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

Marc M. Cohen
Northrop Grumman Integrated Systems

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

Since Yuri Gagarin flew in Vostok 1 in 1961, the US, Russia, and China have launched more than 250 human spaceflights. This paper collects this empirical data and tests the Celentano curves against it. In assessing the data this analysis takes a traditional statistical approach, stating the null hypothesis as no effect between mission duration and volume. It treats the Celentano plot of a quasi-logarithmic curve as the alternate hypothesis stating a causal relationship between mission duration and volume. Many researchers have published variations of the Celentano curve, and this paper considers nine of them as additional interpretations of the alternate hypothesis, plus three versions of the crew size alternate 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 with a coefficient of determination ($R^2$ value) of 72 percent and 60 percent respectively. Within the historic envelope of spaceflight experience of over a year in space, the volume trend does not level off but continues to rise.

INTRODUCTION
Celentano, Amorelli, and Freeman published a set of curves that predicted the amount of pressurized volume per crewmember to conduct a space mission at three levels of accommodation: “tolerable, performance, optimal.” Since this seminal paper, habitability researchers and organizations 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 and 1995 Man-System Integration Standard (MSIS) editions of NASA Standard 3000.

The history of human spaceflight -- from the earliest flights in tiny Mercury capsules to the capacious International Space Station -- provides the baseline from which to evaluate and test these predictions. But first a caveat: it is possible to assert that the spacecraft volume met crew needs only insofar as none of them became sick, performed inadequately, or died from the cause of insufficient volume. What the historical record affords is a metric to analyze how pressurized volume varies with mission duration.

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 700ft$^3$. 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 and historical baseline of spacecraft and missions against which to compare and perhaps validate volumetric designs in the future, and
- To identify the spacecraft volume and mission envelopes in which architectural design of crew living and working environments may make the greatest contribution.
FIGURE 1. The original "Celentano Curve" 1963 shows Volume in \( \text{ft}^3 \) 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."

CAVEAT: VOLUME ESTIMATION FROM FIRST PRINCIPALS

The objectives of this paper do not include developing design guidelines and methodologies to size pressurized spacecraft and space habitats. Certainly, those goals 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.

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, net volume, or usable volume. 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

The quantity of pressurized volume necessary for a space crew to perform their work successfully has been a focus of spirited debate almost since the beginning of the space age. Celentano, Amorelli, and Freeman wrote the first essay on this question. In this seminal paper,
the authors proposed a relationship between spacecraft volume and the duration of a space mission such that the longer the mission duration, the more volume per crewmember would be necessary to support the crew. A scan of the original Celentano plot appears in FIGURE 1. Please note that the minimum volume occurs at a specific point that corresponds roughly to the value of about 45 ft³ (1.28 m³), the volume per crewmember in the Gemini spacecraft.

At the time Celentano, Amorelli, and Freeman wrote this seminal paper, human spaceflight was still 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 they had very few empirical data points from which to project their theory. Nevertheless, this paper became highly influential because it theorized that the required volume would follow a curve that approaches a limit and levels off at a maximum necessary cabin size. This ability to predict is very important because the ability to predict cabin size will minimize the huge potential variations in mass and volume for long duration missions such as a Mars Transfer Vehicle (MTV) or even at a moon or Mars surface base.

FIGURE 2 shows the record of human spaceflight for by spacecraft type, unaggregated, that provides the basis for this survey.

Although Celentano did establish the first baseline for a “habitability index,” researchers increasingly are calling it into question. Most recently, Marianne Rudisill offers a critique of the Celentano methodology:

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]. 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, published by her permission].

This kind of meta-analysis is essential to understand the scientific underpinnings of Celentano. This survey takes a different approach to examine empirically how Celentano et al and their many reinterpretations compare to the historical record as a more direct way to test generalizability, also known as external validity.

Assuming that the design of a spacecraft is never frivolous, the volumes achieved must represent the design realization of what the designers considered essential or minimal to accomplish the mission. Despite the International Space Station’s (ISS) great size, the demand for usable pressurized volume remains intense. Looking at the design studies for the Orion Crew Exploration Vehicle, it is easy to see how readily it is possible to suffer from too little volume. FIGURE 3 gives a glimpse of one early concept for the Orion Crew Exploration Vehicle cabin.

**FIGURE 3.** View of the Andrews Aerospace CEV Mockup for NASA-Johnson Space Center, with the crew in launch position. This version of the CEV would accommodate 10 people. Courtesy of Andrews Aerospace.

**THE DEBATE ABOUT VOLUME AND LIVING SPACE**

What is so striking about this discourse about spacecraft volume is how absolute the assertions of the advocates are. Here are a few of the leading statements.

B. J. Bluth wrote the Soviet Space Stations as Analogs Study (1987), stating the summary findings:

Adequate living space is important, as Soviet Research has established that the lack of space (volume) can lead to negative physical and psychological problems (p. 6).

The levels of bacterial aerosol in manned habitats correlate directly to population density and the activity of people. Humans are the main source of aerosol in pressurized rooms. With the reduction of free volume per person, the size of aerosol particles increase[s] **sic** (Bluth, 1987, p. I-139).
Studies conducted in limited space indicate that with the lack of volume, people also experience a lack of desire to exercise (Bluth, 1987, p. III-34).

Being in closed quarters of limited volume for long periods makes people dependent upon environmental factors that are hardly noticeable under ordinary conditions. This is expressed in the effectiveness and reliability of performance (Bluth, 1987, p. IV-2).

Christopher S. Allen, et al. (2003, p. 49) start their Crew Accommodations with this remarkable 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 $16.99m^3$ (600ft$^3$) of usable space per crewmember (original emphasis. Allen, et al, 2000, p.47).

As another example, the NASA Exploration Systems Architecture Study (ESAS, December 2005, pp. 161-165) report presented proposed volumes for the Lunar Surface Access Module (LSAM,) that seem to fall far short of the Celentano values, especially for the “optimal” criterion. FIGURES 4a, 4b, and 5c illustrate the ESAS concepts.

**APPROACH**

The general approach of this inquiry is to pursue a series of questions concerning our knowledge about human habitation in space insofar as it concerns the allocation of volume per crewmember and its relationship to mission duration:

1. **What do we know?** This question addresses the phenomenon that of the dozens of publications on the Celentano hypothesis, most do not cite the original source, and few cite more than one or two of the other publications.

2. **What do we know that is true?** This question goes to the essence of the present investigation. In testing the Celentano curve, it should be possible to evaluate which of these formulations of received wisdom is true or at least supportable.

3. **What is important?** This question attempts to sort the many claims about human habitation in space to determine where we should devote our efforts.

4. **What does it mean to us?** This question addresses what these findings tell us about space habitation, and the relationship to mission duration, volume, crew size, privacy, functional volumes, etc.

5. **What can we do with this knowledge?** This question concerns how to apply this knowledge to create habitation design tools that we can justify for the design of future spacecraft.

**COLLECTING THE DATA**

The starting point for this study is simply to collect the data. This collection involves 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.

Defining the Spacecraft and its Volume -- This data leads to the first decision point: how to define spacecraft and their missions. Although this definition may seem self-evident at first glance, upon deeper examination it is anything but obvious. For example, the Apollo command module flew in four configurations: Apollo orbital missions, Apollo lunar missions with the Lunar Module (LM), Apollo-Skylab, and Apollo-Soyuz. In the first three cases there were three astronauts; for Apollo-Soyuz there were also the two cosmonauts. In each case, the volume varies, with the last three cases all including the added volume of the LM, Skylab, and Soyuz, respectively. However, in the case of Skylab, the volume of this first US space station was so vastly greater than the Apollo command module that the only reasonable approach is to treat Skylab as its own principal volume, with the docked Apollo capsule as a secondary volume.

Stipulating the Mission Duration -- The second decision point involves how to stipulate the mission duration. For most missions where the crew launches and land in the same spacecraft, this stipulation is simple because the responsible agency records the mission elapse time (MET) to the second. However, when a crew rotates through a space station such as the Salyuts, Mir, or the International Space Station (ISS), the specification becomes more a matter of 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 and simplicity, this analysis uses the responsible space agency’s definition of each mission for a crew. This arrangement means that for example ISS mission duration corresponds to the time that an Expedition occupies the station, and does not include the on-orbit time of transient Shuttle or Soyuz crews.

Identifying the Crew Size — Crew size can vary for most spacecraft. Although the Mercury always flew with one, the Gemini flew with two, and Apollo flew with three crewmembers, other vehicles experienced a more diverse complement. For example, Soyuz flies with two or three crew. The Shuttle flies with two to eight crewmembers. The CEV will fly with two to six crewmembers: two for testing, six for ISS, and four for the moon. There are a few instances of partial crew rotation on space stations where it has been necessary to make an educated judgment about what was the crew size for the purpose of this analysis.

The key point about these variations in crew size is that given the same spacecraft total volume, changing the number of crew also changes the key metric of volume per crewmember.

RESEARCH DESIGN

The central method in the research design is to treat the Celentano curve and each of its variants as hypotheses about the relationship between mission duration and volume. In most cases, the authors present the sufficient elements to distinguish such a hypothesis:

- A theory of causation between mission duration and pressurized spacecraft volume; mission duration drives volume per crewmember.
- Mission duration constitutes the independent variable.
- Pressurized volume constitutes the dependent variable.
- A mathematical or quantifiable relationship between independent and dependent variables.
- Specific properties of the curve or plot that describes the dependent variable that relate back to the hypothesis.

UNIQUE MAXIMA

The pivotal research design decision was to identify the unique maxima values for each combination of crew and volume in each spacecraft. This research design means that rather than use the entire 250 + data points, many of which (e.g. shuttle flights) are quite similar, that there is one data point for the maxima of each combination of crew size and a spacecraft configuration. This unique maxima 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 levels out and approaches a horizontal limit, parallel to the X-mission duration axis?

3. Which curve pattern best fits the data under each hypothesis?

4. Can we evaluate this "best fit" by the coefficient of determination ($R^2$) metric, or do we need some way 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?

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**HYPOTHESIS TESTING**

The research design aims for a measurable and quantifiable basis for hypothesis testing. It postulates a null hypothesis against which to compare all the Celentano curve variations as alternate hypotheses, including the original curve.

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

<table>
<thead>
<tr>
<th>Spacecraft Type</th>
<th>Category</th>
<th>Number of Missions</th>
<th>Max. Mission Duration</th>
<th>Min. Mission Duration</th>
<th>Max. Volume Per Crew</th>
<th>Min. Volume Per Crew</th>
<th>Max. Crew</th>
<th>Min. Crew</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury Capsule</td>
<td>Capsule 6</td>
<td>1.43</td>
<td>0.02</td>
<td>1.70</td>
<td>1.70</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Gemini Capsule</td>
<td>Capsule 10</td>
<td>14.00</td>
<td>0.21</td>
<td>1.28</td>
<td>1.28</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Apollo CM with and w/o LM Capsule</td>
<td>Capsule 11</td>
<td>12.75</td>
<td>6.00</td>
<td>4.27</td>
<td>2.22</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Apollo LM Lunar Landing Capsule</td>
<td>Capsule 7</td>
<td>3.21</td>
<td>1.00</td>
<td>3.33</td>
<td>3.33</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Apollo-Soyuz Capsule</td>
<td>Capsule 1</td>
<td>9.04</td>
<td>9.04</td>
<td>3.33</td>
<td>3.33</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Vostok Capsule</td>
<td>Capsule 6</td>
<td>5.00</td>
<td>1.04</td>
<td>5.73</td>
<td>5.73</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Voskhod Capsule</td>
<td>Capsule 2</td>
<td>1.08</td>
<td>1.00</td>
<td>2.87</td>
<td>1.91</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Soyuz Capsule</td>
<td>Capsule 42</td>
<td>14.00</td>
<td>0.43</td>
<td>1.28</td>
<td>1.28</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Shenzhou Capsule</td>
<td>Capsule 2</td>
<td>5.00</td>
<td>1.00</td>
<td>17.00</td>
<td>8.50</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Space Shuttle Shuttle</td>
<td>Shuttle 89</td>
<td>17.67</td>
<td>2.25</td>
<td>35.75</td>
<td>8.94</td>
<td>8</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Shuttle-Spacelab/SpaceHab Shuttle</td>
<td>Shuttle 25</td>
<td>16.90</td>
<td>4.00</td>
<td>42.70</td>
<td>14.66</td>
<td>8</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Skylab Station</td>
<td>Station 3</td>
<td>84.00</td>
<td>28.00</td>
<td>120.33</td>
<td>120.33</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Salyut Station</td>
<td>Station 17</td>
<td>237.00</td>
<td>16.00</td>
<td>55.25</td>
<td>33.50</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Mir Station</td>
<td>Station 25</td>
<td>437.75</td>
<td>72.82</td>
<td>181.35</td>
<td>45.00</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>ISS Station</td>
<td>Station 12</td>
<td>195.82</td>
<td>128.86</td>
<td>201.13</td>
<td>85.17</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

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The Null Hypothesis, $H_0$. -- In classic Statistics 101 parlance, the null hypothesis, $H_0$, always states that there is no relationship between the independent variable and the dependent variable; there is no relationship – no treatment effect – between mission duration and volume.

The Alternate Hypothesis, $H_a$. -- The alternate hypothesis, $H_a$, states that there is a relationship or treatment effect between the independent variable and the dependent variable; that mission duration effects pressurized volume; longer durations need more volume.

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In addition, this analysis attempts to address:

- Where does the curve begin and end?
- What is the curvature?
- How does the curve begin or end?
- To which types of spacecraft does this curve apply?

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**TABLE 2** lays out the nine Celentano-derived mission duration hypotheses, plus three crew size hypotheses, and one functional operations hypothesis.
### TABLE 2. Summary of Null and Alternate Hypothesis Features:

<table>
<thead>
<tr>
<th>Mission Duration Drives Volume Hypotheses</th>
<th>Volume Description/Crewmember</th>
<th>Log Scale</th>
<th>Type of Curve?</th>
<th>Minimum Value?</th>
<th>Number of Curves</th>
<th>Base on Empirical Data?</th>
<th>Based on Study Predictions?</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₀, No Effect</td>
<td>Pressurized Volume</td>
<td>No</td>
<td>None</td>
<td>No</td>
<td>None</td>
<td>No</td>
<td>No – Null Hypothesis</td>
</tr>
<tr>
<td>H₁, Celentano, Amorelli, Freeman 1963</td>
<td>&quot;Living&quot; Press. Volume, 3 Limits: Tolerable, Performance, Optimal.</td>
<td>No</td>
<td>Quasi-log, flattens to upper limit</td>
<td>~1.28 m³</td>
<td>3</td>
<td>Partially</td>
<td>Limited data</td>
</tr>
<tr>
<td>H₂, Fraser 1966, 1968</td>
<td>Pressurized Volume</td>
<td>Yes</td>
<td>Zones of Points</td>
<td>~25-30 ft³ = ~.71-.86 m³</td>
<td>3, not H₁</td>
<td>Yes</td>
<td>Partially</td>
</tr>
<tr>
<td>H₃, Manned Space Center, 1966</td>
<td>Habitable Living Volume/Man</td>
<td>No</td>
<td>Quasi-log</td>
<td>No. Passes through 0.</td>
<td>3, same as H₁</td>
<td>Same as H₁</td>
<td>Same as H₁</td>
</tr>
<tr>
<td>H₅, Gore, Martin, Trust 1978</td>
<td>Puts Mission Duration Limits on Celentano</td>
<td>No</td>
<td>Quasi-log that does not flatten</td>
<td>No. Passes through 0.</td>
<td>3, same as H₁</td>
<td>Same as H₁</td>
<td>Same as H₁</td>
</tr>
<tr>
<td>H₆, Sherwood, Capps, 1990.</td>
<td>Pressurized Volume</td>
<td>Yes</td>
<td>Curve rises.</td>
<td>~1 m³</td>
<td>2</td>
<td>Mostly</td>
<td>Partially</td>
</tr>
<tr>
<td>H₇, Petro; Perino; Kennedy; Rudisill 1999-2008,</td>
<td>Pressurized Volume</td>
<td>Yes</td>
<td>Straight line rises</td>
<td>~1 m³</td>
<td>1</td>
<td>Mostly</td>
<td>Partially</td>
</tr>
<tr>
<td>H₈, Sforza 2004?</td>
<td>Free &amp; Habitable Volume(undefined)</td>
<td>Yes</td>
<td>S-Curve rises, power curve</td>
<td>40 ft³ = 1.13 m³</td>
<td>2</td>
<td>Partially</td>
<td>Partially</td>
</tr>
<tr>
<td>H₉, Hofstetter, de Weck, Crawley 2005.</td>
<td>Free &amp; Pressurized Volume</td>
<td>No</td>
<td>Same as H₁</td>
<td>No. Passes through 0.</td>
<td>3, same as H₁</td>
<td>Same as H₁</td>
<td>Same as H₁</td>
</tr>
</tbody>
</table>

### Crew Size Drives Volume Hypotheses

<table>
<thead>
<tr>
<th>Crew Size Drives Volume Hypotheses</th>
<th>Volume Description/Crewmember</th>
<th>Log Scale</th>
<th>Type of Curve?</th>
<th>Minimum Value?</th>
<th>Number of Curves</th>
<th>Base on Empirical Data?</th>
<th>Based on Study Predictions?</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₁₀, Davenport, Congdon, Pierce, 1966.</td>
<td>Minimum Volume / Man</td>
<td>No</td>
<td>4 Rising Straight Lines</td>
<td>1.43 m³ increases with crew</td>
<td>4</td>
<td>Not Clear</td>
<td>Yes</td>
</tr>
<tr>
<td>H₁₁, Reynerson, 2004</td>
<td>Facility Volume</td>
<td>No</td>
<td>Straight line rises</td>
<td>No</td>
<td>1</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>H₁₂, Kennedy, Toups, Smitherman, 2008</td>
<td>Three limits: tolerable, performance, preferred.</td>
<td>No</td>
<td>3 Straight lines rising</td>
<td>No</td>
<td>3</td>
<td>Unclear</td>
<td>Unclear</td>
</tr>
</tbody>
</table>

### Mission Function Requirements Drive Volume Hypothesis

<table>
<thead>
<tr>
<th>Mission Function Requirements Drive Volume Hypothesis</th>
<th>Volume Description/Crewmember</th>
<th>Log Scale</th>
<th>Type of Curve?</th>
<th>Minimum Value?</th>
<th>Number of Curves</th>
<th>Base on Empirical Data?</th>
<th>Based on Study Predictions?</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₁₃, Schwartz, 2005</td>
<td>Pressurized and Habitable Volume</td>
<td>No</td>
<td>N/A</td>
<td>~1.25 m³</td>
<td>2</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
THE MISSION DURATION HYPOTHESES

This section presents the hypotheses as interpreted for the purpose of this analysis. It explicates the first alternate hypothesis, Celentano (1963), and the second, Fraser (1966), to demonstrate the method. All the hypotheses appear in TABLE 2 in chronological order, affording each author the presumption that they knew about the precedents.

H2, Celentano, Amorelli, Freeman (1963) – FIGURE 1 shows this famous original graph. The authors posited a minimum value for spacecraft volume of roughly 1m^3, a little less than the per crewmember volume (1.25m^3) in the Gemini spacecraft. They use the term “living space,” which they define as “volume per-man requirements,” as a quantitative measure of the breathable atmosphere that is the pressurized volume. This graph follows immediately after a discussion of breathable atmospheres that uses the same three descriptors to address issues of high and low partial pressures of oxygen and of the total cabin atmosphere. It is clear that they mean the total pressurized volume. They assert that this volume requirement increases on a curve that levels out at an upper limit after about six months.

This requirement falls within several “limits:”

a) A “tolerable” level of about 5.6 m^3 (~200 ft^3),
b) A “performance” level of about 10.6 m^3 (~375 ft^3), and
c) An “optimal” level of about 19 or 20 m^3 (which the authors state at 700 ft^3).

To summarize the parts of the Celentano Hypothesis H1:

- H1a: There is a minimum value of approximately 1m^3 pressurized volume per crewmember.
- H1b: The curve levels off so that beyond a certain mission duration, no more volume is required.
- H1c: There are three levels of volumetric habitability, defined as tolerable, performance, and optimal.
- H1d: The optimal curve for volume requirements levels off at maxima of about 20m^3.

H2, Fraser (1966) – Rather than the three levels – tolerable, performance, and optimal – that Celentano defined by specific curves, T. H. Fraser portrays three levels in terms of impairment to the crew. Whereas Celentano et al were almost entirely speculative beyond a week; Fraser carefully based his distinctions upon experimental and empirical data available to him from a variety of analog and simulator experiences. He describes these degrees of impairment as zones separated by wide bands rather than as thin curves. He was the first to present these curves on a two-axis logarithmic scale graph.

Two years later, Fraser published a second NASA CR in which he presented another version of the graph, but this time, logarithmic on only the X-axis for time duration as shown in FIGURE 7. In this effort, Fraser focused more on the long duration missions and tried to develop a variety of curves for what appear to be seven different data sets from other sources. While it is difficult to recapitulate the subtleties of each of these representations, the total effect is to emphasize the relationship of mission or confinement duration to the recommendations for “free volume per man.”

In LIVING ALOFT (1985, p 61), Connors, Harrison, and Akin discuss certain aspects of 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 ft^3 [1.42 m^3] for very brief confinement, and 150 ft^3 [4.25 m^3] for 60-day confinement. He concludes that a volume of 250-700 ft^3/person [7.08-19.82m^3] [depending upon] length of confinement, is adequate [annotations based upon personal conversation with Mary Connors, NASA-Ames Research Center, July 14, 2006].

Based on the 1966 study (FIGURE 6), Fraser offers the following variations on the Celentano Hypothesis in the 1966 report. However, it is not possible to distinguish a different and meaningful alternate hypothesis from his 1968 study in FIGURE 7.

- H2a. The levels of tolerance of confinement and acceptable crew cabins occur as zones (rather than as precise curves).
- H2b. These zones are:
  - H2b1 No Impairment,
  - H2b2 Detectable Impairment, and
  - H2b3 Marked Impairment.
- H2c. There is a minimum required volume of about .7 m^3 (25 ft^3) for a space cabin, associated with the bottom limit of tolerance for “Marked Impairment.”

H3, Manned Space Center (1966) -- In an early “Earth Orbiting Space Station” report, the staff at the newly constructed Manned Space Center in Houston prepared their own version of the Celentano curve, including consideration of studies by Fraser, Davenport and others. FIGURE 7 shows the MSC plot indicating a habitable zone between two Celentano-like limits. One inexplicable inconsistency is that MSC shows the Gemini capsule as having more volume per crewmember than Mercury capsule, when the opposite was true. The idea of a zone of habitability between upper and lower limits is consistent with Fraser’s 1966 study, which these anonymous authors cited. Unfortunately, they do not indicate how they define these upper and lower limits, so they are not testable. Their choice of analog environments is curious. They
chose the Triton, a conventionally-powered submarine, unspecified nuclear submarines – for which, along with a 1957 Antarctic Sleeping Area (but not the larger base) – one data point falls in the middle of the habitable zone.

The only spacecraft they predict beyond the Apollo program is an undefined Earth Orbiting Space Station that falls below their double curve.

FIGURE 6. Fraser’s 1966 plot of No impairment, Detectable Impairment, and Marked Impairment from confined volumes from NASA CR-511.

FIGURE 8. Manned Space Center (1966) curve suggesting a habitable zone between two Celentano-like curves.

FIGURE 9. Marton, Rudek, Miller, Norman (1971), as reproduced in NASA Standard 3000, Man-System Integration Standard, Figure 8.6.2.1-1. Guideline for determination of total habitable volume per person in the space module.

-Marton et al., (1971) etc. – In 1971, Marton, Rudek, Miller, and Norman published a version of the Celentano Curve in which they made a notable change. Where Celentano, Amorelli, and Freeman placed the minimum value at about 1.2m$^3$/crewmember as signified by the Gemini mission, Marton et al placed the minimum value at the origin: zero. This change makes a kind of mathematical logic: no mission duration: no volume: NO CREW. Subsequently, NASA reproduced the Marton et al plot in the first two editions of NASA STD-3000 (1987, 1995), the Manned Systems Integration Standard (MSIS).
Later, Barbara Woolford and Robert Bond at NASA-Johnson Space Center, who were major contributors to MSIS, published this chart again in Wiley, Pranke, Eds (1999). Woolford and Bond introduce a new element in labeling the ordinate value as “habitable volume.” However, the lack of a definition of “habitable volume” as opposed to the total pressurized volume has led to widely varying interpretations and applications of their meaning. This MSIS version is the most widely cited and reproduced in the literature.

What this analysis can test is whether this curve passes through zero, and whether it levels out horizontally at any of the three value limits for tolerable (~5m$^3$), performance (~10m$^3$), and optimal (18m$^3$). However, given the data furnished by Celentano, Woolford & Bond, or NASA, what we cannot test is whether there is any meaningful distinction between pressurized volume and habitable volume.

FIGURE 9 shows the NASA MSIS Standard 3000’s reproduction of Marton et al’s interpretation of the Celentano curves.

H. Gore, Martin, 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 anticipated Shuttle Orbiter missions. They recognized that although the Celentano curves could theoretically extend indefinitely, the Shuttle crew cabin and habitable modules it might carry in the cargo bay would impose mission duration constraints upon the Celentano curves. They added a set of eight duration limits as lines of negative slope, based on their calculation of how much stowage volume a crew of four would need to sustain them over the various mission durations.

FIGURE 5 shows an enlargement of the Gore, et al graph. This graph shows the volume as a function of mission duration curves somewhat differently from the Celentano original. The curves do not flatten out at maximum volume limits, but rather keep a positive slope in the same manner as the Manned Space Center (1966) showed. See FIGURE 8 to compare.

FIGURE 5. Gore, Martin, and Trust’s (1978) overlay of mission duration limits upon the Celentano curves.
Gore, Martin, and Trust retain the Celentano nomenclature of Optimum and Performance for the two upper curves, but they label the lower curve Minimum instead of Tolerable. In the legend, they equate the Optimum Curve to a Maximum Requirement and the Performance Curve to a Median Requirement, although they give no indication that they intend median in any statistical meaning. They describe the effect of the mission duration limits (page 9) with a modicum of skepticism: 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 [shown in FIGURE 5, their Figure 25].

Gore et al provide a detailed analysis of several metrics for the Space Shuttle Orbiter against mission duration on the X-axis, including delta down weight, subsystem capability and extension requirements, and the duration limits as a function of stowage requirements. These analyses all provided data for the subsequent Extended Orbiter studies at Rockwell International.

H6 Sherwood, Capps (1990) – Brent Sherwood and Stephen Capps of Boeing Space and Electronic Systems in Huntsville, AL prepared the most detailed study to date of the phenomenon that the Celentano curve describes. Their most significant finding was that there are two distinct populations for pressurized volume in the human spaceflight data: launch and landing capsules and “other habitable spacecraft” which includes the Apollo Lunar Module, the Space Shuttle, and all space stations.

FIGURE 8 shows the Sherwood and Capps curves, showing one curve for Capsules and the other for all “other habitable vehicles.” Note that only the “other habitable spacecraft” curve for Space Shuttles and Stations evokes the Celentano model of a quasi-logarithmic curve. Brent Sherwood, now head of the JPL Strategic Planning & Project Formulation Office explains this analysis:

**Historical Spacecraft Total Pressurized Volume Data**

![Historical Spacecraft Total Pressurized Volume Data](image)

FIGURE 8. Sherwood and Capps, 1990, separation of two curves that distinguish aero-entry capsules and all other “habitable vehicles” (courtesy of Brent Sherwood).
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 hate it, I am only trapped for a few hours. The real issue is orbital space, so I wanted to eliminate the distraction of the atmospheric entry systems. There was no deeper statistical reasoning than that. I still believe my logic is valid...CEV might care about the lower curve, but nobody else should (e-mail from Brent Sherwood, March 19, 2008).

The challenge of testing the Sherwood and Capp's hypothesis will be to determine if the data supports the above observation of "not highly-correlated data at the low end.

H7 Petro, (1999), Perino, Rudisill et al. – In the same anthology that Woolford and Bond reproduced the Marton et al, Petro (1999) published a very different plot of the same historical data. He shows the curve as a single straight power curve of positive slope on a logarithmic scale graph. It is reasonable for a curve in a simple graph to appear as a straight line on a logarithmic scale graph. However, a version of this graph is circulating in the PowerPoint ecosystem that does not show the logarithmic scale, leading some viewers to misinterpret the curve as a straight linear relationship. FIGURE 10 shows Rudisill et al’s (2008, p. 4) most recent version of this plot.

Rudisill et al explain their approach:

Dimension and volumetric data from past and present spacecraft (both US and Russian vehicles) were gathered and evaluated. Spacecraft vary across a number of parameters relevant to volume estimation, such as era of development, crew size, and mission duration. In addition, all spacecraft operate in a microgravity environment (other than the Apollo Lunar Module, the only vehicle for which we have crew operations data from the lunar surface, albeit for very short durations, on the order of three to four days), while we were deriving estimates for a 1/6g environment. However, gathering and comparing spacecraft provided a broad view of volumes of built and operated vehicles. We identified another relevant factor: mission “type.” That is, all spacecraft evaluated were found to group into either of two categories, “transportation-like” or “station-like”; understandably, vehicles used primarily to “ferry” crews to a destination serve a rather different function from those designed primarily for long-duration crew operations. This grouping of vehicle “type” can be seen in [FIGURE 10], showing total pressurized volume as a function of mission duration (note that the predicted maximum lunar outpost mission duration of 180 days is indicated on the X-axis as a reference).

Given that we were estimating volume required for a lunar surface habitat serving as an “outpost,” we focused our assessment on “station-like” spacecraft, given the long duration nature of these missions (original emphasis, Rudisill et al, pp. 3-4).

In making this distinction between transportation-like and station-like vehicles, Rudisill et al reflect Sherwood and Capps’ 1990 findings, although they omit mention of the Space Shuttle.
H. Sforza (2004) – Prof. Pasquale Sforza at the University of Florida published on his website a version of the Celentano curve with several new features. He introduces the term “free volume” in lieu of pressurized volume and he seems to use this term interchangeably with “habitable volume.” He emphasizes the minimum volume limit by putting an opposite curve at the bottom creating an overall “S-curve” effect.

FIGURE 11 presents Sforza’s “S”-curve in which the flat curves at the top and the bottom represent the constant minimum and maximum value of pressurized volume per person. The middle section is the power curve from four to 180 days. Sforza explains his approach:

The number of crewmembers and mission duration are basic specifications that strongly influence the vehicle configuration. The habitable volume required for each crewmember may be estimated by applying the Celentano volume criterion (ref.) which is an s-shaped, “learning curve” shown in [FIGURE 11].

[FIGURE 11] suggests that a doubling of the Celentano values is more representative of current experience. . . . The International Space Station will have 15,000 cubic feet (425m$^3$) of habitable volume but a crew complement of only 6, yielding 2500 ft$^3$/person (70.8m$^3$/person), much more than even double the Celentano criterion. Note that 100 ft$^3$ corresponds to a box roughly 4ft by 4 ft square and 6 ft high.

Sforza proposes that “the Celentano criterion curve may be approximated in a piece-wise fashion according to the following equations:"

**EQUATION 1.**

\[
0 < t < 4\text{days} : v_{\text{free}} = 40 \text{ft}^3 / \text{person} \\
\text{[1.13m}^3 / \text{person}] \\
4 < t < 180\text{days} : v_{\text{free}} = 20t^{0.58} \text{ft}^3 / \text{person} \\
t > 180\text{days} : v_{\text{free}} = 400 \text{ft}^3 / \text{person} \\
\text{[11.3}^3 \text{m} / \text{person}] 
\]
Sforza applies his curve fitting to move the decimal point precisely one place to the right from the missions of less than four days to missions of more than 180 days. This outcome implies that the long duration spacecraft would be an order of magnitude larger per crewmember than the short duration transportation vehicle. Even doubling the volume as Sforza suggests, it does not begin to explain the empirical Skylab, Salyut, Mir, and ISS volumes per crewmember that are far larger than $11.3\,m^3$ or $22.6\,m^3$.

Hoffstetter, de Weck, Crawley (2005) — These authors at MIT took the NASA STD-3000 chart and interpolated a curve from the optimal level that falls slightly under the curved portion but lines up exactly with the flat portion. FIGURE 13 show their attempt to fit a curve in the middle of the “optimal” curve. In this respect, they may be thinking along similar lines as Sforza insofar as they are providing a more “custom fitted” plot between the bottom and top limits.

FIGURE 11. Sforza’s interpretation of the Celentano curve and his proposal for a doubled requirements curve.

FIGURE 12. Hofstetter, de Weck, and Crawley’s “analytical interpolation” of a partial logarithmic trend line function below the Celentano curve from NASA STD 3000.
They use the term habitable volume, and go on to propose a rule of thumb to size the total pressurized volume:

Equation 2

\[ V_{\text{Pressurized}} = 3 * V_{\text{Habitable}} \]

While this method of estimating may fall in the ballpark, the design and engineering challenges of calculating spacecraft size are far more complex. Yet, Hoffstetter et al do not shy away from complexity. In laying out their curve-fitting approach, these authors assert that:

There are several approaches to compute the necessary pressurized volume; here, a polynomial of fourth order shall be used to estimate the habitable volume required as a function of mission duration. . . . For mission durations longer than 270 d[ays], the habitable volume is assumed to stay constant at about 19 m³ per crewmember. (p. 4).

CREW SIZE HYPOTHESES

This research turned up three versions of a different alternate hypothesis that crew size is the primary driver of volume per crewmember

H₁₀ Davenport, Congden, Pierce (1963) Crew Size – Davenport et al proposed “preliminary requirements for crew volume versus space mission duration,” in which they posited crews of four sizes: 1, 3, 5, and 10 crewmembers. They present their recommendations as a series of lines – one for each crew size. Each line of increasing crew size appears progressively higher on the graph and of steeper slope than the one before it. Davenport et al’s graph appears in FIGURE 13.


H₁₁ Reynerson (2005): Volume function of crew size – Charles Reynerson of Boeing presented criteria for mission duration of 180 days is about par for ISS and is moderate compared to historical Salyut and Mir missions. However, the proposed number of crew and the facility volume is substantially greater – up to 1.5 orders of magnitude greater.
Crew Number: 0 - 100
Endurance: 0 - 180 days
Facility Weight is Most Sensitive to Endurance

Reynerson appears to argue that although mass scales most closely with mission duration, volume scales more closely with crew number. Reynerson’s plot appears in FIGURE 14.

FIGURE 14. Reynerson’s plot of a linear relationship between number of crew and the pressurized volume of a spacecraft.

FIGURE 15. Kennedy, Toups, & Smitherman’s adaptation of Celentano, Amorelli, and Freeman’s three limits to the crew size as the explanatory variable for volume.

Kriss Kennedy and Larry Toups, space architects at JSC, and David Smitherman, space architect at MSFC interpreted Celentano, Amorelli, and Freeman’s three limit curves to apply to the Crew size as volume driver hypothesis (Kennedy, Toups, Smitherman, 2008). In FIGURE 15, they plot the three Celentano curve limits of tolerable, performance, and preferred [sic, instead of Celentano’s “optimal”] as straight lines of positive slope. The graph shows a data point for each crew size. Like Celentano, they do not run the three curves through the origin, but stop them at one crewmember. Where Davenport assigns one line to each size of crew, this hypothesis presents each of the three limit curves as a continuum of crew sizes from one to six crewmembers.
Kennedy, Toups, & Smitherman present a set of novel predictions (2008, p. 2):

The gross pressurized volume required for space habitats can be estimated based on historical data about human space exploration and remote environments on earth . . . . A first order parametric volume estimation based on crew size and mission duration gives the designer a starting point for the space habitation system. Historical data combined with ISS data show the habitation volumes divided into three categories; minimum tolerable limits, minimum performance limits, and preferred limits . . . . These rules-of-thumb are applicable for medium duration missions. Short duration missions will be roughly analogous to the Shuttle, and for long duration missions there is little data available to make a determination. When determining the initial volume required, one should consider a parametric range of volumes based on the mission objectives and requirements.

FUNCTIONAL OPERATIONS HYPOTHESIS

This hypothesis appears as one-of-a-kind in the sense that it does not presuppose a single quantitative sizing-driver such as mission duration or crew size. Rather, it is more mission- and operations-specific.

$H_{13}$ Schwartz (2005) – Writing in the Draper Lab’s presentation of its Crew Exploration Vehicle for the NASA Concept Exploration and Refinement Study, Jana Schwartz reproduces the NASA STD-3000 chart and the Fraser 1966 chart. She goes on to address the bridge between the minimum “habitable volume” and the larger total pressurized volume of which the “habitable” zone is a subset. She argues that function drives volume more than mission duration and presents a graph in which she shows the pressurized volumes within a confidence interval for specific missions.

Some of Schwartz’s captions are rather cryptic, such as “EVA, 5 Crew.” Although Schwartz’s argument is incomplete, it has a compelling aspect to it: to tie pressurized volume to the purposes for which the crew uses it in conducting a space mission. In this respect, Schwartz’s approach is the most operationalized of all the hypotheses.
HYPOTHESIS TESTING

The research design for hypothesis testing takes the assertions of each hypothesis, and plots their salient characteristics within the historical spaceflight data set. FIGURE 16 represents the total data set until mid-2006 for the maxima-unique points. TABLES 3a and 3b present the summary of how all the hypotheses fared in testing, with the test plots where applicable.

QUESTIONS BEFORE THE ANALYSIS

- How can all the hypotheses appear to enjoy “face validity,” yet argue such contradictory positions?

The remarkable feature of this collection of hypotheses is that each one (with the exception of Reynerson) enjoys a degree of face validity and conveys a kind of common sense. This sense and credibility came from smart and idealistic people imagining how a crewed spacecraft would be or should be, far in advance of having sufficient data to predict volume accurately.

- How well do the hypotheses reflect the historical and empirical data?

Nearly all the hypotheses reflect some facet of the historical and empirical data. The more fundamental question is how to create a hypothesis that combines “all these facets into a big picture that will withstand the test of time and analysis.

- Should the data set include all spacecraft and habitats or exclude capsules of under 14 days duration?

Sherwood and Capps initiated this distinction, and indeed the analysis will show the statistical basis of this separation. However, capsules and small-crewed vehicles have been a large part of space exploration from its inception, will continue do so, and will play an even larger role with the retirement of the Space Shuttle in 2010 and its replacement by the Orion.

- To what degree do the various hypotheses reflect some aspect of reality in addition to duration such as function, crew size, or other criteria?

Each of the hypotheses draws upon the state of knowledge at the time the author proposed it. It would be relatively straightforward to place each of these notions within the space community’s stage of development at that time.

DESCRIPTIVE STATISTICS

The descriptive statistics provide a quantitative context in which to test the hypotheses. TABLE 4a shows the descriptive statistics for the maxima-unique sample of 47 human spaceflights. TABLE 4b shows the complete population of 252 human spaceflights until mid-2006. With \( n=47 \), TABLE 4a is reasonable to produce its confidence intervals of 33 and 15, but TABLE 4b has a much smaller (better) confidence interval. The following discussion uses the numbers in TABLE 4b because it gives a clearer reading (of essentially the same results as TABLE 4a). The mean mission duration was 42 days and the mean volume was 31.4 m\(^3\). However, these means were very far from the medians, which were 8.9 days and 11.9m\(^3\). The standard deviations (SD) are huge, especially for mission duration at 75 days. Thus, the SD for mission duration is about 8.5 times larger than the portion of the range from the median down to the minimum of 0.2. This statistical artifact corresponds with the arguments by Sherwood and Capps, Rudisill et al that there is an important distinction between the capsules in the range below the median and all other habitable spacecraft in the range above the median. These historical space station missions can continue for three or even four standard deviations above the median or the means.

COEFFICIENT OF DETERMINATION

Given non-random data such as mission duration and volume, one of the most effective statistical tools is the coefficient of determination, also known as the R-squared value \((R^2)\), short for the square of Pearson’s produce moment correlation coefficient (Pearson’s R). The National Institute of Standards (NIST) defines \(R^2\) as:

\[
R^2 = 1 - \frac{SSerr}{SStot} = \frac{SSreg}{SStot}
\]

\[
= 1 - \frac{\text{UNEXPLAINED Variance}}{\text{Total Variance}}
\]

\[
= \frac{\text{EXPLAINED Variance}}{\text{Total Variance}}
\]

\(SSreg\) is the Sum of the Squares of the Regression to the Mean; \(SSerr\) is the Sum of the Squares of the Errors of the mean; and \(SStot\) is the Total Sum of the Squares.
R^2. What the R^2 gives is a measure of the variance in the dependent variable Y as a function of variance in the independent variable X, stated as a percentage. X is the explanatory variable and Y is the explained variable. When plotting the variance of Y as a function of the variance in X, the R^2 value gives the probability that the curve Y represents the variance in X. While X is the explanatory and independent variable, it is not necessarily always the causative variable.

There is a common rule of thumb that an R^2 value of 50 percent or more indicates an effect or relationship between the variance in X and the variance in Y. This rule of thumb can be useful, but comes with limitations, primarily that it does not provide a separate measure of significance in the sense inferential statistics do, using random data. Instead, the estimation of significance depends upon the magnitude – absolute or relative – of the R^2 values. R^2 does not address the role of irreducible variance. Another rule of thumb is that if Y_1 and Y_2 are within 10 percent of one another, they represent the same variance. Equation 4 shows how the difference in variances emerges.

**Equation 4: Differences in Y.**

R^2(Y_1) - R^2(Y_2) > 0.1

As the value of Equation 4 increases above zero, Y_1 and Y_2 become more separate and different. When that difference becomes much larger than 10% and one of the Ys is greater than 50%, it suggests that it may be significant compared to a much lower Y or that the difference between the two Ys may be meaningful.

**TESTING THE MISSION DURATION HYPOTHESES**

The tests of the nine mission duration hypotheses all derive from the analysis of FIGURE 16, the empirical test of the historical human spaceflight data. FIGURE 16 shows the empirical representation of the human spaceflight missions upon which Celentano and all successors base their theories. FIGURE 16 portrays both the natural log curve that the original Celentano curves most resemble and the power curve that Petro, Perino, and Rudisill et al advocate. The yellow curve portrays the natural log plot of the data with an R^2 = 0.60. The purple straight line portrays the power curve plot of the data with an R^2 = 0.72. Although the simplest approach is to declare the power curve the “winner” because it returns the larger R^2 value, that solution does not give an adequate explanation of what the data show.

DIAGRAM 1 explains the deeper meaning of these two curves to consider how their variances may differ beyond the size of their R^2, where the colors of the bars reflect the respective power and natural log curves in FIGURE 16. When dealing with R^2 values there is an unfortunate tendency to regard the percentages of variance as an integer scale in which a larger percentage of variance would contain all of a smaller percentage of variance. While this effect is possible, it is not strictly correct. It is possible for the two variances to overlap only by the amounts of (1-Y_1) + (1-Y_2).

DIAGRAM 1 illustrates this distinction regarding the R^2 values in FIGURE 16. The key point is that the two R-squared values for Y may occur as a complete overlay of variance as in bar a, such that Y_2 includes all of the variance in Y_1. Alternatively, these same results for the dependent variable Y may entail a minimum overlap of variance as shown in bar b. Bar b implies that most of the variance in Y_1 is not included in Y_2. In this situation, the two Ys would paint quite different but complementary portions of the total variance in the dependent variable.

The Log plot and the Power plot return R-squared values that are almost close enough to consider them identical. At 12 percent difference in R-squared value, they are just starting to diverge. What is more important, however, is the question of to what extent these two measures may overlap. This question reflects the lesson of DIAGRAM 1 above. Does the 0.72 value of the Power Curve contain all the variance of the 0.60? Alternatively, do both the Power curve and the Log curve contain some variance that does not mutually overlap?
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<th>Reject $H_0$</th>
<th>Remarks</th>
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<tr>
<td>$H_1$ Celentano, Amorelli, Freeman</td>
<td>1963</td>
<td>Pressurized volume requirement increases as a function of mission duration.</td>
<td>X</td>
<td>$R^2 = 0.72$ power, $= 0.60$ log.</td>
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<tr>
<td>$H_{1a}$</td>
<td></td>
<td>Minimum volume of about 1.25 m$^3$/ crewmember.</td>
<td>X</td>
<td>(Approximates Gemini).</td>
</tr>
<tr>
<td>$H_{1b}$</td>
<td></td>
<td>Curve levels off flat after certain duration.</td>
<td></td>
<td>No basis.</td>
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<td>$H_{1c}$</td>
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<td>Maximum volume needed of about 20m$^3$</td>
<td></td>
<td>No basis.</td>
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<td>$H_{1d}$</td>
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<td>Three levels of Optimal, Performance, and Tolerable volumes for crew requirements</td>
<td></td>
<td>Purely speculative.</td>
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<tr>
<td>Fraser</td>
<td>1966</td>
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<td>$H_{2a1}$</td>
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<td>“No Impairment Zone trendline”.</td>
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<td>$H_{2a2}$</td>
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<td>“Detectable Impairment Zone trendline.”</td>
<td>X</td>
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<td>Minimum Volume defined as below the minima of the Marked Impairment Zone.</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Manned Space Center</td>
<td>1966</td>
<td>Pressurized volume requirement increases as a function of mission duration.</td>
<td>X</td>
<td>(Approximates Apollo CM).</td>
</tr>
<tr>
<td>$H_{3a}$</td>
<td></td>
<td>Minimum Volume/crew of about 2.8 m$^3$</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$H_{3b}$</td>
<td></td>
<td>Slope of the curve gradually lessens.</td>
<td>X</td>
<td>Like a log.</td>
</tr>
<tr>
<td>$H_{3c}$</td>
<td></td>
<td>Volume requirement occurs in a band between upper and lower bounds.</td>
<td></td>
<td>No evidence presented.</td>
</tr>
<tr>
<td>Marton; MSIS; Woolford, Bond,</td>
<td>1971</td>
<td>Pressurized volume requirement increases as a function of mission duration.</td>
<td>X</td>
<td>(Approximates Apollo CM).</td>
</tr>
<tr>
<td>$H_{4a}$</td>
<td></td>
<td>No minimum volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_{4b}$</td>
<td></td>
<td>Trendline passes through the origin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_{4c}$</td>
<td></td>
<td>Curve levels off flat after certain duration.</td>
<td></td>
<td>Same as $H_{1b}$.</td>
</tr>
<tr>
<td>$H_{4d}$</td>
<td></td>
<td>Maximum volume needed of about 20m$^3$</td>
<td></td>
<td>Same as $H_{1c}$.</td>
</tr>
<tr>
<td>$H_{4e}$</td>
<td></td>
<td>Three levels of Optimal, Performance, and Tolerable volumes for crew requirements</td>
<td></td>
<td>Same as $H_{1d}$.</td>
</tr>
<tr>
<td>Gore, Martin, Trust</td>
<td>1978</td>
<td>Pressurized volume requirement increases as a function of mission duration.</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$H_{5a}$</td>
<td></td>
<td>Volume curves keep rising and do not level off.</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$H_{5b}$</td>
<td></td>
<td>Volume imposes a Shuttle configuration-specific limit on mission duration</td>
<td>X</td>
<td>Cited studies prove it for shuttles only.</td>
</tr>
<tr>
<td>Sherwood, Capps</td>
<td>1990</td>
<td>Pressurized Volume Requirement increases as a function of mission duration.</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$H_{6a}$</td>
<td></td>
<td>Earth Entry capsules have a different distribution than “other habitable vehicles.”</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>$H_{7a}$</td>
<td></td>
<td>Minimum volume of about 1.25 m$^3$/ crewmember</td>
<td>X</td>
<td>$R^2 = 0.72$ power</td>
</tr>
<tr>
<td>$H_{7b}$</td>
<td></td>
<td>Straight, positive power curve on a logarithmic scale.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 3b. Summary of Hypothesis Testing Results: $H_0$ means that there is no effect. Rejecting $H_0$ means that there is an effect.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Year</th>
<th>Alternate Hypothesis $H_n$</th>
<th>Reject $H_0$</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MISSION DURATION HYPOTHESES, CONTINUED</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_8$ Sforza</td>
<td>2004</td>
<td>Minimum free volume of about 1.13 $m^3$/crewmember (40 ft$^3$).</td>
<td></td>
<td>Unknown basis.</td>
</tr>
<tr>
<td>$H_{8a}$</td>
<td></td>
<td>Free volume requirement increases as a function of mission duration.</td>
<td>Same as $H_1$</td>
<td>Similar to $H_{7b}$</td>
</tr>
<tr>
<td>$H_{8b}$</td>
<td></td>
<td>Straight positive power curve.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_{8c}$</td>
<td></td>
<td>The true free volume requirement is about double the Celentano volume curve.</td>
<td></td>
<td>Insufficient data</td>
</tr>
<tr>
<td>$H_{8d}$</td>
<td></td>
<td>The Celentano volume curve is $V_{free} = 20t^{0.58}$, while the true volume curve is $V_{free} = 40t^{0.58}$</td>
<td></td>
<td>Insufficient data</td>
</tr>
<tr>
<td>$H_{9a}$, Hoffsteter, de Weck, Crawley</td>
<td>2002</td>
<td>Habitable volume requirement increases as a function of mission duration.</td>
<td>Same as $H_1$.</td>
<td></td>
</tr>
<tr>
<td>$H_{9a}$</td>
<td></td>
<td>No minimum volume.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_{9b}$</td>
<td></td>
<td>Trendline passes through the origin.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_{9c}$</td>
<td></td>
<td>The curve between the minima (0) and the maxima of the MSIS ~19 to 20 $m^3$ is a 4th order polynomial trendline.</td>
<td></td>
<td>Questionable Interpolation.</td>
</tr>
<tr>
<td>$H_{9d}$</td>
<td></td>
<td>The optimal curve flattens at a level of 19$m^3$, corresponding to about 6 months duration.</td>
<td></td>
<td>Essentially same as $H_{1c}$</td>
</tr>
<tr>
<td><strong>CREW SIZE HYPOTHESES</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_9$ Davenport, Congdon, Pierce</td>
<td>1966</td>
<td>Recommended minimum volume per man increases as a first order effect of crew size.</td>
<td></td>
<td>No basis. Data show no relationship.</td>
</tr>
<tr>
<td>$H_{9a1}$</td>
<td></td>
<td>Minimum volume of ~1.43 $m^3$ per crew for 1 crewmember</td>
<td></td>
<td>Too small, even for Mercury (1.70$m^3$).</td>
</tr>
<tr>
<td>$H_{9a2}$</td>
<td></td>
<td>Minimum volume of ~2.12 $m^3$ per crew for 3</td>
<td></td>
<td>Too small for Apollo or Soyuz</td>
</tr>
<tr>
<td>$H_{9a3}$</td>
<td></td>
<td>Minimum volume of ~2.83 $m^3$ per crew for 5</td>
<td></td>
<td>Much too small for Shuttle</td>
</tr>
<tr>
<td>$H_{9a4}$</td>
<td></td>
<td>Minimum volume of ~4.25 $m^3$ per crew for 10</td>
<td></td>
<td>No analog, but surely too small.</td>
</tr>
<tr>
<td>$H_{9b}$</td>
<td></td>
<td>Minimum volume/man increases as a second order effect of mission duration.</td>
<td></td>
<td>No evidence to support this claim</td>
</tr>
<tr>
<td>$H_{10}$ Reynerson</td>
<td>2005</td>
<td>Volume scales as a linear function of crew size.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_{10a}$</td>
<td></td>
<td>No minimum volume with zero crew.</td>
<td></td>
<td>Math. Correct but . .</td>
</tr>
<tr>
<td>$H_{11}$ Kennedy, Toups, Smitheman</td>
<td>2008</td>
<td>Volume scales as a linear function of crew size, on three limit curves</td>
<td></td>
<td>No Relationship, No Effect</td>
</tr>
<tr>
<td>$H_{11a}$</td>
<td></td>
<td>Three curves of tolerable, performance, &amp; preferred volumes.</td>
<td></td>
<td>No evidence provided</td>
</tr>
<tr>
<td><strong>FUNCTIONAL CON-OPS HYPOTHESIS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_{12}$ Schwartz</td>
<td>2005</td>
<td>Volume requirements correspond to mission type, which implies specific tasks.</td>
<td></td>
<td>Insufficient data</td>
</tr>
<tr>
<td>$H_{12a}$</td>
<td></td>
<td>Habitable volume requirement is a scaled fraction of the required pressurized volume.</td>
<td></td>
<td>Insufficient data</td>
</tr>
</tbody>
</table>
### TABLE 4a. Descriptive Statistics for the 47 Maxima-Unique Human Spaceflight Missions

Maxima-Unique Data Points

<table>
<thead>
<tr>
<th>Mission Duration in Days</th>
<th>Volume Per Crew Member</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>87.72848404</td>
</tr>
<tr>
<td>Standard Error</td>
<td>16.64301053</td>
</tr>
<tr>
<td>Median</td>
<td>17.66666667</td>
</tr>
<tr>
<td>Mode</td>
<td>14</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>114.0987317</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>13018.52057</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>1.626012804</td>
</tr>
<tr>
<td>Skewness</td>
<td>1.536161704</td>
</tr>
<tr>
<td>Range</td>
<td>436.75</td>
</tr>
<tr>
<td>Minimum</td>
<td>1</td>
</tr>
<tr>
<td>Maximum</td>
<td>437.75</td>
</tr>
<tr>
<td>Sum</td>
<td>4123.23875</td>
</tr>
<tr>
<td>Count</td>
<td>47</td>
</tr>
<tr>
<td>Confidence Level (95.0%)</td>
<td>33.50064212</td>
</tr>
</tbody>
</table>

### TABLE 4b. Descriptive Statistics for 252 Human Spaceflight Missions

<table>
<thead>
<tr>
<th>Mission Duration in Days</th>
<th>Volume Per Crew Member</th>
<th>In m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>41.91500661</td>
<td>Mean</td>
</tr>
<tr>
<td>Standard Error</td>
<td>4.761163412</td>
<td>Standard Error</td>
</tr>
<tr>
<td>Median</td>
<td>8.9</td>
<td>Median</td>
</tr>
<tr>
<td>Mode</td>
<td>5</td>
<td>Mode</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>75.58112604</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Sample Variance</td>
<td>5712.506614</td>
<td>Sample Variance</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>6.297886917</td>
<td>Kurtosis</td>
</tr>
<tr>
<td>Skewness</td>
<td>2.460307417</td>
<td>Skewness</td>
</tr>
<tr>
<td>Range</td>
<td>437.5416667</td>
<td>Range</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.208333333</td>
<td>Minimum</td>
</tr>
<tr>
<td>Maximum</td>
<td>437.75</td>
<td>Maximum</td>
</tr>
<tr>
<td>Sum</td>
<td>10562.58167</td>
<td>Sum</td>
</tr>
<tr>
<td>Count</td>
<td>252</td>
<td>Count</td>
</tr>
<tr>
<td>Confidence Level (95.0%)</td>
<td>9.376921708</td>
<td>Confidence Level (95.0%)</td>
</tr>
</tbody>
</table>

Looking at the curves, the flatter part of the yellow Log curve comes close to the slope of the purple power curve. However, the steep portion of the left side of the yellow Log curve clearly is not contained in the variance of the Power curve. For this reason, the plot of the two curves for pressurized volume may resemble bar b more than it does bar a.

Equation 5 gives the unexplained variance as the probability of 28 percent that the power curve does not represent the variance in Y.

**Equation 5**

\[
\text{UNEXPLAINED Variance}_{\text{Power}} = 1 - 0.72 = 0.28
\]

Simultaneous with Equation 5, Equation 6 gives the unexplained variance as the probability of 40 percent that the log curve does not represent the variance in Y.
Equation 6

\[
\text{UNEXPLAINED Variance}_{\text{Log}} = 1 - 0.60 = 0.40
\]

Now what is fascinating here is that unexplained variance in the Power curve of 28 percent is roughly half the total explained variance of 60 percent in the Log curve. Thus, DIAGRAM 1b shows the black area of overlap of represented variance between the power and log curves, with a minimum overlap of 32 percent. Therefore, the difference of \( R^2 \) probability in representation of the same variance by the two curves ranges from a minimum of 32 percent to a maximum of 60 percent.

The two curves represent somewhat different, but substantially overlapping views of empirical reality. It is easy to envision the left half of the log curve that rises steeply from the right of the origin as the 28 percent of the variance that the power curve leaves unexplained. Conversely, it is easy to imagine that the start of the power curve above the origin and continuing in a straight diagonal of positive slope as the 40 percent of the variance that the log curve leaves unexplained. Taken together, the two curves overlap somewhere across a range of 32 to 60 percent probability that they represent the variance in the same way. Nevertheless, please keep in mind that the total difference in \( R^2 \) values is only 12 percent, making the curves virtually identical in terms of statistical power.

Therefore, both curves describe important aspects of the pressurized volume result. The power curve represents more of the “big picture” in the sense that it spans from the smallest capsules and shortest mission durations to the upper right hand corner of missions that when extrapolated approach a human lifetime, if not infinity. The log curve represents more accurately the steeper slope from the smallest spacecraft to larger ones that figured so prominently in the original Celentano curve.

Testing \( H_1 \), Celentano, Amorelli, Freeman (1963 – The discussion above of Testing the Mission Duration Hypothesis answers essentially all the questions for \( H_1 \). The key affirmative is that we reject the null hypothesis on the basis that there is a relationship between mission duration and pressurized volume and that there is a minimum volume of about 1.25m\(^3\)/crew member. However, we fail to reject \( H_0 \) for the other three parts of this hypothesis.

Testing \( H_2 \), Fraser (1966, 1968) – The test plot of Fraser’s data was based upon a scan of coordinates of the data points he provided for his curves. It was not possible to use the survey of spacecraft data because very few of his data came from spacecraft. FIGURE shows \( R^2 = 0.68 \) for No Impairment and \( R^2 = 0.56 \) for Detectable Impairment, suggesting that there may be a relationship between mission duration and volume for these two curves. However, for Marked Impairment, \( R^2 = 0.05 \) shows no effect. The analysis allows us to reject the null hypothesis for No Impairment and Marked Impairment and to find a relationship between mission duration and volume, although it is stronger for No Impairment.

Fraser’s 1968 semi-logarithmic graph is notable for the way it carefully cites Celentano and Davenport. It compares the confines of a spacecraft to the crew quarters of submarines and ships, but neglects to include the other areas and volumes including open decks. Therefore, it was not testable, and makes no further contribution to this analysis.

Testing H₃ Manned Space Center (1966) – For this anonymous report, we reject the null hypothesis for three of the four assertions. In addition to H1, we find effects for the minimum volume/crew of about 2.8m³, which approximates the Apollo Command Module, and for the gradual lessening – but not flattening – of the slope of the quasi-log curve. The report does not provide evidence for the last assertion that the volume requirement would fall within a band between upper and lower bounds, and so fails to reject H₀.

Testing H₅ Marton et al (1971); NASA STD-3000 (1987, 1995); Woolford & Bond (1999), – Marton’s revision of the Celentano curve is the most widely published through MSIS. However, except for the volume increasing with time initially, it was not possible to reject the null hypothesis for any of the sub-hypotheses. To test this hypothesis correctly it is necessary to overlay the truth on top of the NASA STD-3000 version. FIGURE 16 shows this overlay. The two curves that most faithfully represent the data appear as a yellow curve and a purple straight line. The yellow curve portrays the natural log plot of the data with an R² = 0.60. The purple straight line portrays the power curve plot of the data with an R² = 0.72.

Except for the basic H₁ effect that volume increases as a function of mission duration, we fail to reject H₃ for the other five assertions of this hypothesis. Neither trendline passes through the origin, and the log curve that most resembles H₅’s curves misses it much farther than the power curve. Regarding the maximum volume, at the 180 days when the H₁₀ and H₁₄ would have the curve level out at about 19 or 20m³, in fact the log and power curves cross nearby at 100m³ – 5 time more than Marton et al, MSIS, Woolford and Bond predict. Finally, the empirical curves display no evidence of the optimal, performance, and tolerable predictions.

Testing H₅ Gore, Martin, and Trust (1978) – The evaluation of Gore et al follows closely upon the evaluation of the original Celentano, H₁. The one difference is the addition of the shuttle based mission duration limits. Although the analysis does not include the type of constraints that Gore et al envisioned, their negatively sloping duration limit lines appear to predict realistically and reasonably well the longer shuttle missions, particularly the shuttle-Spacelab and SpaceHab missions. If NASA had chosen to develop the 30+ day Extended Orbiter, it would have afforded a better range of data to test these predictions. Insofar as the record of Shuttle extensibility allows, we reject H₀ for H₅₆ as applied to Space Shuttles.

Testing H₁₀ Sherwood and Capps (1990) – Sherwood and Capps performed the first analysis of spacecraft volume that distinguished among different spacecraft types. In parsing the data, they identified the parameters of variance for the types of spacecraft, individually and in various combinations. When they separated the different types of spacecraft, they found that the correlation values for capsules were very low compared to shuttles and stations taken together.

Sherwood and Capps included the Apollo LM in the set with Space Shuttles and Stations because they did not meet their definition of a geometrically driven “atmospheric entry vehicle.” However, based on the loose criterion that the Apollo Lunar Module (LM) was a short duration launch and landing vehicle of very short flight duration, it would seem to be a bit of an outlier among Shuttle and Stations, and would fit better on the capsule curve.

<table>
<thead>
<tr>
<th>Set of Spacecraft</th>
<th>L(n)</th>
<th>e¹ R²</th>
<th>Effect?</th>
<th>Sig?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capsules</td>
<td>0.24</td>
<td>0.19</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Space Shuttles</td>
<td>0.06</td>
<td>0.05</td>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>Space Stations</td>
<td>0.06</td>
<td>0.03</td>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>Capsules &amp; Shuttles</td>
<td>0.08</td>
<td>0.09</td>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>Shuttles &amp; Stations</td>
<td>0.45</td>
<td>0.58</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Capsules &amp; Stations</td>
<td>0.50</td>
<td>0.40</td>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>Aggregated, All Sets</td>
<td>0.60</td>
<td>0.72</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>

Combining two or more types of spacecraft increased the R² substantially – by up to 50 percent, even for capsules and shuttles. Therefore, they relegated the very low-scoring capsules to a second curve separate from the combined Space Stations and Shuttles.

Testing H₇ Petro (1999); Perino (2005); Rudisill (2008) — This hypothesis advocates for the purple power curve representation as shown in FIGURE 16, enabling us to reject H₀ to this extent. It would appear that these authors found that the power curve returns the highest R² value, and so accepted it as the best representation of the data. However, the power curve has the shortcoming of missing the steep starting curve that Celentano observed and that the yellow log curve portrays. This representation makes a distinction between Space Stations and capsules, but does not explicitly include Space Shuttles. If we apply the values from TABLE 5, the Space Stations return an R² = 3 percent compared to the capsules at 24 percent.. This phenomenon is susceptible to the explanation of distribution in the Discussion of Threats to Validity below.
Testing H7 Sforza (2004) -- Sforza presents his definition of “Free Volume” and offers two curves or limits – one roughly replicating the “Celentano volume criterion” although he does not specify which one, and constructs another that tracks the Kliper, Shenzhou, and Space Shuttle at their maximum crew size. Sforza recognizes that there must be a minimum volume per crewmember, and levels out his interpretation of the bottom of the Celentano curve to create sort of “S-curve.”

We would test whether the curve levels out at the lower end as Sforza suggests, runs straight, and just levels out near the top. Further, we can compare the Gemini/Apollo data to the Kliper/Shenzhou/Shuttle data. Since Sforza’s effective minimum for all spacecraft is 40 ft³ (1.13 m³), what he does is create the upper curve by moving it to the left along the timeline so that where 1.13 was sufficient for five days in a capsule on the lower curve, it is acceptable for only one day in a spacecraft in the upper curve. Although Sforza’s methods are commendable, his numerical value for the volume is too low to reject $H_0$.

Testing $H_8$ Hoffstetter, de Werk, Crawley (2005) – Two can play at curve fitting with exotic formulae. The idea of interpolating from the data points contained in the original Celentano plot was intriguing, and we wanted to see if it is reproducible. It was reproducible, but given the huge extrapolations in Celentano, to do so involves “putting a micrometer at the end of a furlong.” For this reason, we fail to reject $H_0$.

Inspired by Hofstetter’s curve fitting, we made an exercise of taking the points where the original three curves intersect the grid, and then plotting them as log curves. While they do fall a little under the curving portion of the Celentano curves, the logarithmic trendlines continue rising above the flat portion of the Celentano curves, with very high $R^2$s. This exercise illustrates how overly precise curve fitting and high $R^2$ values from a fallacious set of assumptions can mislead.

Test of Sherwood-Capps Alternate Hypothesis:
Two Separate Curves for Capsules and Shuttle/Stations

![Graph showing log and power plots with equations and $R^2$ values](image)

FIGURE 18. Test plot of Sherwood and Capp’s dual curve hypothesis, using the empirical and historical data.
TESTING THE CREW SIZE HYPOTHESES

The three-crew size hypotheses proved testable using the empirical. For all three hypotheses, the sets of trendlines that showed the historic record turned out vastly different from their predicted value.

Testing $H_9$, Davenport, Congden, and Pierce (1963) – In the analysis, it was straightforward to plot the trend lines for all space missions and their spacecraft having one, three, and five crewmembers. It was not possible to plot a mission for 10 crewmembers as there have been none to date, and it would not be consistent to count Shuttle visits to ISS or ISS crew change-outs. Instead, the analysis plotted eight power curves to represent crews of one to eight members.

FIGURE 21 shows these results for Davenport, from which we fail to reject $H_0$. Only the curves for one, two, and three crewmembers sloped positively in the general direction of Davenport's graph, which perhaps is not surprising given that at the time in 1963, the authors found data and mission planning available only for those sizes of crew. However, none of these test curves follow Davenport's neat ordering, (where each larger one appears above the smaller one but more steeply sloped). As the crews grow larger, the curves stray even farther from Davenport, with negative slopes for the $n=6$ and $n=8$ and trendlines.

Testing $H_{10}$, Reynerson (2005) – We fail to reject $H_0$ because the empirical trendline plots decrease with the number of crew. If they had a higher $R^2$ Value, they would be steeper to reflect the large number of two and three crew missions at higher volumes, namely, all the Space Station missions. The Reynerson hypothesis makes no purchase on historical or empirical reality. FIGURE 22 displays these results.

Testing $H_{11}$ Kennedy, Toups, and Smitherman (2008) -- Because of the generality of Kennedy, Toups, and Smitherman in addressing all sizes of spacecraft and missions, it became necessary to develop a general solution to the crew size hypothesis. This solution would determine the empirical relationship between crew size and volume. This general solution would need to address whether there is such a relationship, and if so, whether there is an effect one way or the other. That means assessing whether either crew size or volume acts as the explanatory variable for the other. FIGURE 23 shows the graph for crew size as the independent variable $X$ and pressurized volume as the dependent variable $Y$. The authors do not provide any data or documentation to substantiate their three limit curves (tolerable, performance, preferred), so it is not possible to evaluate this vestige of Celentano with respect to the crew size hypothesis.

The curve in FIGURE 23 appears as a shallow but normal curve with a tail at the larger crew sizes. This empirical curve bears no resemblance to the predicted straight line in FIGURE 15. On the contrary, this curve suggests the opposite: that volume per person declines inversely to the number of crewmembers.

The general solution for the maxima-unique data reveals no relationship between increasing crew size and volume. The $R^2$ values are too low: 32 percent for crew size as $X$. Finally, nothing in these results suggests any demarcation between the short-, medium-, and long-term missions to which the authors allude.
Test of Davenport, Congdon, and Pierce's Hypothesis of Crew Size-Determined Volume

![Graph showing the relationship between crew size and mission duration, with R² values for different crew sizes.]


Test of Reynerson's Hypothesis that Spacecraft Pressurized Volume Increases Linearly with Number of Crew

![Graph showing the relationship between number of crew and pressurized volume, with linear and logarithmic fits.]

Testing the Functional Sizing Hypothesis

Testing $H_{12}$ – Schwartz (2005) -- Not Testable with currently available information. Fail to reject $H_0$. This hypothesis may suffer from a measure of naiveté insofar as it assumes that operational functions make up a significant portion of the spacecraft’s volume. In fact, structure, mechanisms, utility chases, and life support systems make up a much larger fraction of spacecraft mass and volume as overhead than operational functions do as a sizing driver.

Schwartz’s concept demonstrates clearly the importance of moving beyond raw pressurized volume to a more nuanced and complex comprehension of the architectural living and working environment in a spacecraft or space habitat. Marianne Rudisill makes exactly this point:

The space habitation community uses a series of terms to define types of spacecraft pressurized volumes. A primary concept is “net habitable volume,” the generally accepted “usable spacecraft volume” after subsystems, stowage, outfitting, etc. have been accommodated and design inefficiencies are considered (traditionally, “net habitable volume” has equaled ~60% of total pressurized volume (Rudisill et al, p. 2, 2008).

Discussion: Threats to Validity

An essential aspect of this research design and its results is to understand its limitations in the form of potential threats to validity. The main categories of the threats that apply to this research are Internal Validity, External Validity, Construct Validity of Cause, Construct Validity of Effect, and Statistical Conclusion Validity (Campbell,.Stanley,.1966; Cook, Campbell,.1979). First, however, a brief discussion of Face Validity is in order.

Face Validity

Face Validity is the prima facia evidence that an alternate hypothesis can make its case with a good probability of rejecting the null hypothesis. This study encounters three conditions of Face Validity: yes, no, and uncertain.

Celentano et al and their mission duration hypothesis enjoy positive face validity for their central theory that mission duration drives pressurized volume per crewmember. This face validity, perhaps more than any other factor is what attracts so many followers. Stated simply, the Celentano hypothesis at its core reflects common sense, and so do most of the variations upon it, even when the quantitative data does not support them.

The crew size hypotheses all fail to achieve face validity, perhaps reflecting a failure of common sense as much
as any quantitative measure. Try this thought experiment: You own a house with a living room, dining room, kitchen, two bathrooms and three bedrooms. You want to add a bedroom and perhaps a bathroom, increasing the "crew capacity" of the house by 33 percent, assuming that the new bedroom will replicate the average size of the existing ones. Will you also add 33 percent to the living room, dining room, and kitchen – or perhaps proportionally more area as Davenport, Reynerson, and Kennedy et al suggest? Certainly not, therefore these crew size hypotheses lack face validity.

Finally, Schwartz presents the intriguing but ambiguous functional operations hypothesis. Face validity for this hypothesis remains uncertain: she does not plainly demonstrate common sense, but neither does she violate it outright.

CONCLUSION VALIDITY

In discussing conclusion validity, there are two principal types of error to consider:

1. Conclude that there is no effect or relationship when there is.

2. Conclude that there is an effect or relationship when there is not.

Type 1 Error – The hypotheses evaluated in this survey did not exhibit any type 1 errors of finding no effects when they existed.

In general, the challenge to this analysis for Type 1 error concerns the low statistical power, because the main tool available for use with non-random data is the coefficient of determination (R²). The R² does not allow the researcher to use the inferential statistics that afford many more tools. While this analysis has a sufficiently large n of 252 human spaceflights to provide a rich database, this n does not necessarily translate into statistical power in the standard sense.

The four elements of statistical power are sample size, effect size, significance level, and power – the odds that the researcher can observe a treatment effect. In this research, there is a respectable sample size, but it is not a random sample, which means that tests for significance are not available. The effect size in terms of the range of volumes measured is quite large – ranging from about 1.25m³ per crewmember in Gemini to more than 200 times that much in the current ISS missions. The power in terms of observing the treatment effect is excellent – we know the pressurized volumes of each spacecraft and module precisely.

Low reliability of measures is a possible Type 1 threat. However, the measurement data for mission duration is amazingly precise, with timelines available to the minute for all flights and to the second for many. Measurement of pressurized volume is only slightly less precise, but still highly accurate. The issue of possible errors of reporting in the spacecraft literature comes under the Instrumentation section for Internal Validity.

Bearing in mind these components of statistical power, Type 1 errors do not pose a threat to the conclusions.

Type 2 Error – Many of the hypotheses evaluated in this survey suffer from Type 2 errors; they find effects and relationships where there are none including most of the Mission Duration and all of the Crew Size hypotheses. The Functional Operations hypothesis remains unclear in this regard.

In general, the main threat from a Type 2 error would concern "fishing" for data points or "cherry picking" from among the non-random data, without a reasonable argument. Conversely, this threat may incur the selective exclusion of non-random data-points without a reasonable argument. This study handled the potential Type 2 error by standardizing the data on the maxima for each series. It chose a way to standardize the data to use only the maxima for each spacecraft in terms of crew size and volume. This standardization on the maxima was particularly important for the Mir and ISS, for which not only do the crew sizes change, but the volume grows over time. This standardization applied to the complete data set of 252 spaceflights.

INTERNAL VALIDITY

The central question of internal validity is “Is there an effect, a relationship?” For the mission duration hypothesis, the results show a relationship of large effect. For the crew size hypothesis, the results are just as clear that there is no relationship. Beyond this central question, the key threats to internal validity include history, maturation, selection bias, experimenter bias, non-random sample, and instrumentation.

History – The history threat states spacecraft and space habitats have grown over time and that we would build bigger habitats over time anyway, regardless of mission duration. The analogy is that in the suburbs, people are building "McMansions" and are living in them longer than they did in smaller houses. The refutation of this argument is that these spacecraft and space habitats support longer missions, which reduces the launch costs per mission. The longer the same crew can stay on a space station, the fewer launches are required to keep the station staffed.

Maturation – The maturation threat states that we build larger spacecraft because over time we learned how to build bigger spacecraft. Although this threat may seem similar to history, it differs in the respect that it may take into account the beneficial effects of learning how to conduct long duration missions. It is also true that since the beginning of the space age in 1957, the spacefaring countries have learned to build bigger and better spacecraft of all varieties. However, the fact that the
maturation argument is true to that extent does not address how and why we use these larger spacecraft, which is to support crews for longer durations.

**Selection Bias** – The parsing of the data sets into different samples can skew the results. This potential issue arises in the question of whether to distinguish between different space vehicles. Sherwood and Capps make this distinction between “capsules” and all other spacecraft. There is a fascination in separating each class or model of spacecraft from the larger distribution into different sets and examining them for the R² value of the degree of variance in Y (volume) caused by the variance in X (mission duration). The wide range of results for the R² value raises a question about the extremes of this exercise. However, Herbert Simon, Nobel Prize winner in economics, explains:

> To explain the word distribution, we make some assumptions that might be thought outrageous if applied in detail, but that might be plausible if only applied in the aggregate.” (Emphasis added, Simon, 1989, p. 145).

Applying the analysis R² in the aggregate is vital to addressing the complete distribution of mission duration and spacecraft sizes, and it helps avoid the selection bias threat.

**Experimenter Bias** – The Celentano Curve and its underlying hypothesis have been cited and published in many more variations than the dozen that appear in the review section of this research. In many cases, the curve appears with little or no explanation. There is even one version that derives from Petro’s straight-line logarithmic plot that entered the Power Point ecology without the logarithmic scale markings on the axes. The selection of curves for this survey arose from seeking the hypotheses that advanced new and testable assertions or embodiments of the curves

**Non-Random Sample** – This data is empirical and historical, but not random. Nearly all historical data is non-random, but that is not an obstacle to quantitative historical research. There are some good statistical measures that do not require random data, and this research attempts to make the best use of them.

**Instrumentation** – Instrumentation means the ability to measure the data accurately and consistently. The instrumentation threat arises primarily in terms of how authors describe spacecraft volume. This survey found that authors use a variety of terms, often with differing definitions and protocols for actual measurement: living volume, living space, habitable volume, etc. The only quantity for which it is possible in almost all cases to find definitive engineering data is the pressurized volume within the pressure vessel. In some studies, the authors refer to free volume, habitable volume, or living volume. However, all these other metrics are highly subjective, some including or excluding equipment, seating, internal structures and sometimes even the crew members themselves based upon criteria that rarely are stated or obvious. In addition, there are some serious errors in the literature. For example, the original Apollo literature states that the Command Module has a crew cabin pressurized volume of 366 ft³ (10.34 m³) and that the “unoccupied” volume is 210 ft³ (5.94 m³) (Spacecraft Systems Operations Branch, 1969, p. 1-10). However, a NASA publication and website gives the CM pressurized volume as 6.17 m³; Wikipedia picked up this value and now it is all over the web. This study addresses the instrumentation threat by using only documented, original engineering values for pressurized volume in almost all cases.

**Time Measurement** – Although there appear to be some variations in how the US and Russian Space agencies measure mission duration, and that these metrics have changed over the years, these differences are so small as not to constitute an instrumentation threat.

**CONSTRUCT VALIDITY OF CAUSE**

The construct validity of cause threat asks whether the x that causes variance in y is really the “x” the alternate hypothesis says it is. The major causal validity challenge states that crew size is the first order determinant of volume, before mission duration. Connors, Harrison, and Akin (1985, p. 162) discuss this issue with regard to whether having more people allows the vehicle to have smaller volume per person (e.g., the transition from Mercury to Gemini). They quote TM Fraser on this question, who does not see crew size as dispositive. Their consensus is that that number of crewmembers as a driver of volume per person is not proven.

A second causal validity challenge states that functional requirements drive the volume. Much depends upon what the people who write the requirements include in their requirements documents. All too often, the developing organizations have not granted sufficient recognition or devoted enough effort to address human requirements for living volume.

**Generalizing Across Time** – This threat would imply that it might not be possible to draw the same results from a mission in the 1990s as one in the 1960s. This threat arises in plotting the data for the early test flights in first programs – notably Mercury, Vostok, Gemini, and Shenzhou. These (Mercury, Vostok) outliers had very short durations, that force an additional order of magnitude in the logarithmic scale. The Shenzhou V flight with one crewmember in 17 m³ and the 14-day Gemini 6 flight may pose problems as outliers that can skew the coefficient of determination. The defense against this threat is to apply the maxima-unique data, which uses the longest mission for each spacecraft for each crew size.
CONSTRUCT VALIDITY OF EFFECT

The major validity of effect threat concerns what the volume means in terms of meeting requirements. Cynthia Null, former Chief (Acting) of the Human Factors Research Division at NASA-Ames articulated this threat:

The only reason we say that the volume met crew requirements is that nobody died. The crew takes what we give them and suck it up, so we say it meets their requirements. (Personal conversations, June 2006)

This threat is the most important of all the threats to validity. We do not yet possess data to show how well a spacecraft design met the crew's needs over the mission duration. The best we can do is to apply this threat as a large asterisk to all claims that volume meets crew requirements: "we do not know if the volume actually met crew requirements beyond basic survival." Neither do we yet have a good documentation for how space agencies defined crew requirements historically for volumes mission type or mission duration.

A second validity of effect threat argues that Longer Duration has a different primary effect – more mass. It is easy to measure and quantify the mass of equipment, outfitting, and consumables necessary to support the crew over a given duration of time. However, like the "functional requirements" validity of cause argument, the computation of mass only addresses the "solid" portions of the spacecraft – not the free volume in which the crew will live. Certainly, there is a mass penalty associated with free volume in primary (pressure vessel) and secondary (decks, stand-offs, partitions), but it does not correspond with the living volume.

EXTERNAL VALIDITY

External validity means entails how widely it is possible to generalize from a result. Sherwood and Capps challenge generalizing from capsules to space stations and shuttles. Rudisill et al challenge generalizing from short missions (a week or less) to long durations up to a year or more. Thus, the external validity threat can apply to extrapolating too far beyond the actual data, as Celentano et al did, or it can mean generalizing to other types of situations, known as generalizing across effect constructs. This threat resonates with the underlying effect threat that we do not know if the spacecraft volume meets crew needs or requirements. It poses the limitation that it may not be possible to generalize from spacecraft or space habitats to other human habitations because spacecraft do not share reciprocity with the terrestrial analogs that researchers cite so often as relevant data sets. Stated simply, these results from crewed spacecraft may generalize only to other, future spacecraft, and even that may be subject to constraints.

SUMMARY OF THREATS TO VALIDITY

The outcome of this discussion is that the totality of the threats does not undermine the investigation nor does it invalidate the fundamental and universal result that pressurized volume per crewmember must increase in concert with mission timeline, up to any presently imaginable duration. The fundamental weakness arises in claims that the volume meets crew needs or that it can correspond to vaguely described levels of crew comfort or performance. The fact that the human spaceflight community cannot yet make those correlations -- and this lack may pose a threat to mission planning of various durations -- only points out the need for further research on this topic using direct observation and measurement of space habitats and the crews who live and work in them.

FINDINGS: ANSWERING THE QUESTIONS

This section collects the questions that informed this investigation, and attempts to answer them based upon the findings.

THE QUESTIONS IN THE APPROACH

• What do we know?

The evidence does not support many of the effects claimed over the past 44 years.

• What do we know that is true?

Stated simply, habitable volume requirements increase with mission duration; it neither passes through zero nor levels off at some speculative upper limit.

• What is important?

It is important to understand the area "between the curves" as the domain where design can be most effective.

• What does it mean to us?

These results give us a much better metric to apply in assessing spacecraft and mission design.

• What can we do with this knowledge?

It can lead to a rigorous methodology for a quantifiable and testable basis to evaluate Space Architecture design.
THE QUESTIONS AFTER THE ANALYSIS

1. Has the evolution of spacecraft from Voskhod and Mercury to the International Space Station followed the path predicted by the Celentano Curve?

Yes, to a remarkable extent it has, although the upper ranges will rise to about an order of magnitude higher than Celentano’s 20m$^3$.

2. Specifically, does the volume prediction follow a curve that levels out and approaches a horizontal limit, parallel to the X-mission duration axis?

The curve does not level out, but in the logarithmic representation of the dependent variable, volume, the slope lessens.

3. Which curve pattern best fits the data under each hypothesis?

The two curves, power and log curves both represent an aspect of reality in the dependent variable. The slightly higher R-squared value for the power curve does not mean that the power curve is the correct or even best representation.

4. Can we evaluate this “best fit” accurately by the R-Squared Value metric or do we need to test for correlation significance among the curves?

The R-squared value plus the graphical form of the curve are the best indicators of what variance the curves represent and how well they represent it. Testing for “correlation significance,” did not emerge as a weakness, and so is probably not necessary given the inherent difficulty in doing so.

5. Does this curve pass through the origin of otherwise show no minimum value?

If the curve passes through zero, the volume is no longer that of a crewed spacecraft, so the question is moot.

6. How does the aggregation or disaggregation of the data affect the results?

This question takes the inquiry into the nether regions of the statistics. As shown in TABLE 6, the tricks of aggregating or disaggregating data can alter the results ($R^2$) by orders of magnitude. The challenge is how to handle the data in an impartial and objective way to avoid this kind of skewing.

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?

No, there was not sufficient information available initially, nor was there any substantive result to confirm the conjecture of these three limits or levels.

CONCLUSION

This empirical and historical survey shows that there is no single or simplistic answer for predicting pressurized spacecraft volume as a function of mission duration. The findings reveal that the historical data set exhibits the characteristics of both a logarithmic and a power curve. The common and dispositive characteristics of these curves are that:

- Spacecraft pressurized volume per crewmember increases as a direct function of mission duration. Mission duration is the independent or explanatory variable to the volume as dependent variable. Crew size and functional operations may exert secondary effects upon volume, but these effects have yet to receive carefully documentation.

- The minimum historical spacecraft size in terms of volume per crew member are stated in the literature variously as the accommodations of the Mercury, Gemini, Apollo, Voskhod, Vostok, and Soyuz spacecraft. It does not signify which of these spacecraft researchers or designers select as a minimum because they are all so small that the differences in size are statistically unimportant.

- These results tend to support the Sherwood and Capps hypothesis that small capsules are fundamentally different from larger vehicles such as shuttles and space stations. This hypothesis states that analysis of volumetric requirements for the capsules (particularly the Orion Crew Exploration Vehicle) belongs in a different data set presented on a different curve than much longer duration and larger volume space stations and shuttles.

- The pressurized volume curve rises and does not level off, but keeps rising as extrapolated out to about 1000 days, the nominal length of a Mars mission. The difference in the upper slope between the power curve and the log curve is de minimus.

- The difference is not significant between a logarithmic curve plot and a power curve plot of the volume vs. mission duration data. They represent the same phenomenon, just portraying different but overlapping portions of the variance in both volume and mission duration.
The crew size does not provide an explanatory variable for volume. The analysis revealed no relationship between the number of crew and volume per crewmember.

As the space habitability and architecture community prepares for the second half-century of human spaceflight, it must progress beyond well-intentioned but speculative predictions for architectural, outfitting, and volumetric requirements. Instead, the space habitability community will need to develop sound quantitative models based upon documented empirical realities. For future spacecraft sizing studies, it will be vital to start from first principles with functional, mission, and operational requirements, translated into volumetric units of analysis and design. This approach may incorporate a Bayesian analysis to help avoid the Type 2 Error of “false positives” by better separating the factors that are acting from those that are not acting in driving form, size, shape and volume.

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CONTACT
Marc M. Cohen, Arch.D
Space Systems Business Segment
Northrop Grumman Integrated Systems
One Hornet Way, MS 9QS4/W5
El Segundo, CA 94025-2804 USA
+1 310 332-0819
marc.cohen@ngc.com

ADDITIONAL SOURCES


DEFINITIONS, ACRONYMS, ABBREVIATIONS

AIAA: American Institute of Aeronautics and Astronautics

ASCE: American Society of Civil Engineers

Coefficient of Determination ($R^2$): A measure of the variance in the dependent variable $Y$ that the variance in the independent variable $X$ can explain.

CEV: The Orion Crew Exploration Vehicle

CM: Apollo Command Module


$x^e$: Exponential or power curve.

ISS: International Space Station.

LEO: Low Earth Orbit.

LM: The Apollo Lunar Module

LSAM: Lunar Surface Access Module from the ESAS Report

MTV: Mars Transfer Vehicle

$H_0$: The null hypothesis

$H_1,...,n$: The alternate hypothesis or hypotheses.

Hypothesis, Null: The null hypothesis always states that there is no effect of the independent variable upon the dependent variable.

Hypothesis, Alternate: The alternate hypothesis states that the independent variable has an effect on the dependent variable.

JPL: NASA Jet Propulsion Lab

JSC: NASA Johnson Space Center

LaRC: NASA Langley Research Center

$\ln(x)$: Natural Log of $X$.

MIT: Massachusetts Institute of Technology

MSC: Manned Space Center, the original name of JSC.

MSFC: Marshall Spaceflight Center


NASA: National Aeronautics and Space Administration

NASA CR: NASA Contractor Report

NASA SP: NASA Special Publication

NASA TM: NASA Technical Memorandum

Natural log curve: A curve based on a natural logarithm to represent the variance in the dependent variable.

NIST: National Institute of Standards

Polynomial curve: A curve based on a polynomial expression to represent the variance in the dependent variable.

Power curve: A curve based on an exponential function to represent the variance in the dependent variable.

SD: Standard Deviation

SSerr: Sum of the Squares of the Error of the Mean.

SSreg: Sum of the Squares of the Regression to the Mean.

SStot: Total Sum of the Squares.

Type 1 Error: Find no effect when there is one, e.g. a false negative

Type 2 Error: Find an effect where there is none, e.g., a false positive.

X: Concerning the $R^2$ value is the independent or explanatory variable.

Y: concerning the $R^2$ value is the dependent or explained variable.