

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

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ABSTRACT

In 1963, Celentano, Amorelli, and Freeman of North American Aviation described a set of curves as an *Index of Habitability* that can predict the amount of pressurized volume necessary per crewmember to conduct a mission at “tolerable, performance, or optimal” levels. This paper presents an analysis of the “Celentano Curve” that depicts a relationship between spacecraft pressurized volume and the duration of a space mission.

Since Yuri Gagarin flew in Vostok 1 in 1961, the US, Russia, and China have launched more than 250 human spaceflights. This survey collects the empirical data and tests the Celentano curves against it. The statistical approach treats the Celentano curve as the hypothesis stating a causal relationship between mission duration and volume. Many authors have published variations of the Celentano curve, and this author considers nine interpretations, plus three versions of the crew size hypothesis and one functional operations hypothesis.

This analysis shows that pressurized volume increases as a function of mission duration, both as a power curve and a logarithmic curve. This volume trend does not level off but continues to rise throughout the historic envelope of human spaceflight.

INTRODUCTION

Since Celentano, Amorelli, and Freeman’s seminal paper, habitability researchers published dozens of citations, interpretations, and variations of the Celentano curves. This paper presents an analysis of the Celentano hypothesis and its acolytes, testing them empirically against the historical data of human spaceflight. In each case, the authors frame their predictions in terms of “meeting crew needs.” Most notable among these predictions of volumetric “requirements,” NASA adopted an embodiment of the Celentano curve in the 1987 Man-System Integration Standard (MSIS).

The history of human spaceflight -- from the earliest flights in tiny capsules to the capacious International Space Station -- provides the baseline from which to evaluate and test these predictions. What the historical record affords is a metric to analyze how pressurized volume varies with mission duration, crew size, and other causes.

FIGURE 1 shows the original Celentano plot that features the volume prediction rising steeply over the shorter missions, but leveling out after six months at about 700ft³ (19 to 20 m³). Celentano et al posited three levels of accommodation “tolerable, performance, and optimal,” but did not define them clearly.

OBJECTIVES

The objectives of this research are:

- To determine what the facts are and what is true about volume and mission duration.
- To provide an empirical baseline of historical spacecraft and missions against which to compare and perhaps validate volumetric designs in the future, and
- To identify the spacecraft volume and mission envelope issues to which architectural design research may make the greatest contribution.

CAVEAT: VOLUME ESTIMATION FROM FIRST PRINCIPLES

This research does not address design guidelines and methodologies to size pressurized spacecraft and space habitats. Certainly, those topics are essential future steps, but they exceed the scope of the present effort.

- The scope of this study extends only to identifying, clarifying, and assessing the historical and empirical record of human spaceflight. It is not a substitute for

calculating volume and mass requirements from first principles in the design of crewed spacecraft. What this caveat means is that the human spaceflight community must develop and validate the tools to

predict and plan these spacecraft parameters and requirements to meet crew needs across a broad range of functions, missions, and operations.

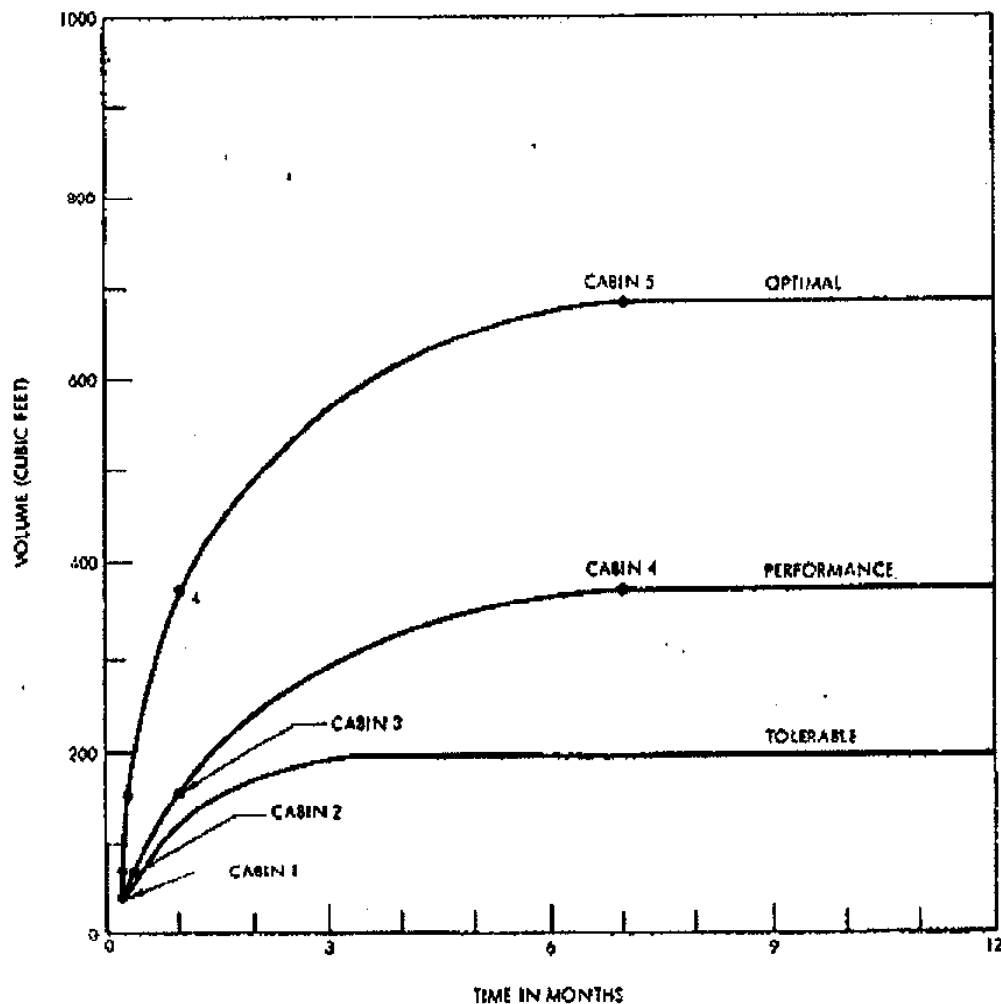


Figure 11. Living Space Per Man (Volume)

FIGURE 1. The original “Celentano Curve” 1963 shows Volume in ft^3 on the Y-axis and Mission Duration in months on the X-Axis. The three curves appear from top to bottom as “Optimal, Performance, and Tolerable.”

A further caveat is that this study addresses only gross pressurized volume. It does not make distinctions among subtractive properties within the pressurized cabin, known variously as *habitable volume*, *free volume*, or *living space*. There are two reasons for this choice:

1. There is good documentation available only on actual pressurized volume. Very few spacecraft have any measurements available for the subtractive volumes. At the same time, there are sometimes inaccurate and conflicting values published for certain spacecraft volumes, so it may take real detective work to find the true data.
2. There is no agreement on how to measure habitable volume or free volume or even how to define it, but there is universal agreement that pressurized volume is the entire space within the pressure vessel that contains the crew cabin.

HISTORICAL CONTEXT

At the time Celentano, Amorelli, and Freeman posed their hypothesis, human spaceflight was in its earliest period of the Vostok, Mercury, Voskhod, and Gemini spacecraft. The experience of zero gravity was limited to very small cabin volumes. Even the Apollo and Soyuz programs seemed far in the future, so that they had few data points for their theory. Never the less, by predicting

quantitative relationship between mission duration and spacecraft size their paper became highly influential. This relationship is very important because the ability to predict cabin size will minimize huge potential variations

in mass and volume for long duration missions such as a Mars Transfer Vehicle (MTV) or at a moon or Mars surface base.

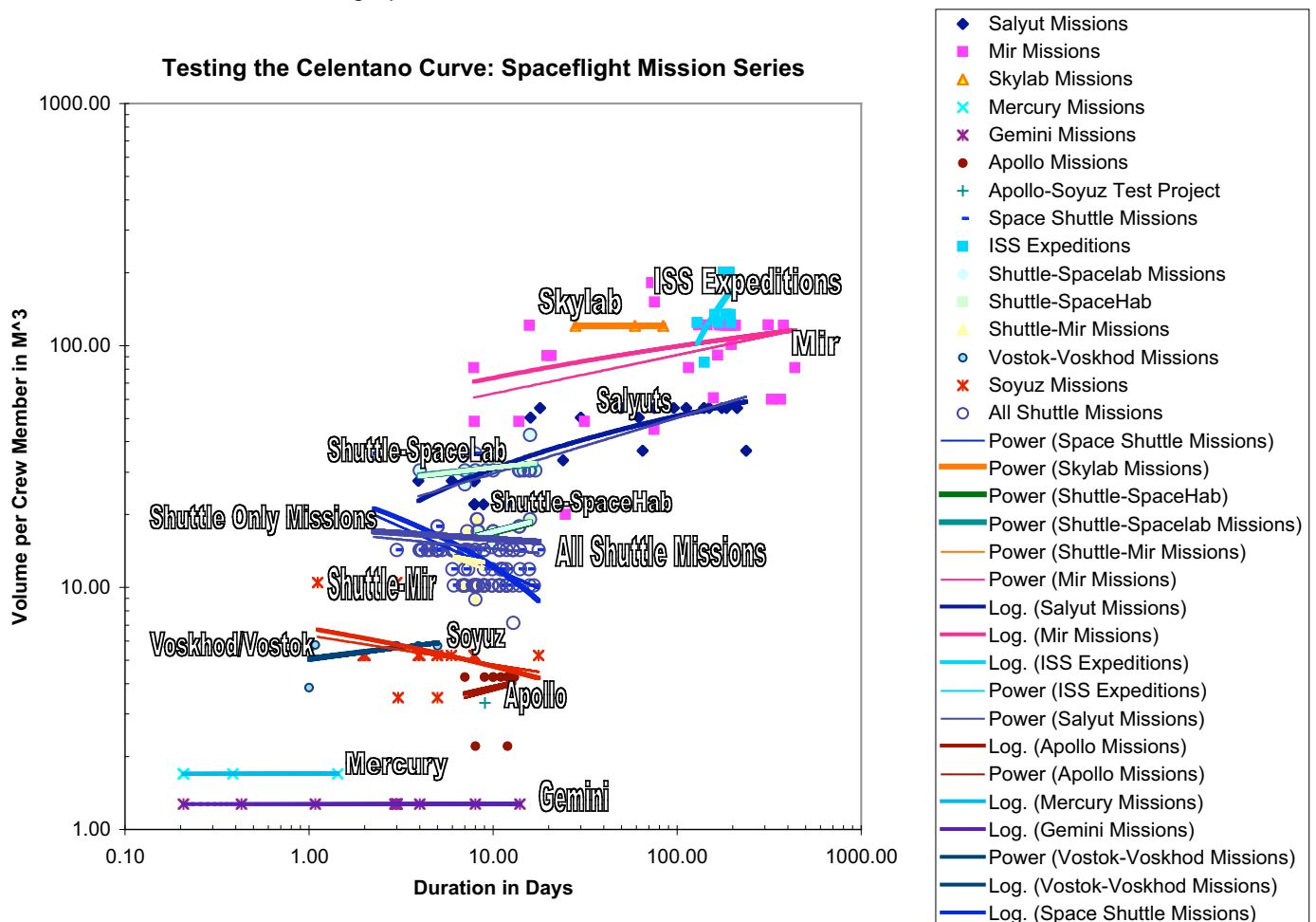


FIGURE 2 shows the complete historic spaceflight data set for all spaceflights through the period of this study in 2006, omitting the outliers of Mercury and Vostok test flights for $t < 0.1$ days.

FIGURE 2 shows the record of human spaceflight by spacecraft. How far has the space habitability community progressed since Celentano? Christopher S. Allen, et al. (2003, p. 49) offered this stark assessment:

There is currently no method available to determine with absolute certainty, the amount of habitable space needed per crewmember for missions beyond LEO. *Until better data is available, designers should plan on allocating a minimum of 16.99m³ (600ft³) of usable space per crewmember* (original emphasis. Allen, et al, 2000, p.47).

Researchers increasingly are calling the Celentano habitability index into question. Most recently, Marianne Rudisill, a psychologist in the Space Mission Analysis Branch at LaRC offers this critique:

On reviewing the original Celentano, et al. paper, here is a summary of their experimental method:

“...They did a good job in describing the multiple factors that impact living space and ‘habitability’; however, my primary concern with their work is that their ‘habitability index’ was based on studies done with very few subjects under controlled laboratory conditions for very short durations from which they extrapolated to multiple months. In particular, they based their habitability index on studies including the following conditions:

Cabin A: living volume = 200 cu ft, living space = 39 cu feet, 13 sq ft/man, 3 subjects, 7 days’ duration (at, essentially, bed rest) = **Tolerable**.

Cabin B: living volume = 1500 cu ft, living space = 150 sq ft, 37 sq ft/man, 4 subjects, 7 days' duration (at sedentary activity level) = **Performance.**

Cabin C: living volume = 1600 cu ft, living space = 400 sq ft, 200 sq ft/man, 2 subjects, 4 days' duration (at average office worker activity level) = **Optimal.**

So, yes, their work was done in gravity, but under conditions that were different to the extreme from the long durations on the lunar surface and it leads me to question its generalizability..."

This is what I was referring to in my talk [at the 2008 ASCE Earth and Space Conference, March 4, 2008]. I have found that many people quote Celentano, et al. (because the curve they generated is in MSIS and it's the **ONLY** reference to volume in MSIS) without having read the original paper and, therefore, without being aware of the conditions in their study; as an experimental psychologist, I find their conditions very short in duration (the maximum was 7 days and they extrapolated to several months), very controlled, and with very few subjects (a total of 9 subjects across 3 conditions where there should have been at least 10 subjects in each of the 3 conditions), **which leads me to question the generalizability of their findings** [emphasis added; e-mail from Marianne Rudisill, April 7, 2008 published by her permission].

This meta-analysis is essential to appreciate what Celentano et al actually did to create their "Habitability Index." Assuming the design of a spacecraft is never frivolous, the volumes represent what the designers consider at least minimal to accomplish the mission. For example, in the design studies for the Orion Crew Exploration Vehicle, one can see how it is possible to suffer crowding from too little volume. FIGURE 3 gives a glimpse of an early concept for the Orion with a crowded cabin that expresses the criticality of simple volume.

RESEARCH DESIGN

The research design treats the Celentano curve and its variants as hypotheses about the relationship between mission duration and volume. The elements to distinguish such a hypothesis consist of:

- A theory of causation for spacecraft pressurized volume; e.g., mission duration drives volume per crewmember.

- Mission duration as the independent variable.
- Pressurized volume as the dependent variable.
- A quantifiable relationship between independent and dependent variables.
- Specific properties of the plot of the dependent variable that relate back to the hypothesis.



FIGURE 3. Andrews Aerospace 10 Crew CEV Mockup for NASA-Johnson Space Center, Courtesy of Andrews Aerospace Corp.

COLLECTING THE DATA

The starting point for this study is simply to collect the data for three key parameters:

1. Defining pressurized volume for each spacecraft,
2. Stipulating the mission duration in days, and
3. Identifying the number of crewmembers in the spacecraft for each mission.

TABLE 1 presents the summary of human spaceflight data collected and considered for this study.

TABLE 1. Summary of the Human Spaceflight Data Set as of July 18, 2006.

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

Defining the Spacecraft and its Volume -- The first decision point was how to define spacecraft and their missions. Although this task may seem self-evident, it is far from obvious. For example, the Apollo Command Module (CM) flew in five mission/configurations: Apollo orbital missions, Apollo lunar missions without and with the Lunar Module (LM), Apollo-Skylab, and Apollo-Soyuz. In the first four cases, there were three astronauts; Apollo-Soyuz had also the two cosmonauts. In each case, the volume varied, with the last three adding the volume of the LM, Skylab, and Soyuz. The Skylab volume was so much greater than the CM that the reasonable approach is to treat Skylab as its own volume, with the docked CM as a secondary volume.

Stipulating the Mission Duration -- The second decision was the mission duration. For missions where the crew launches and lands in the same spacecraft, this stipulation is simple because the space agency records the mission elapsed time (MET) to the second. However, when a crew rotates through a space station, it becomes a matter for analysis and judgment.

- Does the mission extend for the entire time that the space station is continuously inhabited?
- Does the mission duration include the time from launch to docking or from undocking to landing?

- How does the mission change when one crewmember arrives to replace another who then returns to earth?

For clarity, this survey uses the responsible space agency's stipulation. This way implies that, for example, ISS mission duration means the time that an *Expedition* occupies the station, and does not include the transportation time in a Shuttle or Soyuz.

Identifying the Crew Size -- Crew size can vary for post-Apollo and post-Vostok spacecraft. For example, Soyuz flies with two or three crewmembers. The Shuttle flies with two to eight. The CEV will fly with two to six crewmembers. There are instances of partial crew rotation on space stations that necessitate an educated judgment about what was the crew size. Given a spacecraft volume, **changing the number of crew changes the volume per crewmember.**

47 MAXIMA-UNIQUE DATA POINTS

The pivotal research design decision was to identify the unique maxima values for each combination of crew and volume in each spacecraft. Rather than use the entire 254 data points, many of which (e.g. shuttle flights) are nearly identical and produce a dense "square plot", this

analysis selects one data point for the maxima of each combination of crew size and a spacecraft configuration for a total of 47. This maxima-unique approach means that there is one data point for a shuttle mission with a single SpaceHab module for a given crew size and another data point for a shuttle/single SpaceHab mission with a different number of crew. Similarly, there would be two separate maxima for a Shuttle flights with the same number of crew, but one with a single SpaceHab module and the other with a double SpaceHab module.

QUESTIONS FOR THE HYPOTHESES

In approaching these hypotheses, the research design poses a set of questions as a basis for testing them.

1. Has the evolution of spacecraft from Vostok and Mercury to the International Space Station followed the path predicted by the Celentano Curve?
2. Specifically, does the volume prediction follow a curve that rises then levels out at six months?
3. Which curve pattern best fits the data under each hypothesis?
4. Can we evaluate this “best fit” by the R^2 value, or do we need to test for correlation significance among the curves?
5. Does this curve pass through the origin or otherwise show no minimum value?
6. How does the aggregation or disaggregation of the data affect the results?
7. Is there any substantiation in our years of human spaceflight for the guidelines for pressurized volume in terms of tolerable, performance, and optimal limits or levels?

HYPOTHESIS TESTING

The research design postulates a null hypothesis against which to compare all the Celentano curve variations as alternate hypotheses, including the original curve.

The Null Hypothesis, H_0 -- H_0 always states that there is no relationship between the hypothesized independent variable and dependent variable; there is no relationship – no effect – between mission duration and volume.

The Alternate Hypothesis, H_a -- H_a states that there is an effect between the independent the dependent variables; mission duration affects pressurized volume.

THE MISSION DURATION HYPOTHESES

This section presents the dozen hypotheses, explicating in detail the first one, Celentano (1963), and the second, Fraser (1966), to demonstrate the methodology. TABLE 2 shows the hypotheses in chronological order.

H_1 Celentano, Amorelli, Freeman (1963) – FIGURE 1 shows this famous graph. The minimum occurs at about 45 ft³ (1.28m³), for the Gemini spacecraft. They use the term “living space” as “volume per-man requirements.” This graph follows a discussion of breathable atmospheres, so it is clear that they mean total volume. Their principal assertion states that this volume requirement increases over mission duration to an upper limit after six months.

This accommodation occurs within three “levels:”

- a) A “tolerable” level of about 5.6 m³ (~200 ft³),
- b) A “performance” level of about 10.6 m³ (~375 ft³), and
- c) An “optimal” level of about 19 or 20 m³ (which the authors state at 700 ft³).

To summarize the parts of the Celentano Hypothesis H_1 :

- H_{1a} : There is a minimum value of approximately 1.25m³ pressurized volumes per crewmember.
- H_{1b} : The curve levels off beyond a duration of six months; no more volume is required.
- H_{1c} : There are three levels of volumetric habitability, defined as tolerable, performance, and optimal.
- H_{1d} : The optimal curve for volume requirements levels off at maxima of about 20m³.

H_2 Fraser (1966) – T. H. Fraser portrays three zones of impairment to the crew: *no impairment*, *detectable impairment*, and *marked impairment* in FIGURE 4. Fraser built his data from habitat analog and simulator studies as curves on a two-axis logarithmic graph. Two years later, he published another version of the graph, but logarithmic only on the X-axis for time as shown in FIGURE 5. In *LIVING ALOFT* (1985, p 61), Connors, Harrison, and Akin discuss Fraser’s contributions:

Fraser (1968a) evaluated the results of 60 confinement studies to determine at what point physiological or psychological impairment occurred which was related to spatial restriction. He found that impairment (which he defined as the demarcation between “no impairment” and “marked impairment”) occurred at between 50 ft³ [1.42 m³] for very brief confinement, and 150 ft³ [4.25 m³] for 60-day confinement.

TABLE 2. Summary of Null and Alternate Hypothesis Features:

	Volume Description/ Crewmember	Log Scale	Type of Curve	Minimum Value	Number of Curves	Base on Empirical Data?	Based on Study Predictions?
MISSION DURATION DRIVES VOLUME HYPOTHESES							
H ₀ No Effect	Pressurized Volume	No	None	No	None	No	No – Null Hypothesis
H ₁ Celentano, Amorelli, Freeman 1963	"Living" Press. Volume, 3 Limits: <i>Tolerable, Performance, Optimal.</i>	No	Quasi-log, flattens to upper limit	~1.28m ³	3	Partially	Limited data
H ₂ Fraser 1966, 1968	Pressurized Volume	Yes	Zones of Points	~25-30 ft ³ = ~.71-.86 m ³	3, not H ₁	Yes	Partially
H ₃ Manned Space Center, 1966	Habitable Living Volume/Man	No	Quasi-log	Yes	2 with a zone between	Yes	Partially
H ₄ Marton 1971; MSIS, 1987, 1995; Woolford, Bond, 1999;	Habitable Volume (Undefined)	No	Same as H ₁	No. Passes through 0.	3, same as H ₁	Same as H ₁	Same as H ₁
H ₅ Gore, Martin, Trust 1978	Puts Mission Duration Limits on Celentano	No	Quasi-log that does not flatten	No, varies with criteria curve.	3 plus 8 limit slopes	Crew stowage Req'ts.	Space Shuttle Studies.
H ₆ Sherwood, Capps, 1990.	Pressurized Volume	Yes	Curve rises.	~1m ³	2	Mostly	Partially
H ₇ Petro; Perino; Kennedy; Rudisill 1999-2008,	Pressurized Volume	Yes	Straight line rises	~1m ³	1	Mostly	Partially
H ₈ Sforza 2004	Free & Habitable Volume(undefined)	Yes	Power S-curve rises	40 ft ³ = 1.13m ³	2	Partially	Partially
H ₉ Hofstetter, de Weck, Crawley 2005.	Habitable & Pressurized Volume	No	Same as H ₁ , but part fit with poly.	No. Passes through 0.	Show 3 but test only 1.	Modeling MSIS	No, relies on MSIS.
CREW SIZE DRIVES VOLUME HYPOTHESES							
H ₁₀ Davenport, Congdon, Pierce, 1966.	Minimum Volume / Man	No	4 Rising Straight Lines	1.43 m ³ , increases with crew	4	Not Clear	Yes
H ₁₁ Reynerson, 2004	Facility Volume	No	Straight line rises	No	1	No	Yes
H ₁₂ Kennedy, Touns, Smitherman, 2008	Three limits: <i>tolerable, performance, preferred.</i>	No	3 Straight lines rising	No	3	Unclear	Unclear
MISSION FUNCTION REQUIREMENTS DRIVE VOLUME HYPOTHESIS							
H ₁₃ Schwartz, 2005	Pressurized and Habitable Volume	No	N/A	~1.25 m ³ ,	2	Yes	Yes

He concludes that a volume of 250-700 ft³/person [7.08-19.82m³] [depending upon] length of confinement, is adequate [annotations based upon personal conversation with Mary Connors, NASA-Ames Research Center, July 14, 2006].

Fraser offers his variations on the Celentano Hypothesis:

- H_{2a}: The levels of tolerance of confinement and acceptable crew cabins occur as zones (rather than as precise curves).
- H_{2b}: These zones are:
 - H_{2b1} No Impairment,
 - H_{2b2} Detectable Impairment, and
 - H_{2b3} Marked Impairment.
- H_{2c}: There is a minimum required volume of about 0.7 m³ (25 ft³) for a space cabin, associated with the bottom limit for "Marked Impairment."

Fraser's minimal volume of 0.7m³ is impossibly small for a spacecraft, and *marked impairment* would be an unsurprising consequence.

H₃. Manned Space Center (1966) -- The staff at the newly constructed Manned Space Center in Houston prepared a version of the Celentano curve in FIGURE 6. The zones of habitability between upper and lower bounds are consistent with Fraser's (1966) concept, which they cited. Unfortunately, the anonymous authors did not define these upper and lower bounds. One inconsistency is that MSC shows the Gemini capsule as having more volume per crewmember than Mercury capsule, when the opposite was true. Their choice of analog environments is equally curious. They chose the Triton, a conventionally powered submarine, unspecified nuclear submarines, and a 1957 Antarctic Sleeping Area. The only spacecraft they predict beyond Apollo is a Space Station that falls below the lower bound.

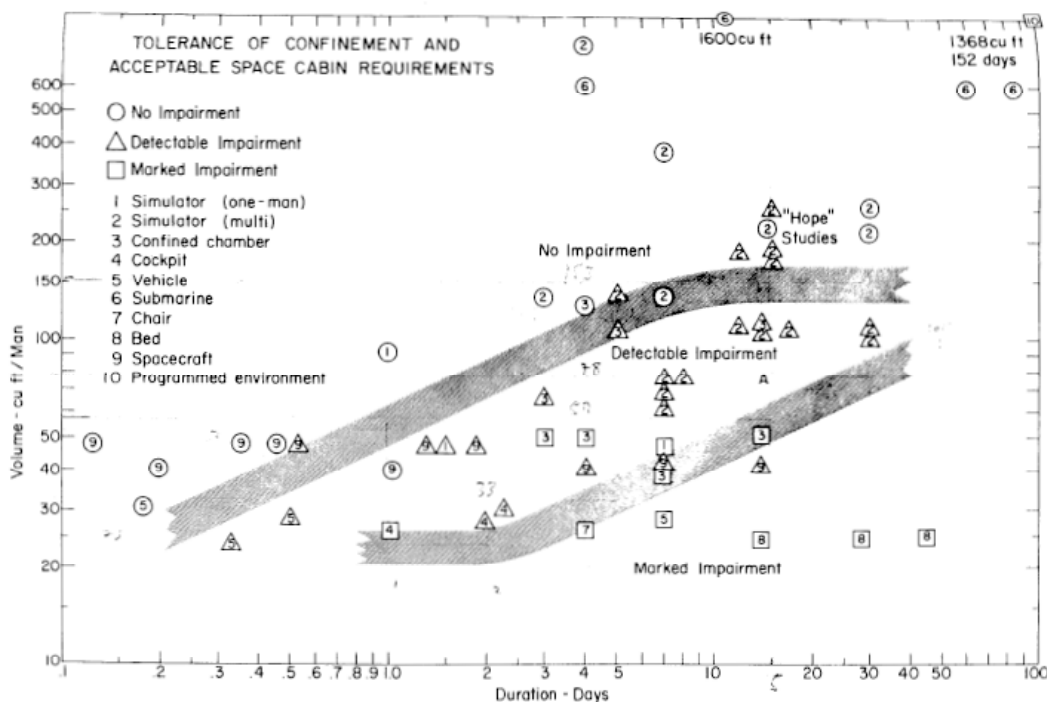


Figure 8. Tolerance of Confinement and Acceptable Space Cabin Requirements.

FIGURE 4. Fraser's 1966 plot of No impairment, Detectable Impairment, and Marked Impairment from confined volumes from NASA CR-511.

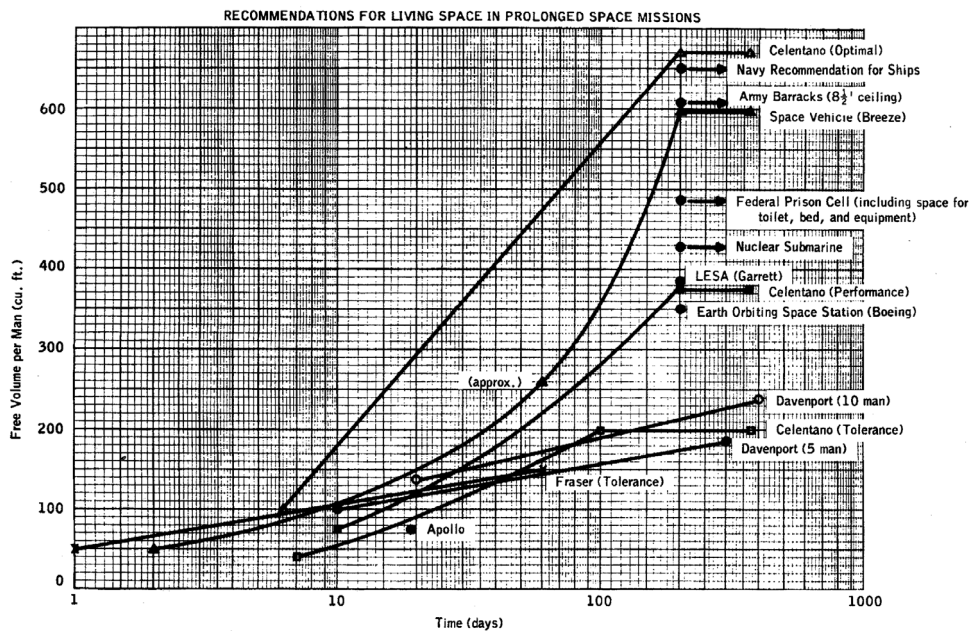


Figure 1

FIGURE 5. T. M. Fraser's 1968 "half-logarithmic" plot of *Free Volume* versus Time (NASA CR-1084, p. 2)

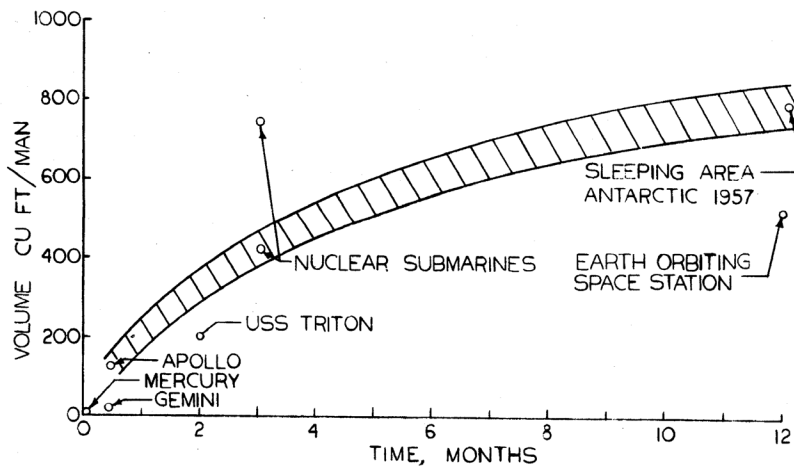


FIGURE 2.3 TOTAL HABITABLE LIVING VOLUME

FIGURE 6. Manned Space Center (1966) curve suggesting a habitable zone between two Celentano-like curves.

H₄ Marton et al., (1971) etc. – In 1971, Marton, Rudek, Miller, and Norman published a version of the Celentano Curve but placed the minimum value at the origin -- zero -- making a *kind of* arithmetic logic:

Zero mission duration = zero volume = zero crew.

NASA reproduced the Marton et al plot in the first two editions of the *Manned Systems Integration Standard*

(MSIS), NASA STD-3000 (1987, 1995), in FIGURE 8. Later, Barbara Woolford and Robert Bond in the Human Factors organization at JSC, who were major contributors to MSIS, published this chart in Wiley, Pranke, Eds (1999). The Y-axis bears the label “habitable volume.” However, the lack of a definition of “habitable volume” has led to widely varying interpretations. As Marianne Rudisill notes, this MSIS version is the most widely cited in the literature.

What this analysis can test is whether this curve passes through zero, its slope, and whether it levels out horizontally at any of the three value limits for tolerable (5m^3), performance (10m^3), and optimal (20m^3). However, it cannot test the hazy distinction between pressurized and habitable volume.

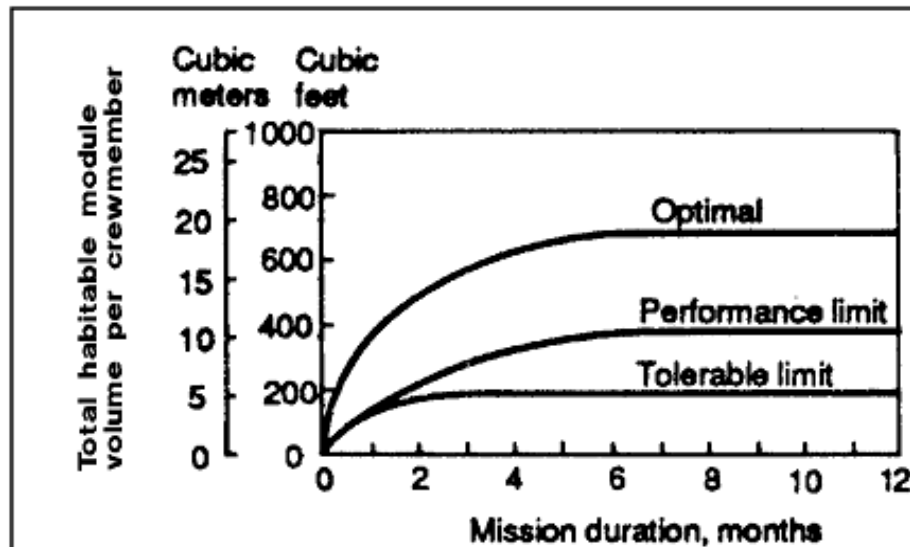


FIGURE 7. Marton, Rudek, Miller, Norman (1971), as reproduced in NASA Std. 3000, Man-System Integration Standard, Figure 8.6.2.1-1. Guideline for determination of total habitable volume per person in the space module.

H₅ Gore, Martin, and Trust: Celentano with Duration Limits (1978) -- During the period of developing the Space Shuttle, Gore, Martin, and Trust of Rockwell International applied the Celentano curve to planning Shuttle missions. In FIGURE 8, they recognize that available volume could impose mission duration limits, anticipating Spacelab and SpaceHab. They defined eight duration limits as lines of negative slope, based upon their estimates of delta down weight, subsystem capability and extension requirements, and the stowage volume a crew of four would need above what Celentano indicates. The curves resemble MSC's. Gore et al retain the terms *Optimum* and *Performance* for the upper curves, but label the lower curve *Minimum*. In the legend, they equate the *Optimum* curve to a *Maximum Requirement* and the *Performance* curve to a *Median Requirement*, (they do not imply a statistical meaning). They apply Celentano with reservations:

For a crew of four, habitability [sic] or “free” volume does not become a limiting factor

until durations of about 90 days, assuming the Celentano “performance” criteria provide such a measure. Furthermore, orbiter free volume improves well before the Celentano “performance” threshold by the needed addition to stowage volume (Gore et al, 1978, p. 9).

Gore, Martin, and Trust's goal was to prepare for the Extended Duration Orbiter (EDO) project. NASA planned EDO in at least two phases, first to extend the original seven to ten day orbiter missions to the range of 16 to 20 days, and second to 30 to 32 days (also called the 30-day orbiter). These two extensions appear in FIGURE 8 as the AL-20 and the AH-30 lines that intersect the “Optimum” curve. The EDO project involved much more than augmenting the Shuttle cabin volume; “The heart of the EDO is the cryogenic pallet,” (Saucier, 1992, p. 1). The cryogenic pallet added LH2 and LOX to extend the life support, power, and propulsion systems capabilities.

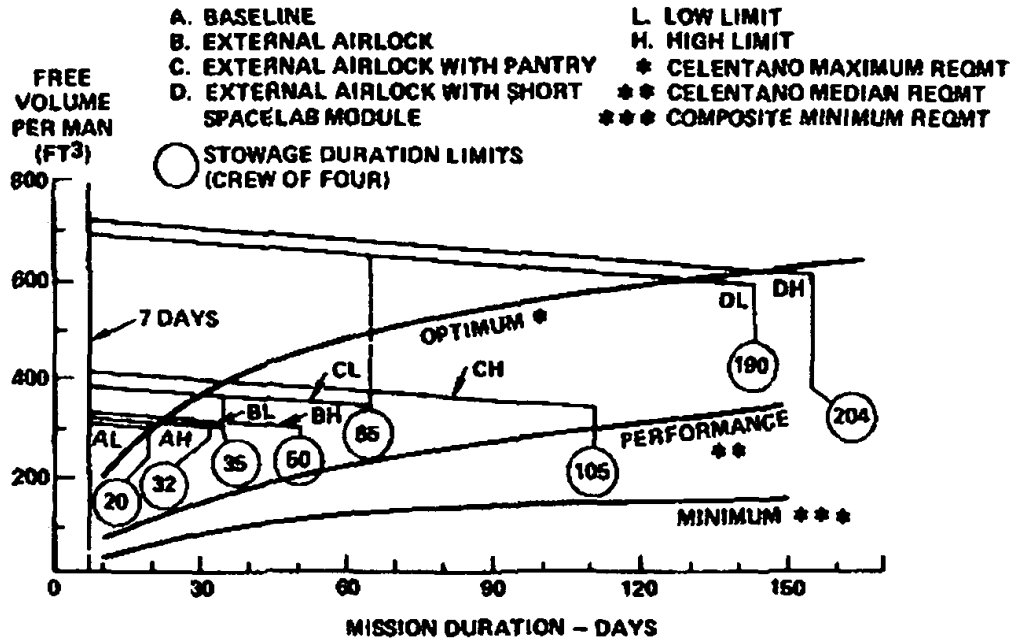


Figure 25. Duration Limits as Function of Habitability Requirements (Crew of Four)

FIGURE 8. Gore, Martin, and Trust's (1978) overlay of mission duration limits upon the Celentano curves.

H₆ Sherwood, Capps (1990) – Brent Sherwood and Stephen Capps of Boeing Space and Electronic Systems in Huntsville, AL performed the first analysis of spacecraft volume that distinguished among different spacecraft types. Their most significant finding was to identify two distinct populations for pressurized volume in the human spaceflight data: launch and landing capsules defined by aerothermal geometry and “other habitable spacecraft” including the Apollo Lunar Module (LM), the Space Shuttle, and all space stations. In parsing the data, they identified the parameters for the types of spacecraft, individually and in various combinations.

FIGURE 9 shows Sherwood and Capps' graph, with one curve for Capsules and the other for all “other habitable vehicles.” Only the curve for Space Shuttles and Stations evokes the shape of the Celentano curve. Brent Sherwood, a Space Architect, who is now head of the JPL Strategic Planning & Project Formulation Office recalls:

Let me tell you how it really happened when I did the hab analysis. I assembled data on prior

designs from easily available sources, which inevitably meant total pressurized volume, as you note elsewhere. When I plotted the data, it struck me (just visually) that one way to make sense out of the messy (*i.e., not highly correlated*) data at the low end was to divide it into two classes. I convinced myself that this made sense because atmospheric entry vehicles (not the LM, which is why I didn't include it in that set) have an overriding geometry constraint due to shape that orbital systems don't have (*e.g., the LM*). Cones are horrible for packaging efficiency.

So I reasoned that the overwhelming nature of the aeronautical shape constraint would contaminate any thoughts about how much space people needed...besides, who cares about how much space they need when they're only in it for a few hours? Even I can stand flying United overseas, because although I