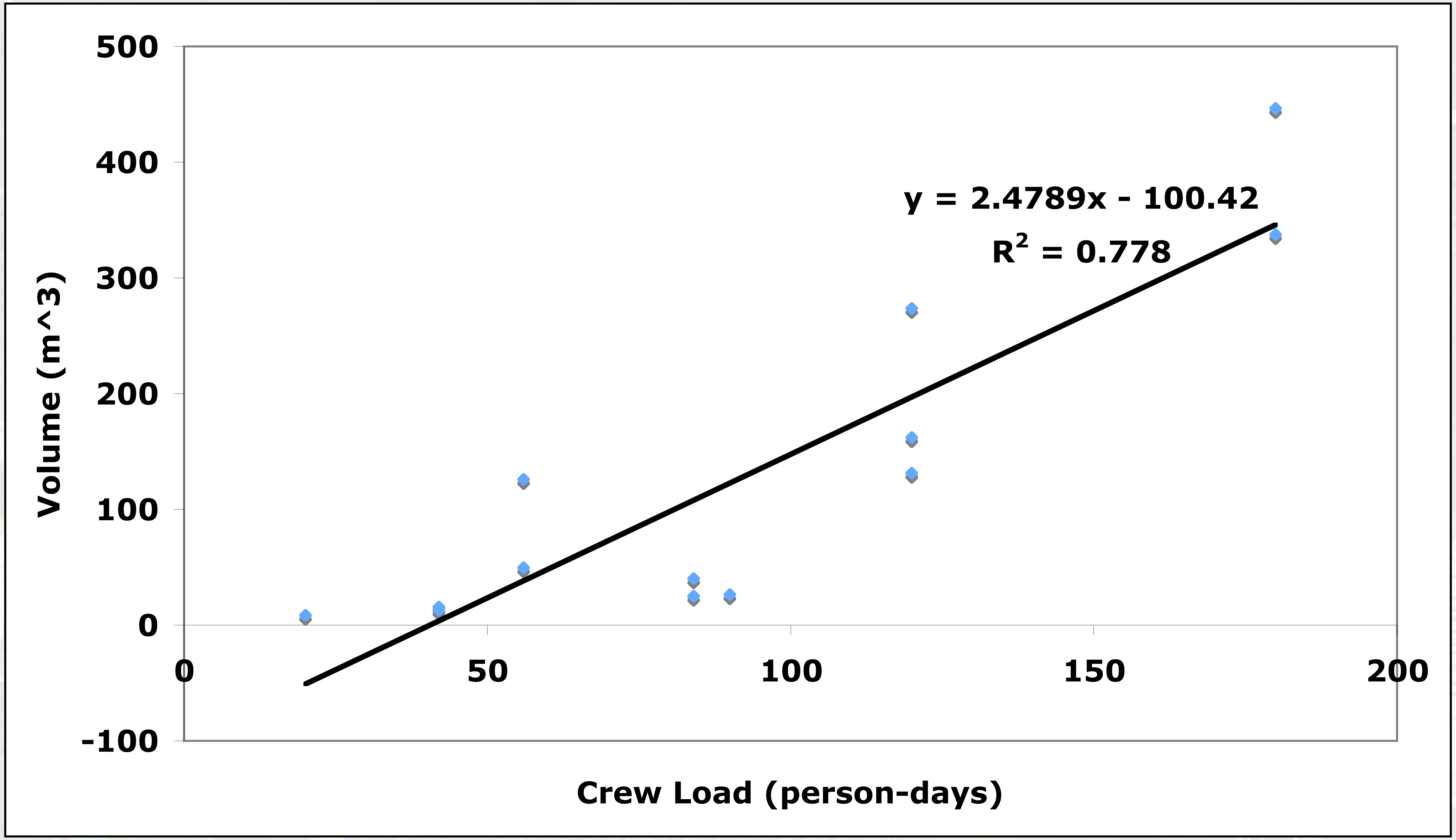
Required Habitat Volume vs. Crew Load



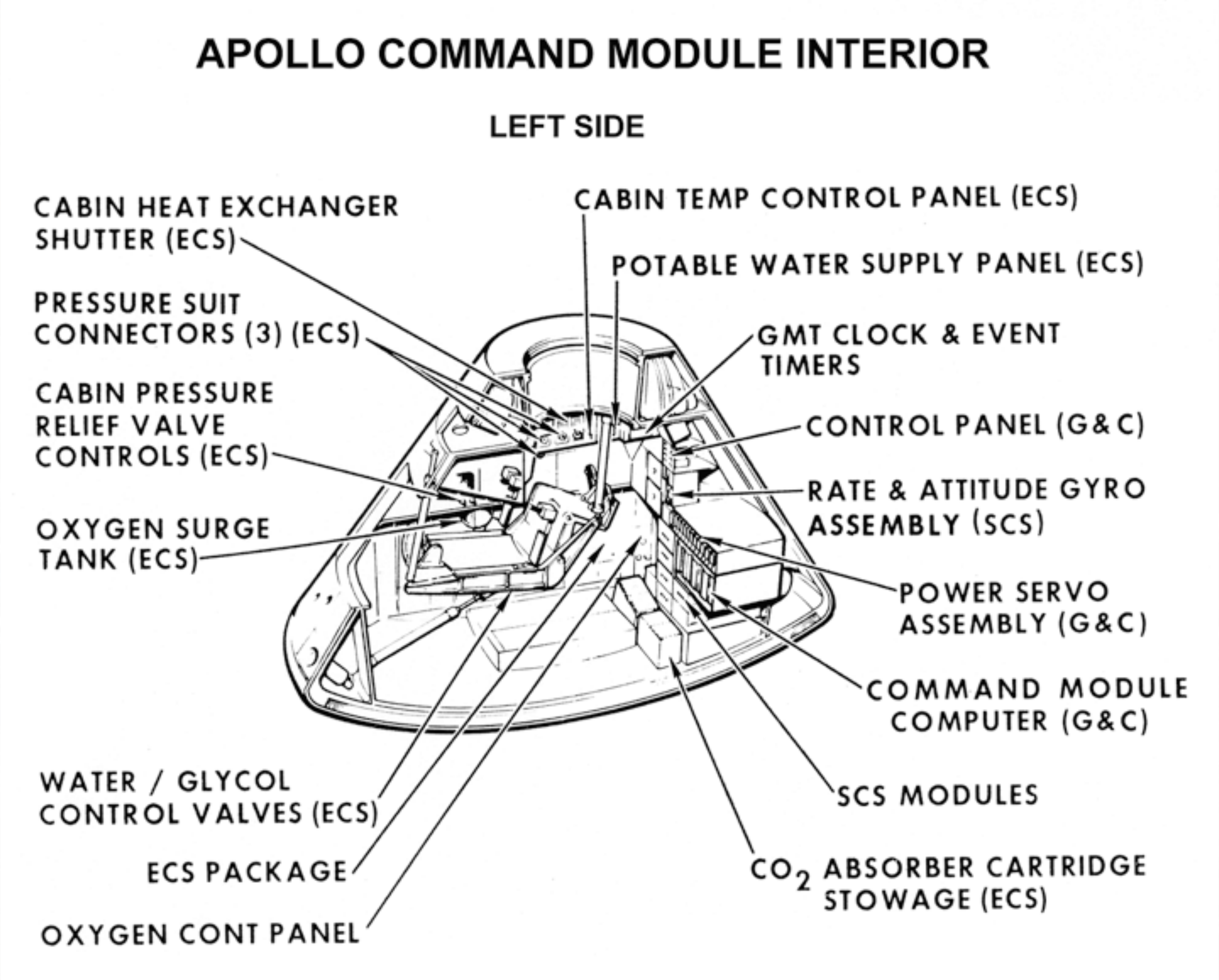
Restricting Data to Durations≤180 Days



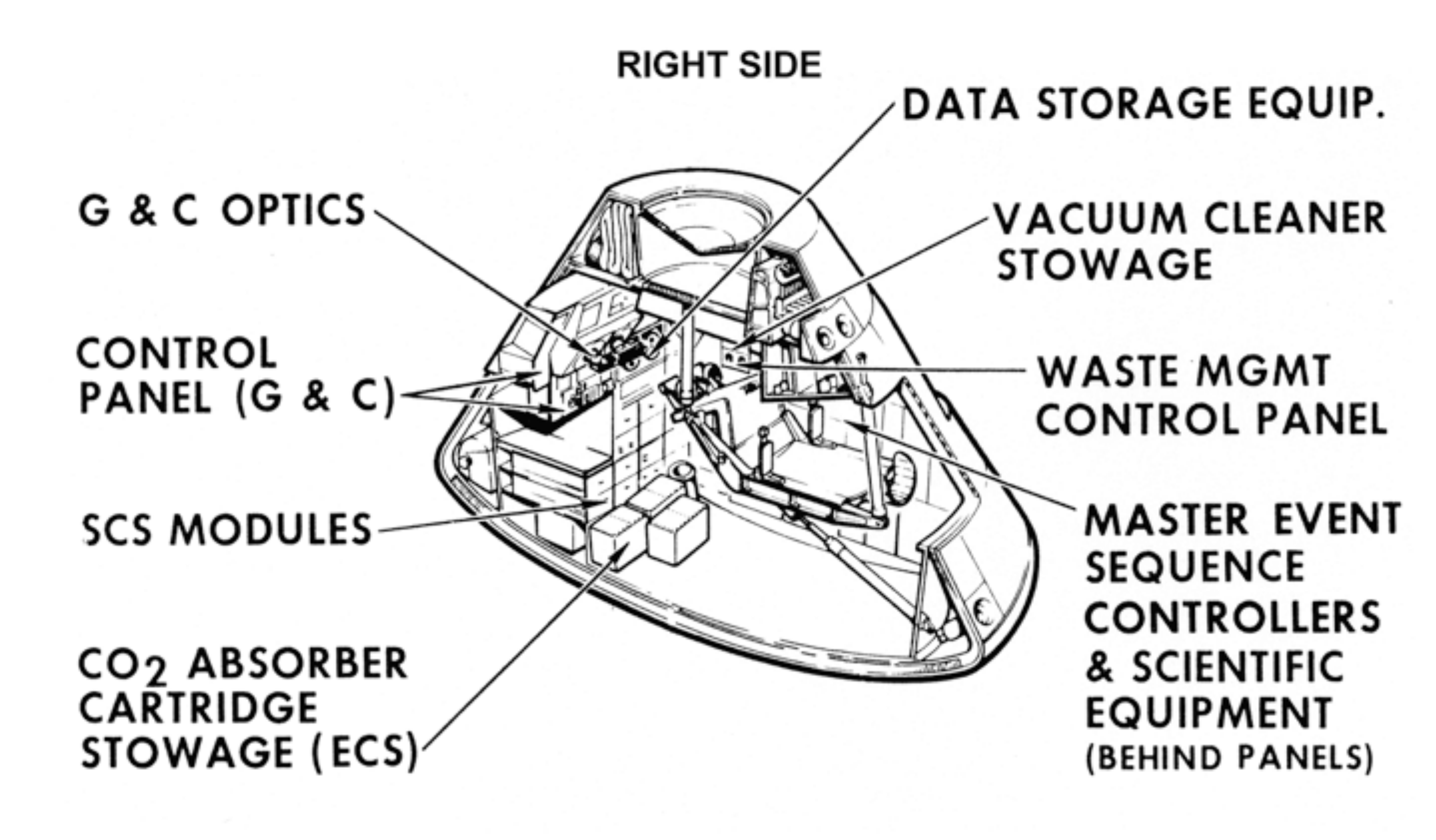
Restricting Data to Crew Loads ≤200



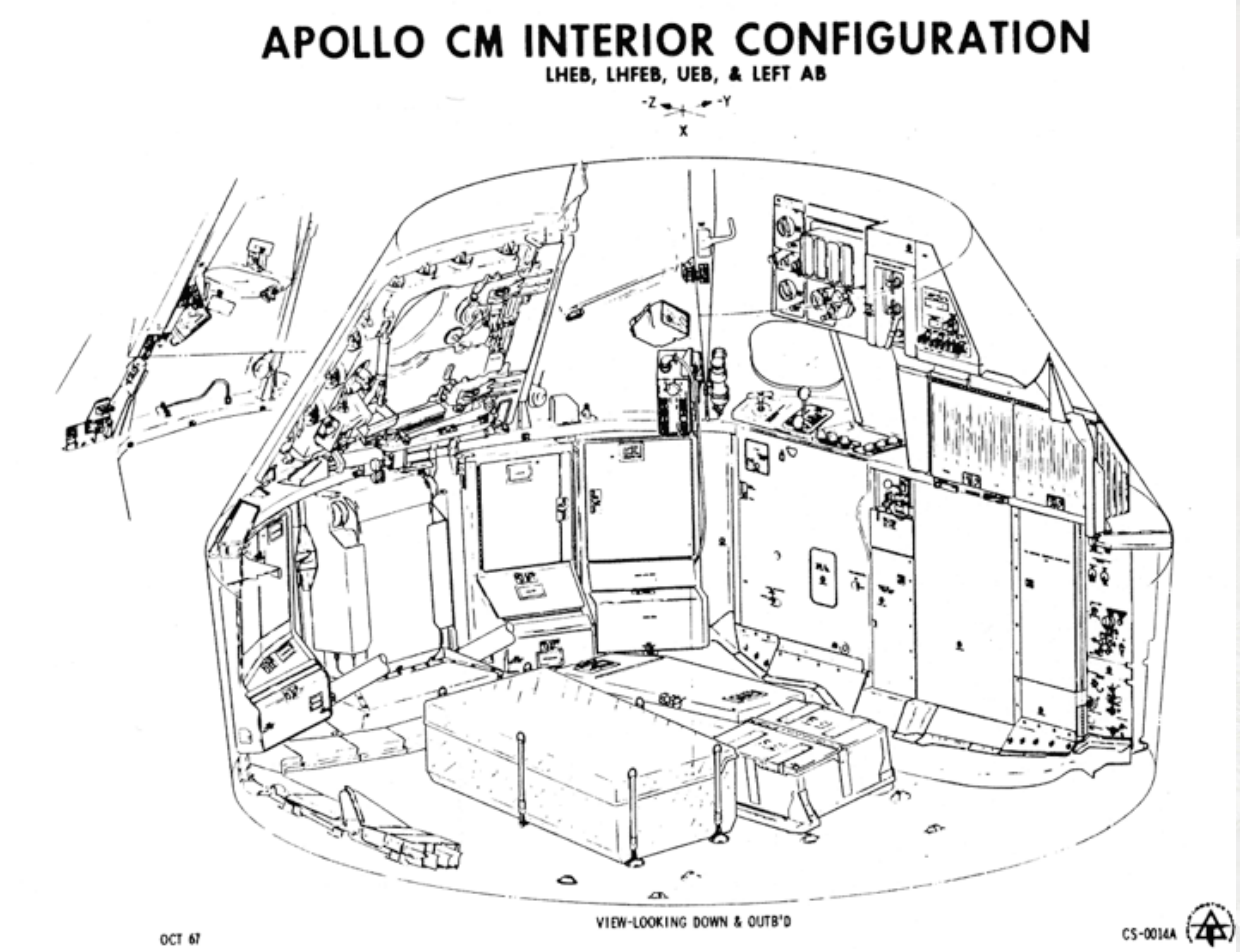
Apollo Command Module Interior



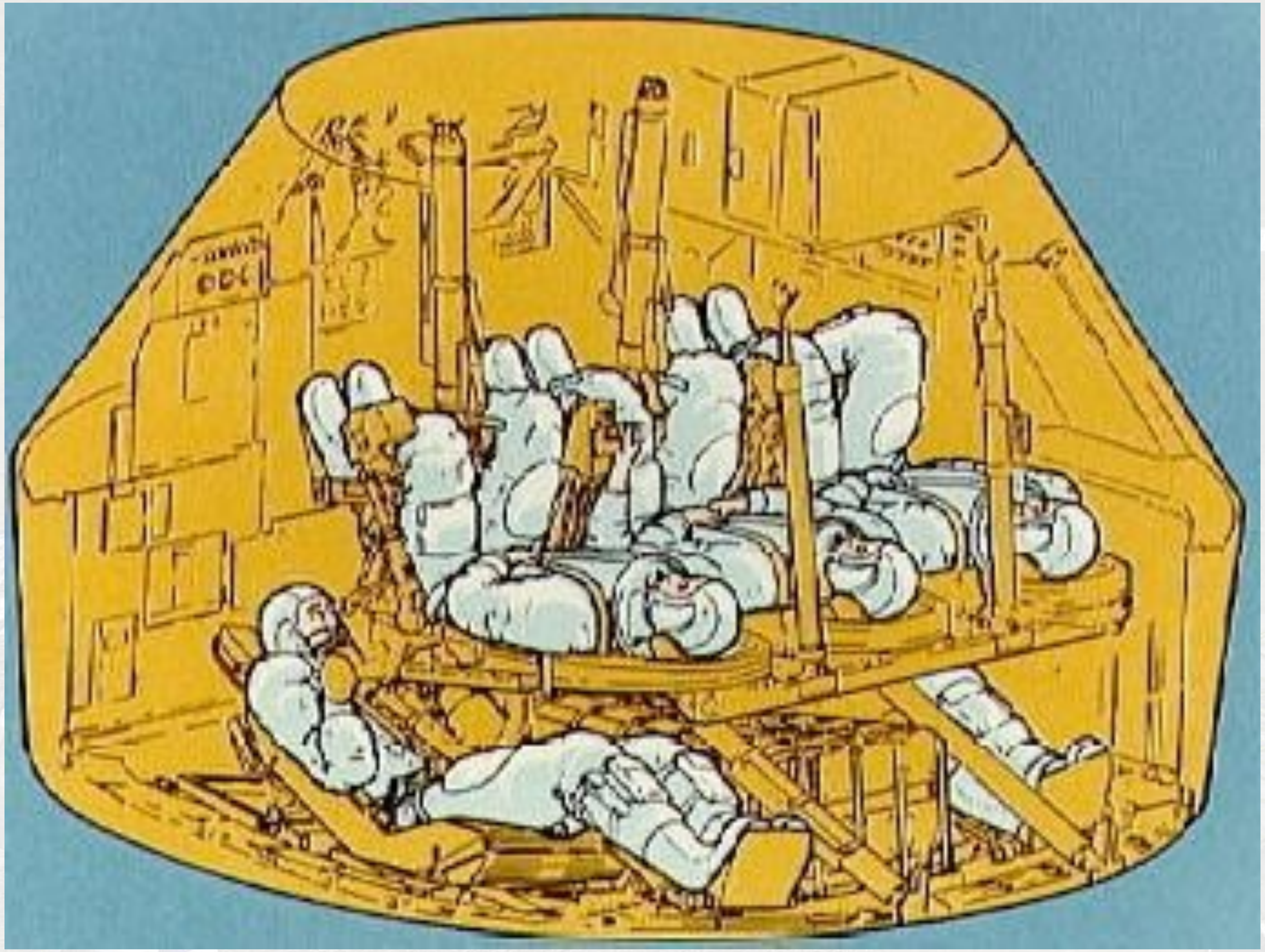
Apollo Command Module Interior



Apollo Command Module Interior



Apollo Spacecraft (Rescue Configuration)



Soyuz Interior

Space Shuttle Flight Deck

Space Shuttle Mid-Deck Panorama

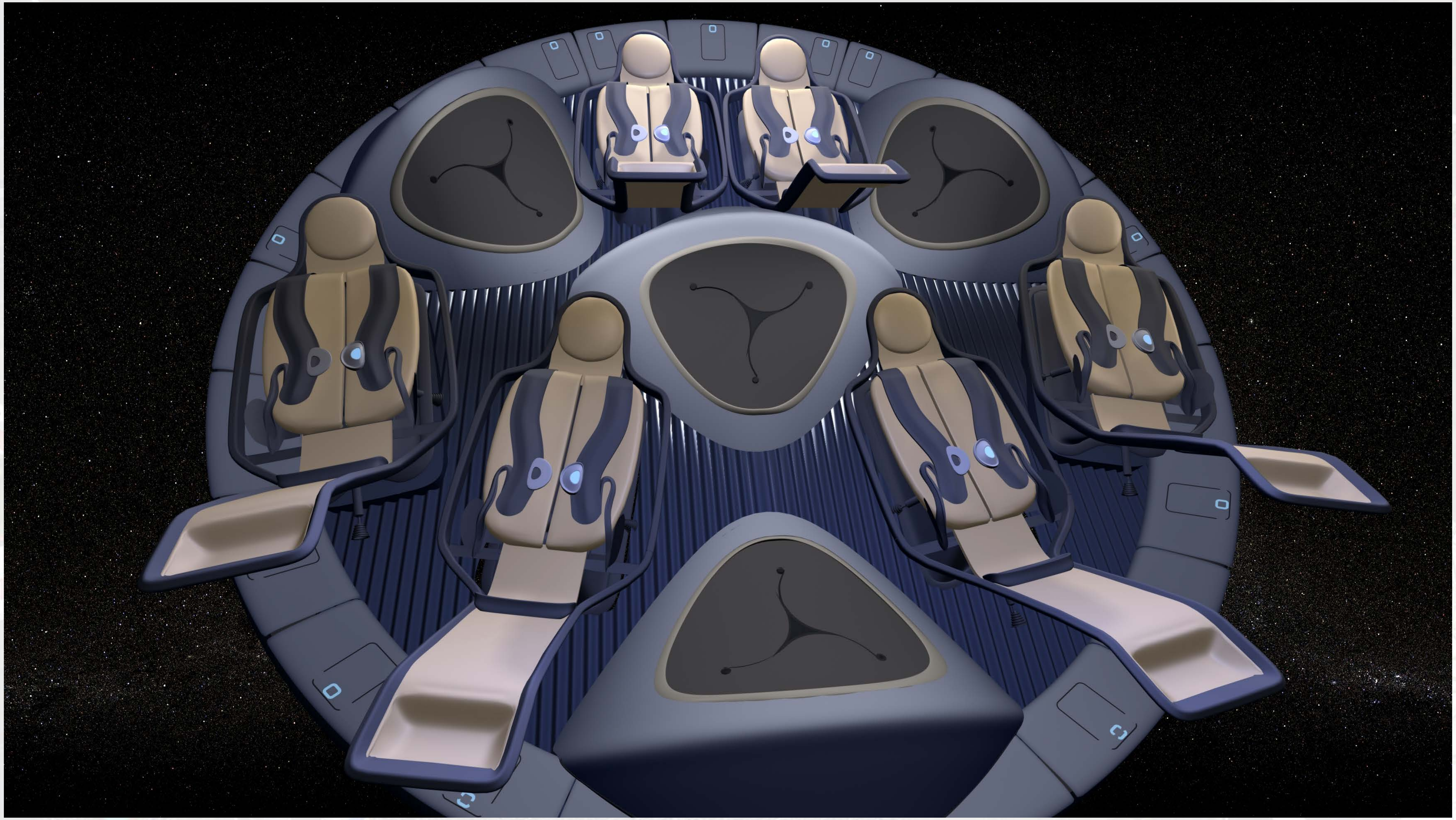
Space Shuttle Mid-Deck

Orion Seating Arrangement

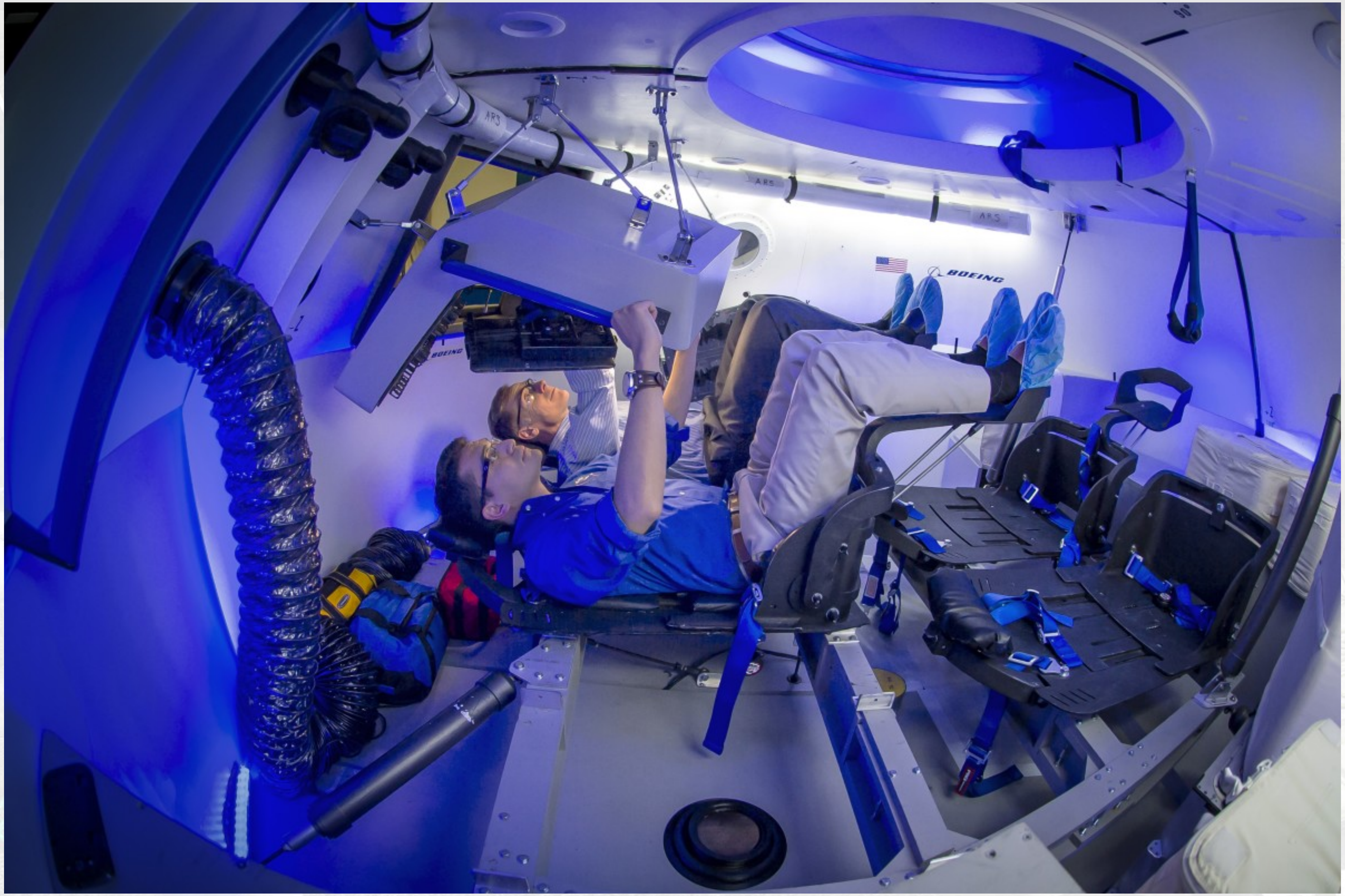
Orion (Mockup) Interior

Orion Developmental Seat System

Boeing CST 100 Notional Interior



Starliner (Mockup) Interior



Starliner Interior (Training)

Crew Dragon Interior (Prototype)

Crew Dragon Interior (Crew-2)

Dragon Hull and External Items

Limitations to Internal Outfitting

- *Never* put anything inside a pressurized crew volume that could hurt the crew or threaten the mission
  - Toxic substances (e.g., propellants, ammonia coolant)
  - Cryogenic fluids (e.g., LOX)
  - Pressurized gases that would asphyxiate the crew or overpressure the crew compartment (e.g., GN2)
  - Fire or explosion risks (e.g., batteries)
- Experience indicates that it is easier to build and test items external to the pressure hull anyway

CRS-7 Falcon 9 In-Flight Failure

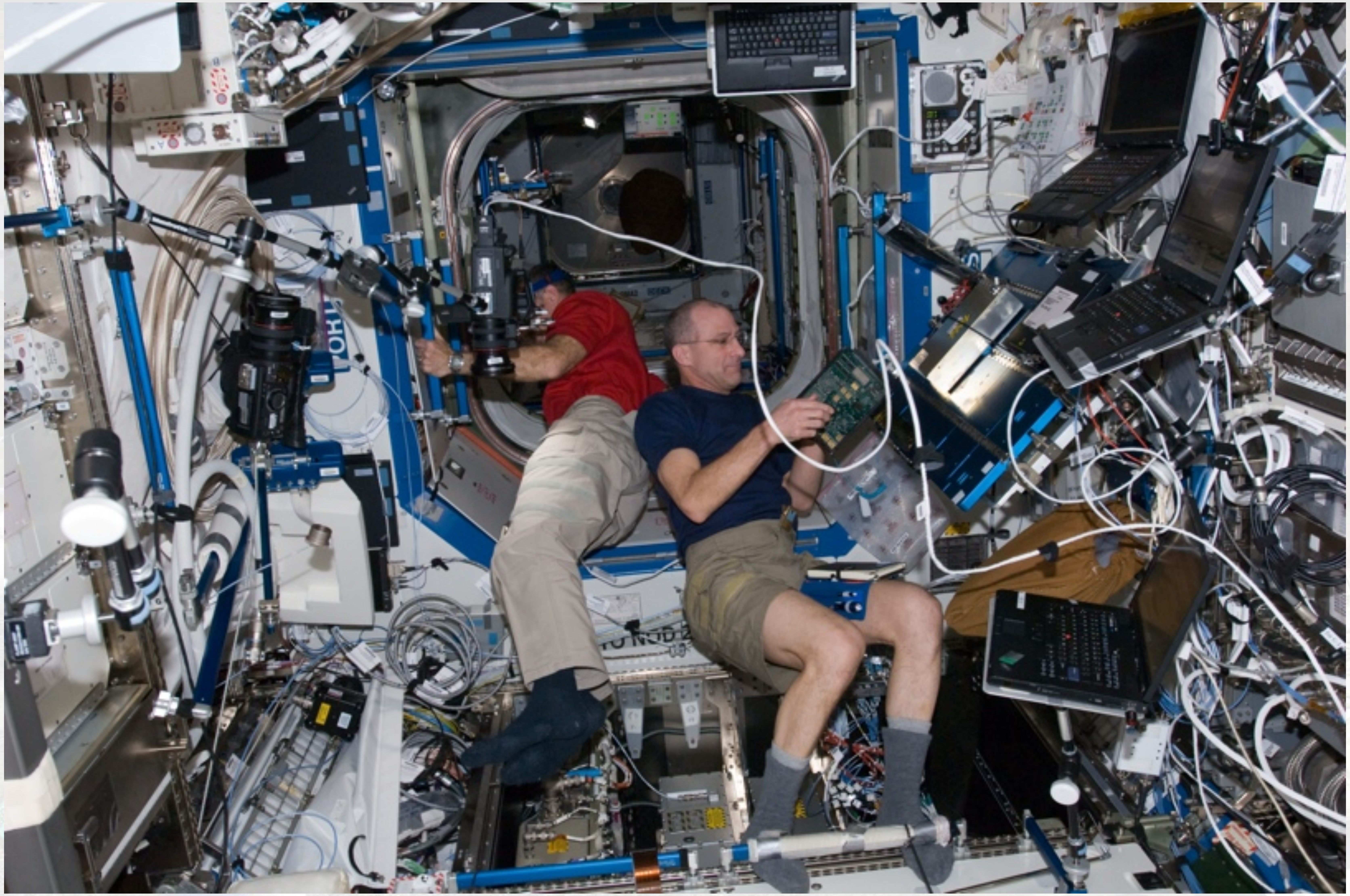
Orion Control Panel Concept

Starliner Control Panel

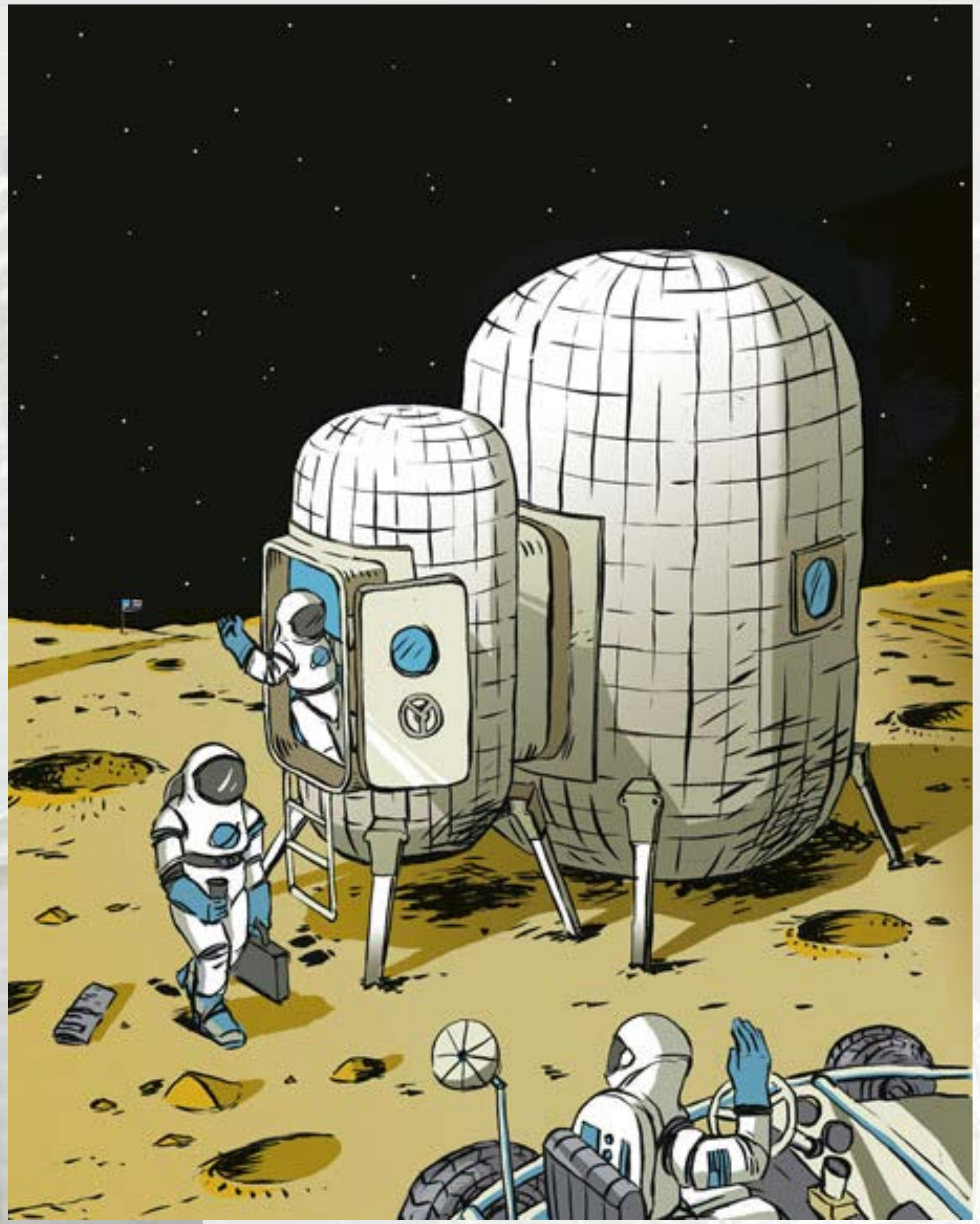
Crew Dragon Control Panel

Space Shuttle Flight Deck Interfaces

International Space Station



Inflatable Lunar Habitat Concept (Vertical Layout)



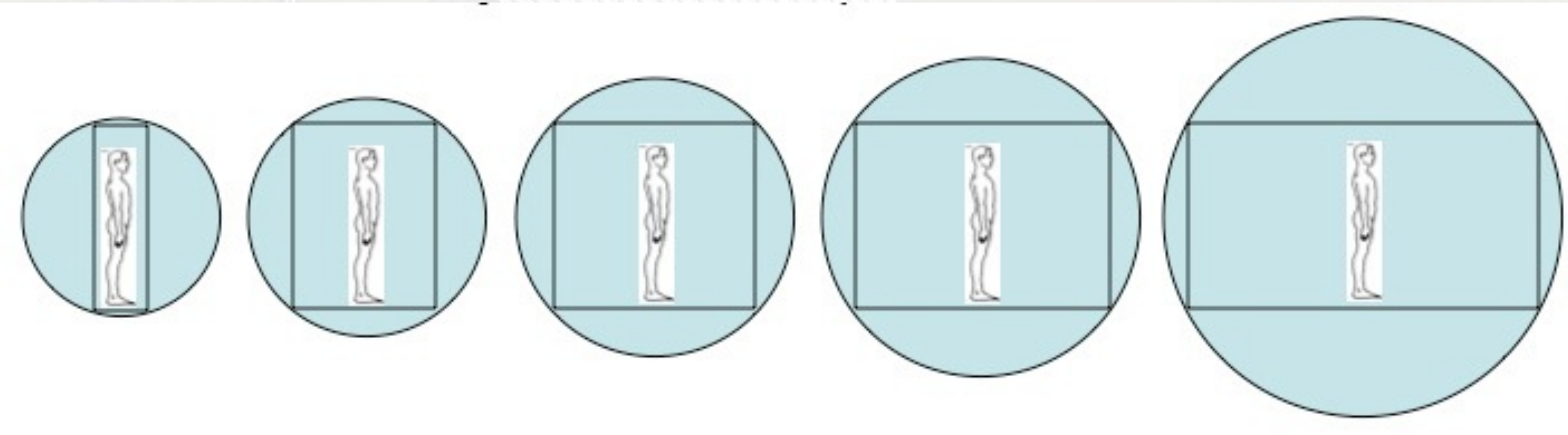
Horizontal Habitat Interior

Pressure Vessel Shape and Orientation

- Pressure hull - assumed to be cylindrical with ellipsoidal end caps
  - Toroidal configurations modeled as low L/D cylindrical
- Orientation of internal outfitting could be “horizontal” (floors parallel to long axis) or “vertical” (floors perpendicular to long axis)
- Assumption of consistent internal orientation
  - Enforced by physics for partial gravity systems
  - Standard practice for microgravity systems due to strong crew

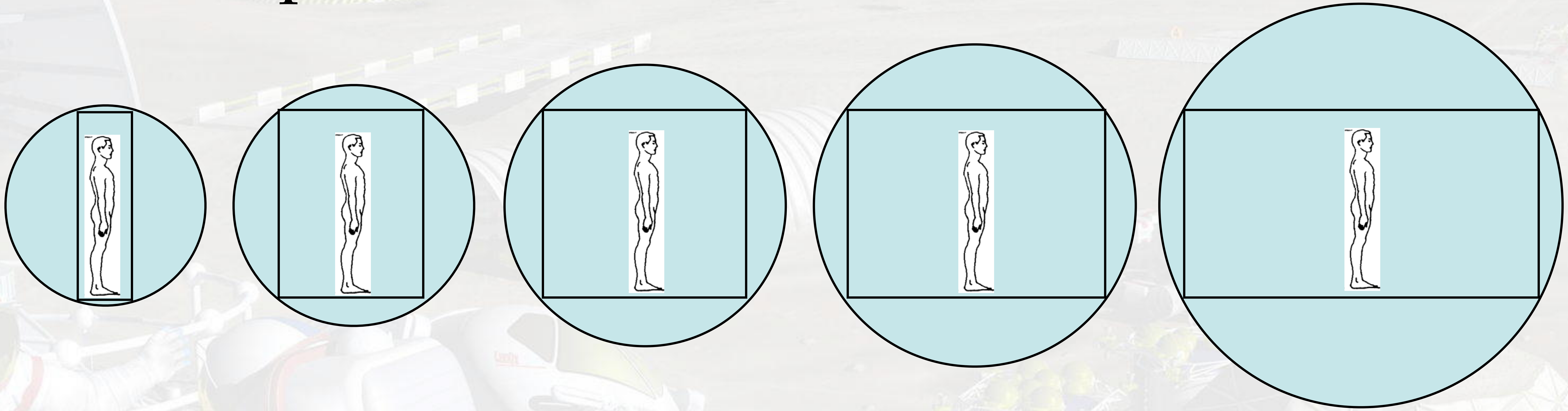
Challenge to Maximize Habitable Volume

- Assume "habitable volume" involves standing headroom
- Human volume is rectangular; pressure vessels are curved



Habitat Layout - Vertical or Horizontal?

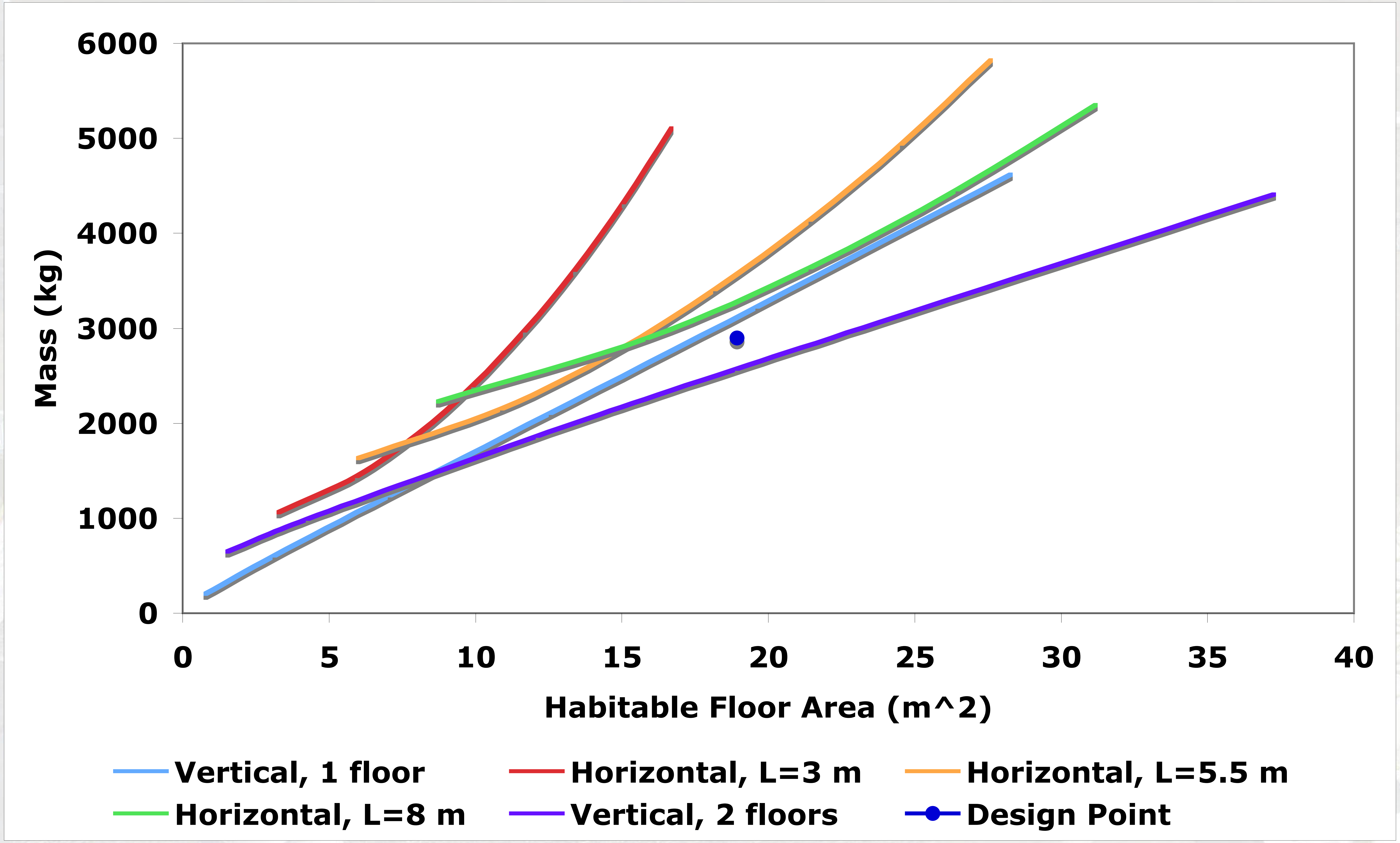
- Geometric modeling of “packing factor” to fit humans into cylindrical shapes



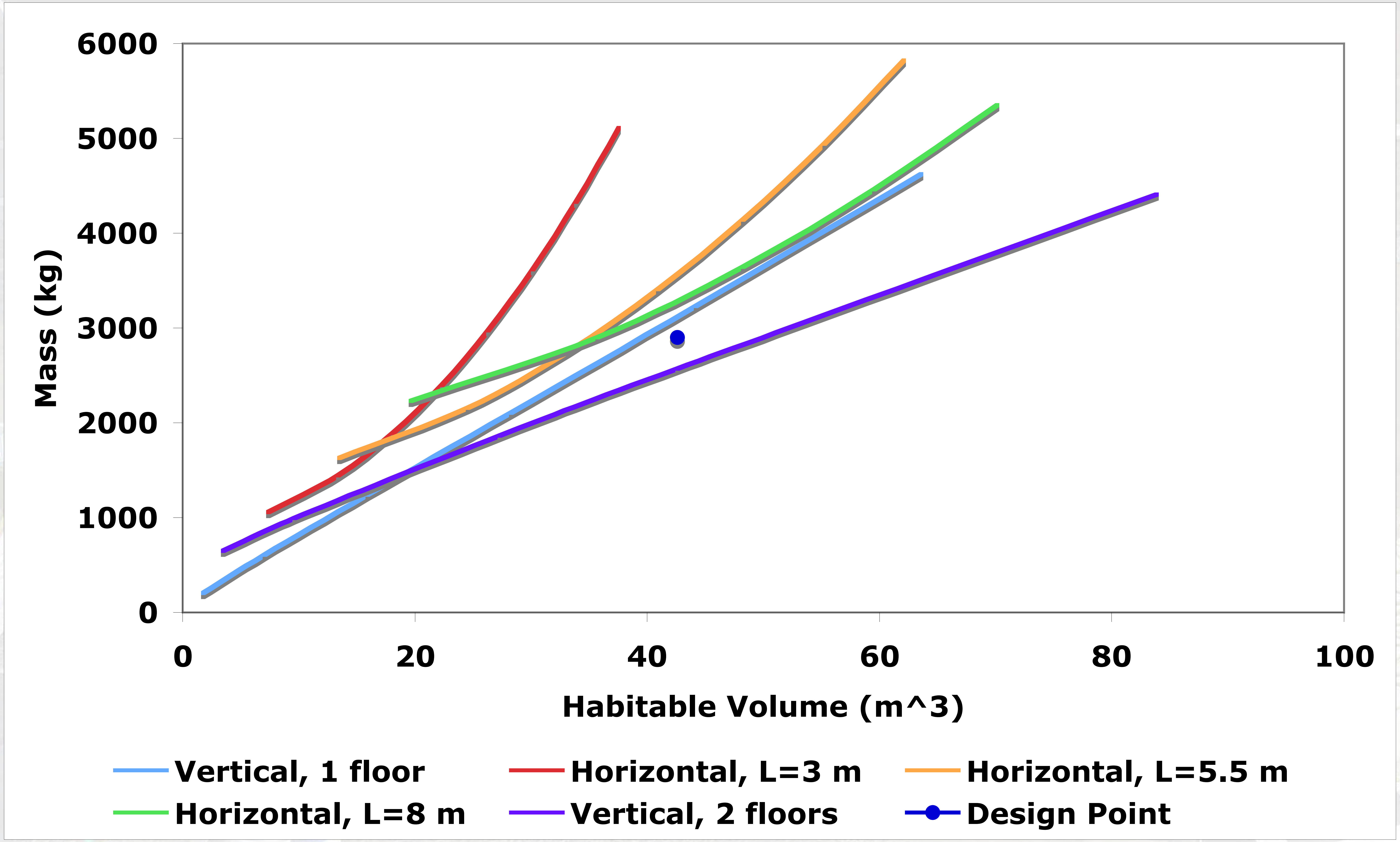
- Mass estimation for human-rated pressurized volumes from JSC-26096 (converted to metric)

$$M < kg >= 13.94 \left(A_{surface} < m^2 > \right)^{1.15}$$

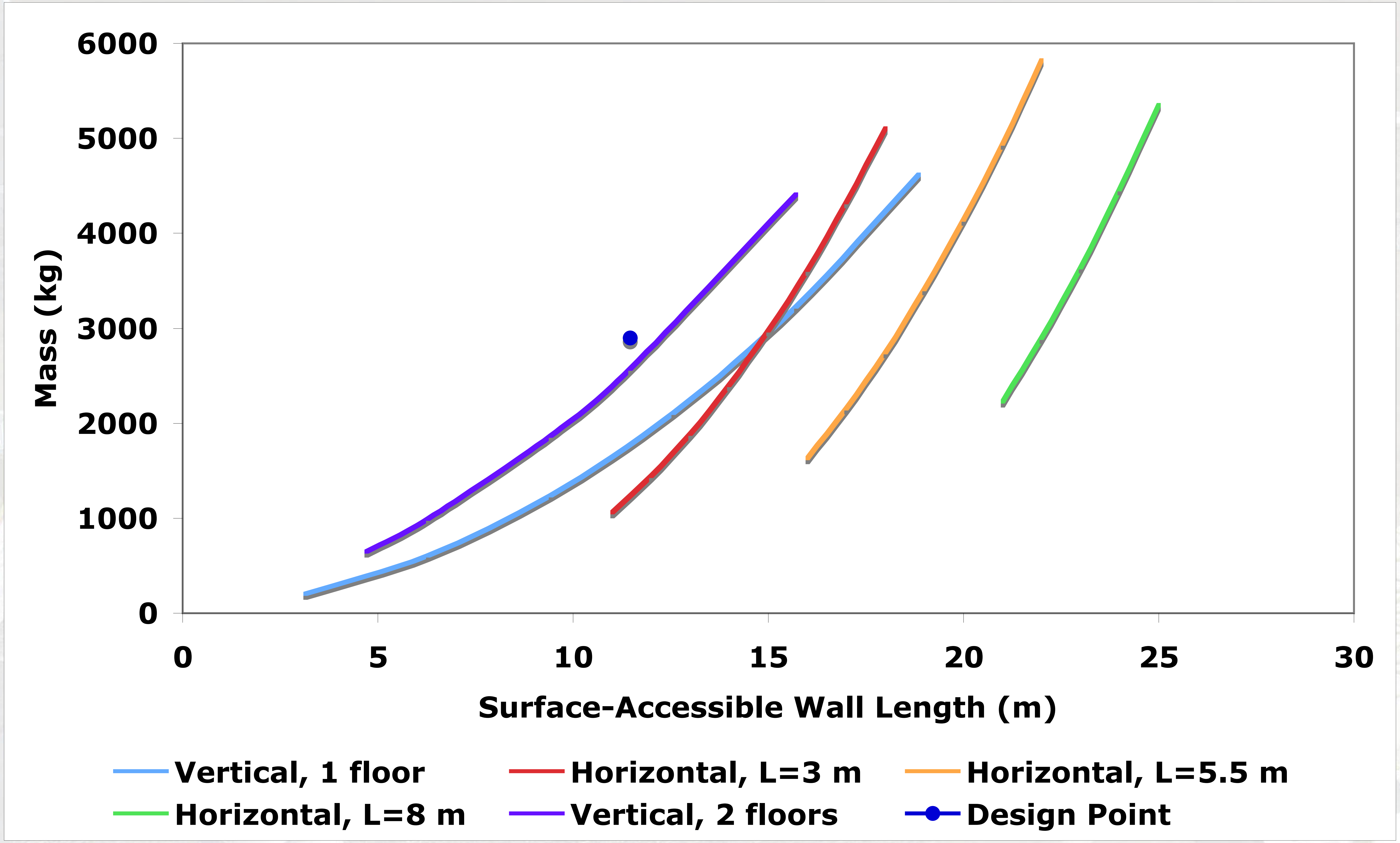
Habitat Layout Trades - Floor Area



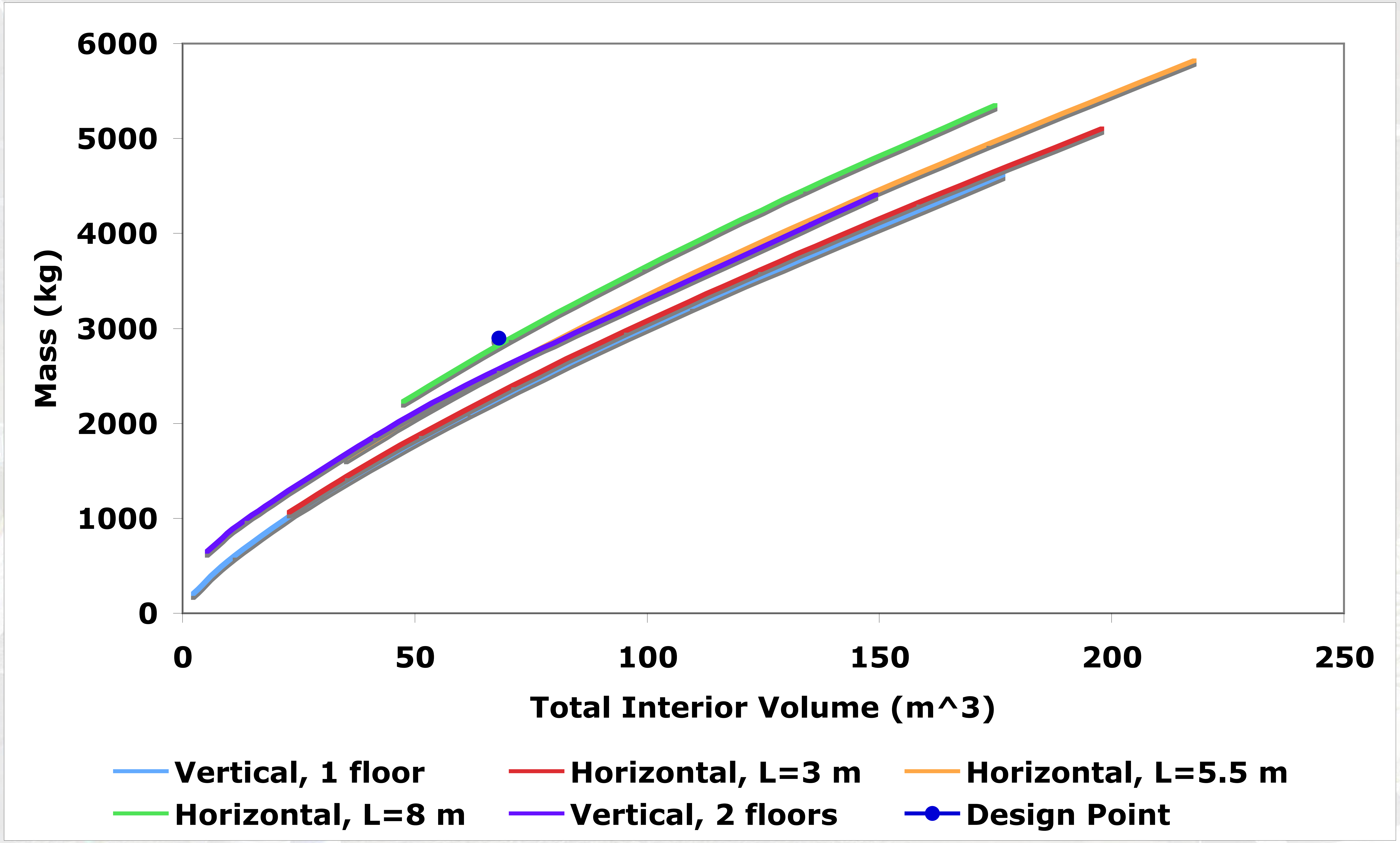
Habitat Layout Trades - Useful Volume



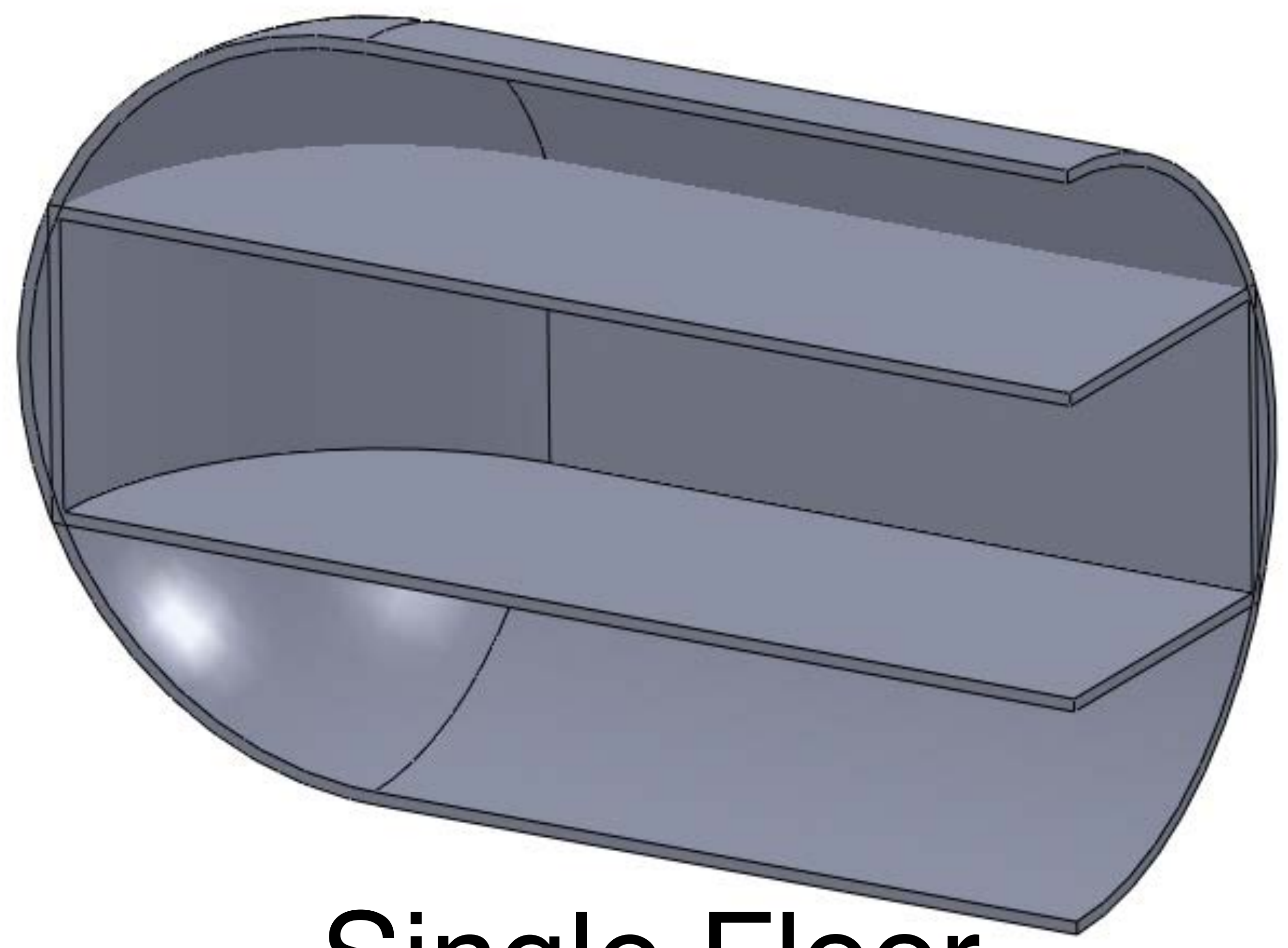
Habitat Layout Trades - Accessible Wall



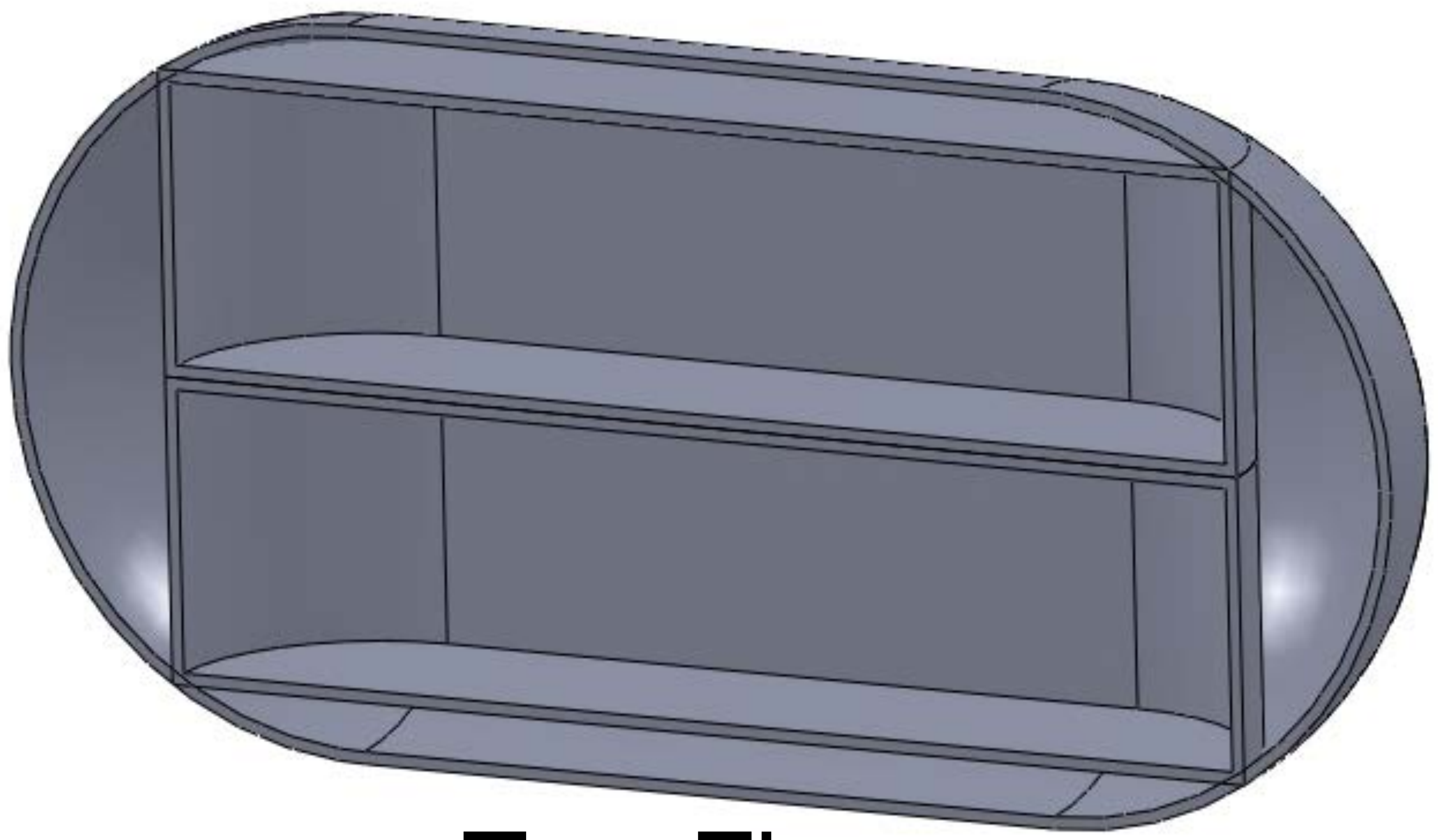
Habitat Layout Trades - Total Volume



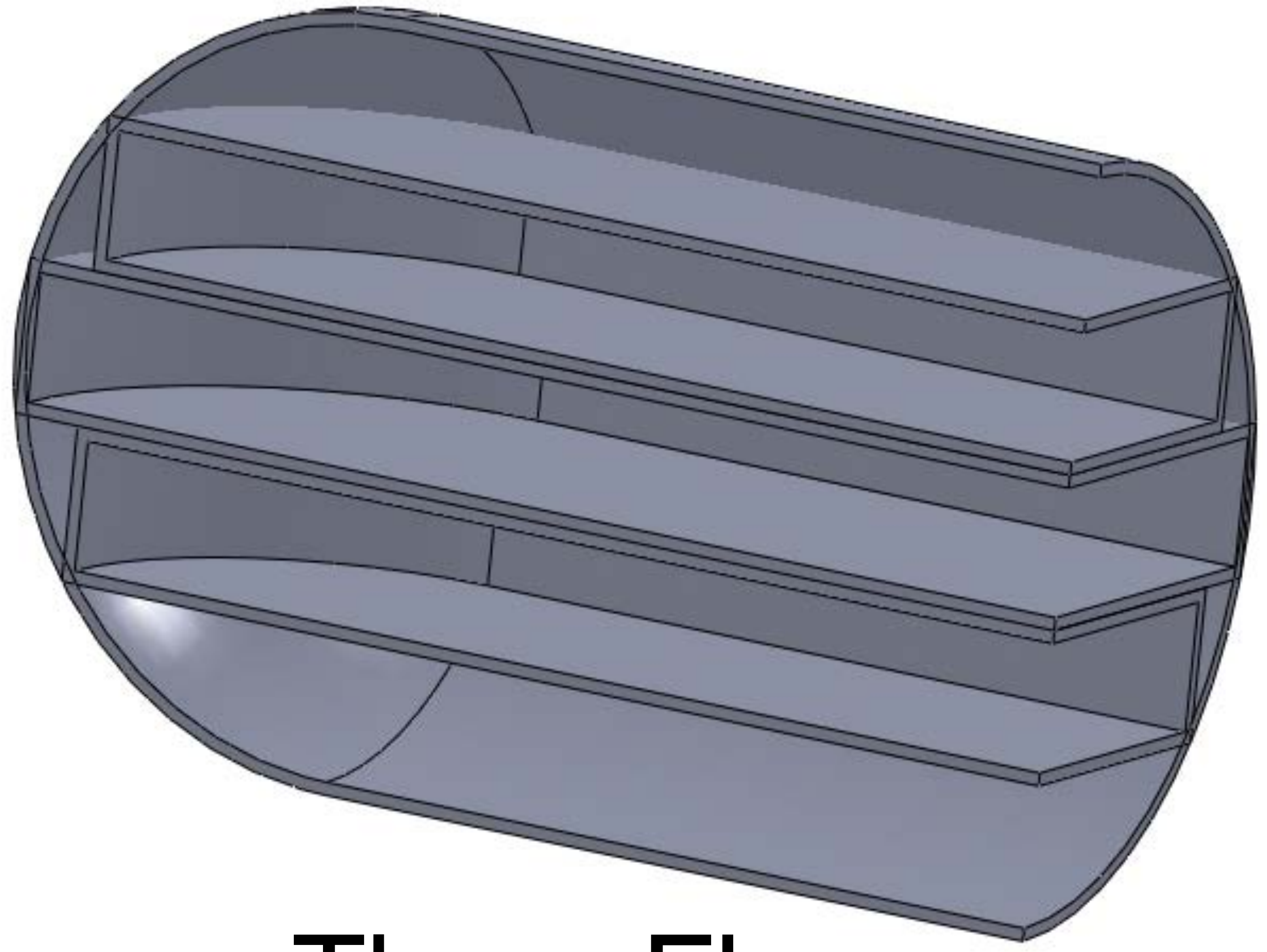
Internal Layout for Horizontal Habitats



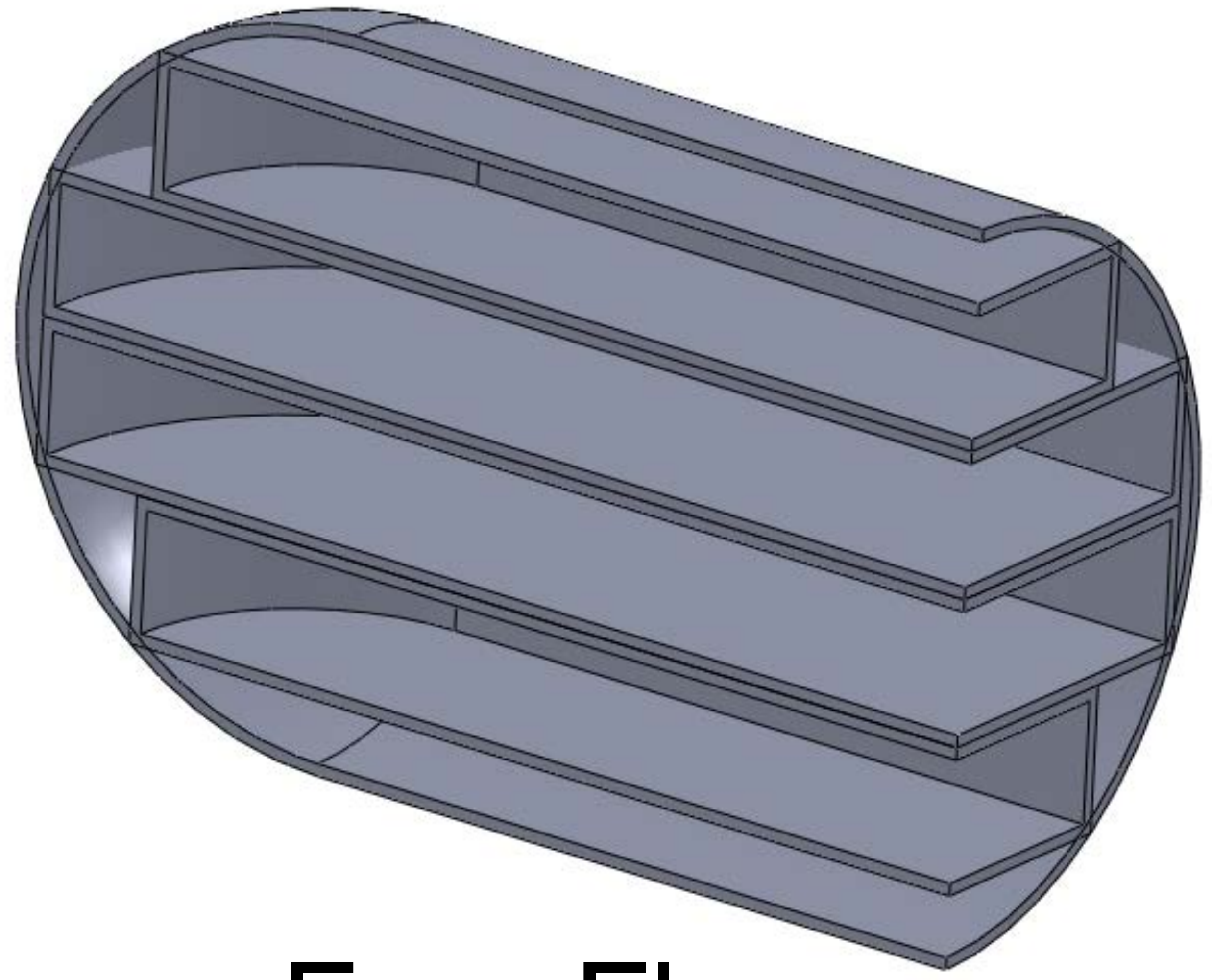
Single Floor



Two Floors

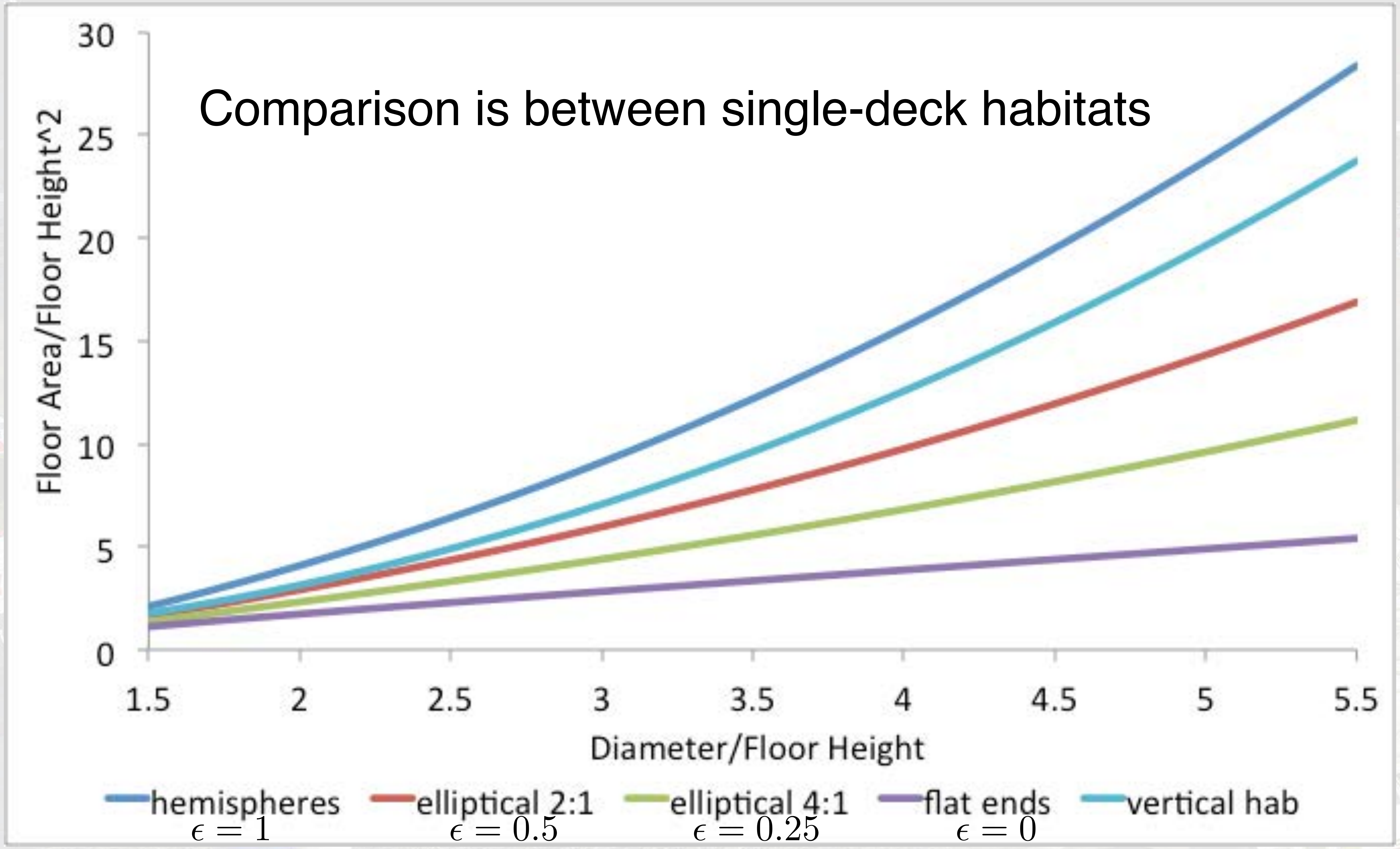


Three Floors

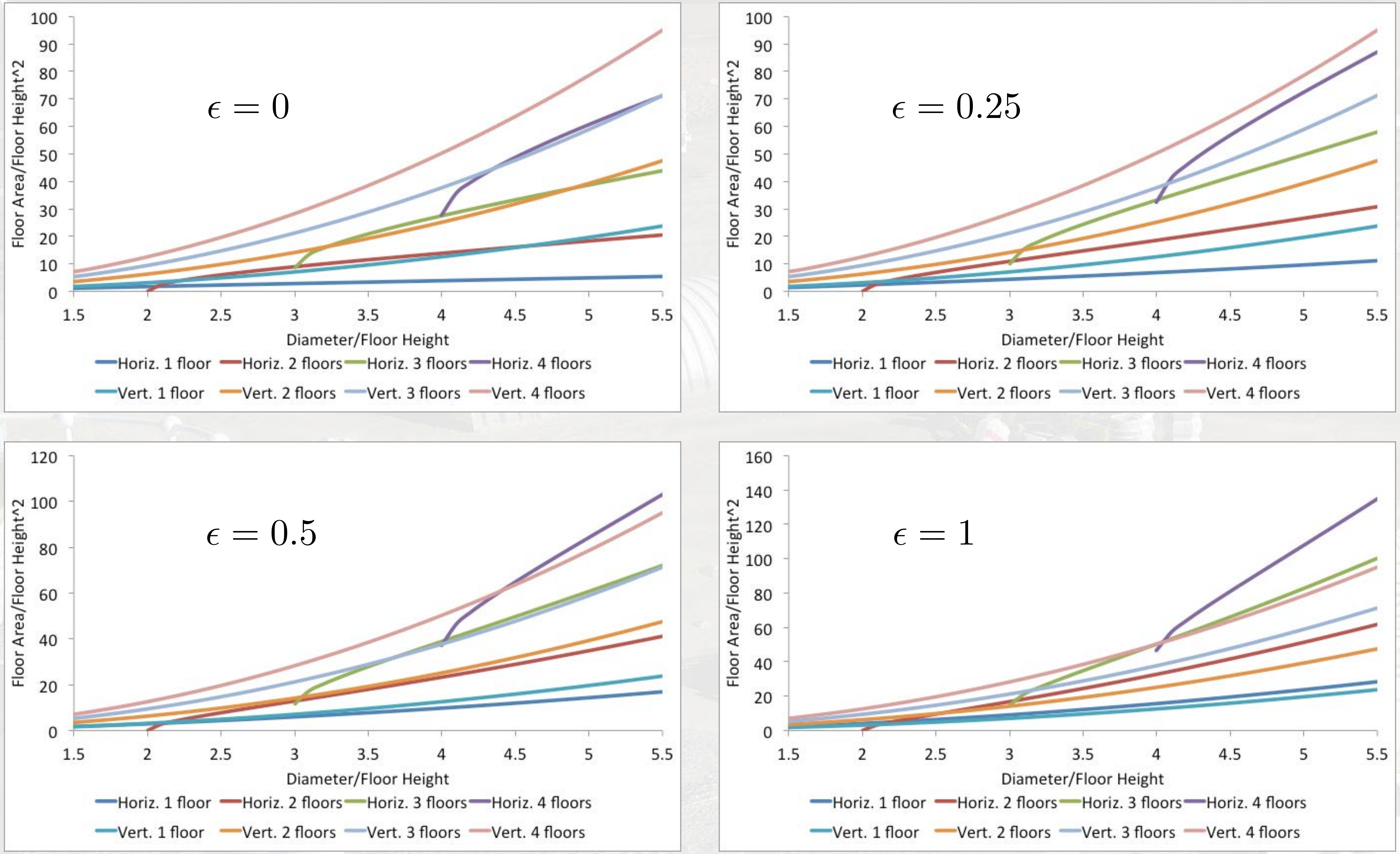


Four Floors

Endcap Effect on Available Floor Area



Effect of Endcap Shape on Floor Area



Endcap and Cylinder Effects on Mass