Activity-Based Habitable Volume Estimating for Human Spaceflight Vehicles

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Abstract—Accurate estimation of required working volumes is a vital aspect of the design process for any vehicle involving humans. This is all the more important when such a vehicle must serve as the crew's sole habitable volume during a mission of any duration in the harsh environment of space.[1][2]

The key to accurate estimation of required crew volumes is to properly analyze the volume necessary to perform the entire range of tasks that will be required of the crewmembers.

This paper discusses activity-based estimation techniques and methodologies that lead to the determination of realistic, justifiable, and cost-effective habitable volumes for new spacecraft, which are physically safe and promote sustained behavioral health.

The categories of activities considered include command and control, typical mission accomplishment, scientific, exercise/recreational, medical/health maintenance, food preparation/eating, group gatherings/entertainment, sleeping/privacy, clothing changes, EVA preparation, and personal hygiene activities. Each activity is assigned a volume derived from anthropometric "first principles" using position and motion studies together with accepted industry standards for crewmember sizes and ranges of motion. A matrix of the activities for each mission element is developed to show "nesting" or co-location possibilities. Where groups of activities can be reasonably nested, the activity requiring the largest volume is used for the habitable volume calculation, while the smaller nested volumes are accommodated in the process.

Using these techniques and methodologies consistently results in substantial reductions in volume (thus mass) for each of the vehicles considered when compared with the recommendations based on NASA-STD-3000 [1].

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1. INTRODUCTION

As NASA embarks on a new generation of spacecraft to accomplish American space exploration goals, and launch costs per unit mass continue to climb, the question of crew volume requirements seems worthy of revisiting. Space transportation vehicles as well as habitats must be designed to accommodate the wide anthropometric range of potential female and male crewmembers performing routine, contingency, and emergency operations in a variety of settings in order to crew safety and effectiveness.

The team of space life science engineers at Paragon Space Development Corporation conducted an expert analysis of historical data and existing requirements to develop a preliminary report on the volume necessary to meet the mission requirements of future human spacecraft. The preliminary analysis was based on a hypothetical vehicle capable of a maximum 15-day mission duration and a maximum crew of seven astronauts [2].

2. DISCUSSION

For this study, we estimated crew volumes for generic nominal, contingency, and emergency operational scenarios based on the 95th percentile American male crewmember (representing the largest specimen at approximately 1.93 meters or 6'4" tall, passively occupying about 0.102 cubic meters of volume). The following categories of functional activities were considered:

- command & control
- mission-related
- scientific

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[1] 978-1-4244-2622-5/09/$25.00 ©2009 IEEE
[2] IEEEAC paper #1098, Version 19, Revision j. Updated 2008:12:12.

- exercise/recreation
- medical and health maintenance
- passive/sleeping
- food preparation/meals
- group gatherings/meetings
- personal privacy
- clothing don/doff
- personal hygiene
- extravehicular activity (EVA) preparation
    - spacesuit don/doff
    - pressurization check
    - pre-breathe

Table 1 below identifies the specific types of tasks that fall within each of these functional categories, with the exception of EVA preparation, which is treated separately.

Each of these categories of activities was assessed for the amount of volume they would require, as well as the maximum number of crewmembers to be engaged simultaneously in that particular activity. Table I is a compilation of the required space needs that we derived for each activity.

The activity envelope volumes were derived from anthropometric "first principles", involving fundamental body position and motion studies, using NASA standards for astronaut sizes and ranges of motion [1]. Noting also that to some degree these NASA standards may be biased for larger shuttle and space station type spacecraft, a historical overview of U.S. and Russian spacecraft was also used to corroborate the volumes derived from our study [2].

It is important to note that any use of historical vehicle volumes does not in and of itself result in advisable volumes for future spacecraft. Habitable volume may be viewed as a function of mission duration and crew size, but this function is in reality a reflection of mission objectives and the activities that are actually to be performed by the crew within the spacecraft. Therefore crewmember intra-vehicular activities should be the main driver for spacecraft habitable volumes, rather than simply historical spacecraft volumes used for missions with similar durations and numbers of crewmembers.

In order to establish a range of limits on our analysis, at the lower extreme compatible categories of functional activities could "time-share" space in "nested" volumes, which would house all required equipment and furnishings associated with the nested group of compatible categories. At the higher extreme, each category of functions could take place in a volume specifically and solely dedicated to that category.

Using the worst case design scenario that no functional activity categories are nested, estimated volume envelopes required for individual categories of functions were summed to determine an upper limit on the total free crew movement volume necessary to accommodate all activities for a maximum crew of seven on a 15-day mission. This total maximum volume was determined to be 61 cubic meters.

A lower limit on the total free crew movement volume was established by analyzing which types of functional activities could be considered compatible enough to share space in coincident volumes, and summing the volumes of the shared areas. As a starting point, we designated four Common Activity Areas: the Mission Area (comprised of overlapping Mission Areas A and B), the Health Maintenance Area, the Wardroom/Galley Area, and the Privacy Area.

The Mission Area would house equipment to accommodate command and control in Mission Area A, and mission-related as well as scientific activities in Mission Area B. Mission Areas A and B would share crew working volumes, but little if any equipment real estate, since safety-critical piloting activities require undivided focus of attention on cockpit resources. The Health Maintenance Area would house the necessary equipment for exercise and recreation, medical and health-related, and sleeping or passive activities. The Wardroom/Galley Area would be furnished to accommodate food preparation and meals, as well as group meetings and entertainment. The Privacy Area would provide a personal one-person enclosure for hygienic maintenance, waste management, changing clothes, and other activities requiring individual privacy.

Extravehicular activity is handled as a special case in this analysis, depending upon whether EVA is considered to be a nominal or contingency capability. If EVA is a nominal capability for the spacecraft under consideration, a two-person airlock with a minimum volume of 5.03 cubic meters is required. Per our activity-based analysis, this volume is necessary to accommodate two crewmembers donning or doffing spacesuits, as well as performing safety checks for each other. The spacesuits would also be stowed in the airlock between EVAs. If EVA is considered to be solely an "off-nominal" or contingency capability, the EVA functions (i.e., don/doff, safety checks, suit stowage) would have to be nested within one of the other "Common Activity Areas", such as Mission Area B or the Health Maintenance Area.

The estimated volume for each Common Activity Area was determined by identifying the housed activity requiring the greatest amount of volume.

Area	**Activities Analyzed**	**Activity Requirement**	**Results in M, or m^3**
Mission Area (MA) (mission area A)	**Command/Control** piloting flight/attitude control communications atmospheric flight emergency/abort procedures flight computer activities navigation monitor displays & controls thermal/power control station-keeping	30 inches lateral 36 inches depth 60 inches length/height 38 cubic feet per crew Maximum of 3 crew Total volume: 114 cubic feet	0.76 0.91 1.52 **1.06** **3.18**
(mission area B)	**mission-related** payload interaction monitoring equipment handling **scientific** research experimental activities monitoring measurements	50 inches lateral 36 inches depth 80 inches length/height 83 cubic feet per crew Maximum of 3 crew Total volume: 250 cubic feet	1.27 0.91 2.03 **2.36** **7.08**
Health Maintenance Area (HMA)	**passive/sleeping** rest relaxation	28 inches lateral 31 inches depth 60 inches length/height 30 cubic feet per crew Maximum of 7 crew Total volume: 210 cubic feet	0.71 0.79 1.52 **0.85** **5.95**
	medical/health maint. physical examinations physiological tests physiological measurements treatments therapies	30 inches lateral 36 inches depth 60 inches length/height 38 cubic feet per crew Maximum of 3 crew Total volume: 114 cubic feet	0.76 0.91 1.52 **1.06** **3.18**
	exercise/recreation treadmill running rowing machine bicycle ergometer resistance training games	55 inches lateral 40 inches depth 85 inches length/height 108 cubic feet per crew Maximum of 4 crew Total volume: 432 cubic feet	1.40 1.02 2.16 **3.06** **12.24**
Wardroom/Galley (WG)	**food preparation/meals** eating/drinking cooking clean up **group gatherings/meetings** briefings entertainment	30 inches lateral 36 inches depth 60 inches length/height 38 cubic feet per crew Maximum of 7 crew Total volume: 114 cubic feet	0.76 0.91 1.52 **1.06** **7.42**
Privacy Area (PA)	**personal privacy** personal time **clothing don/doff** changing clothes **hygiene** waste elimination bodily cleansing personal toiletry activities	50 inches lateral 36 inches depth 80 inches length/height 83 cubic feet per crew Maximum of 1 crew Total volume: 83 cubic feet	1.27 0.91 2.03 **2.36** **2.36**

Table 1: Breakdown of Activity Areas & Requirements

In the case of the Mission Area, the volume-driving activities were predicted to be both the science- and mission-related activities, each at 2.36 cubic meters per crewmember involved, and a maximum of three crewmembers participating at one time, or a total of 7.08 cubic meters. In the case of the Health Maintenance Area, the volume-driving activities were expected to be exercise and recreation, at 3.06 cubic meters per crewmember involved, and a maximum of four crewmembers participating at one time, or a total of 12.24 cubic meters. In the case of the Wardroom/Galley Area, each activity was forecasted to require the same volume of 1.06 cubic meter per crewmember involved, and up to seven crewmembers participating at one time, or a total of 7.42 cubic meters. In the case of the Privacy Area, the volume-driving activity was predicted to be donning and doffing of clothing, at 2.36 cubic meters per crewmember involved, and just one crewmember involved at a time, for a total of 2.36 cubic meters. The total volume of the summed Common Activity Areas derived in this manner sets a lower limit on the crew movement volume at about 29 cubic meters.

On a historical note, this lower limit was reduced even more on the Gemini and Apollo spacecraft by combining the Mission, Health Maintenance, Wardroom/Galley and Privacy Areas. However, applying such an approach today would require many deviations from the current NASA-STD-3000 requirements [1].

Thus, our analysis for a 15-day mission with a crew of seven produces a range of free crew volume values. At the lower end, we have a limit of 29 cubic meters for a design incorporating nested or time-shared functions. At the high end, we have an extreme of 61 cubic meters for a design using separate dedicated functional spaces.

As a sanity check, we plotted "Volume versus Mission Duration" (Figure 1) and "Volume versus Number of Crew" (Figure 2) values for historical manned transport-to-orbit vehicles, to see where our hypothetical mission duration and crewmember driving requirements would fall on a trendline. For our hypothetical mission's 15-day duration, the volume estimated using the historical trendline would be 16 cubic meters, and for our hypothetical mission's crew of seven, the volume estimated by the trendline would be 55 cubic meters. Based on this sanity check, our estimated volume limits are within a reasonable range but may be slightly high. This can be understood by the fact that the trendlines used are heavily influenced by the multiple small spacecraft of the early spaceflight era. It can also be argued that the current Shuttle Orbiter crew volume specifications influence our higher end limit since we also used NASA-STD-3000 values in that analysis [1][2]. Given this set of circumstances, we recommend that the lower limits shown by the trendlines should be taken as the *absolute minimums* in easing the current rather extravagant crew volume standards.

On a normalized basis (i.e., looking at volume *per crewmember* vs. mission duration), the historical trendline shown in Figure 3 would estimate a volume per crewmember for a 15-day mission of about 3.6 cubic meters. For a seven-person crew, this would dictate a crew volume of about 25.4 cubic meters, which is somewhat lower than the lower limit of 29 cubic meters determined by our analysis.

It is important to remember that our analysis assumes a scenario of accommodating seven crewmembers for a 15-day mission duration. The graphs contained in Figures 1 through 3 show trendlines that illustrate the effect of these assumptions within the historical context and allow for extrpolation of volumes based on different mission scenarios. Because the trendlines are always increasing in slope, as the duration and number of crewmembers numbers are increased, the effects on volume are more dramatic as the numbers get higher.

However, this is largely due to the curve-skewing effect of the Shuttle Orbiter's relatively large crew volume, and is not supported by a sensitivity analysis using our activity-based evaluation method. For example, if we increase the number of crewmembers in our analysis to 8, the volume increases by 3.42 cubic meters. If we reduce the crew size to 6, a decrease in volume of 4.13 cubic meters is expected. But this is mainly due to the granularity of the data and the split of even and odd numbered groups that do tasks such as exercise. If we reduce the crew size from 6 to 5, the drop in volume was found to be 3.42 cubic meters, the same as the volume difference between a crew of 8 and a crew of 7.

There may be a lower limit to the reductions, as it is expected that the minimum crew complement would be three. This would account for Commander, Pilot and one of the following: a) mission specialist; b) flight engineer; c) scientist.

3. SUMMARY AND CONCLUSIONS

The activity-based volume analysis described in this paper shows that crew volume requirements for the hypothetical 7 crew, 15-day mission would be 29.0 cubic meters. The 29 cubic meter volume can be accommodated and still meet the requirements of NASA-STD-3000 and other NASA documentation [1]. A lower value indicated by historical trends could be 16 cubic meters, which while highly desirable to reduce vehicle weight, would require changes to current NASA crew volume requirements, and more importantly, adversely impact crew performance.

The biggest drivers of crew volume requirements are the activity profile (which, as mentioned previously, is associated with but not determined by mission duration) and total crew size.

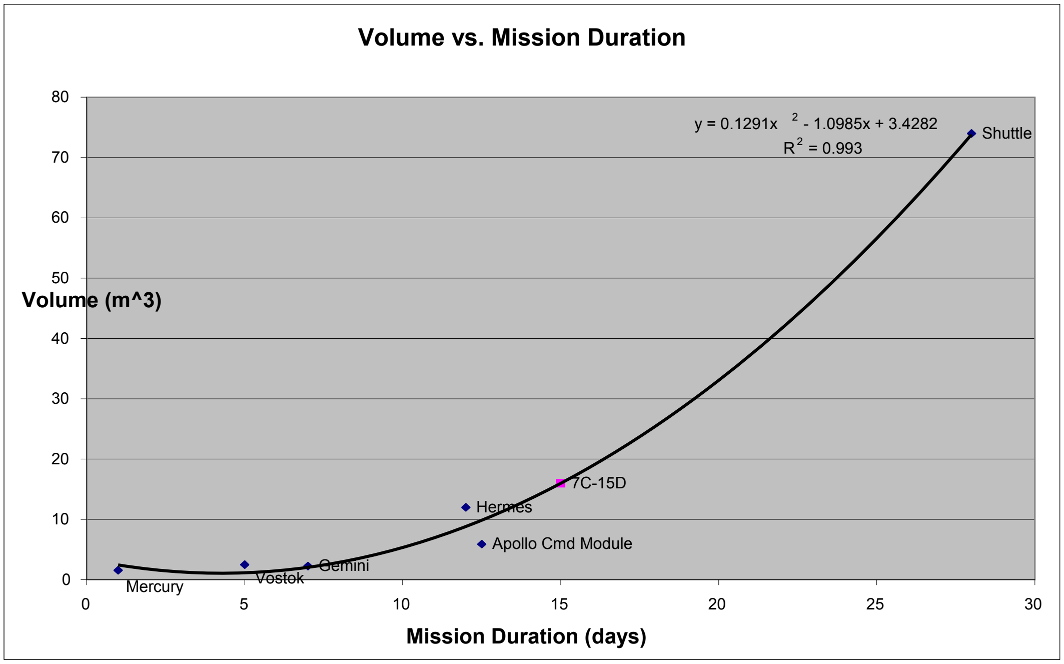

Figure 1: Volume vs. Mission Duration. This graph shows volume vs. duration for transfer-to-orbit spacecraft. Note the equation for use for other durations.[3] "7C-15D" = 7-Crew/15-Day hypothetical mission.

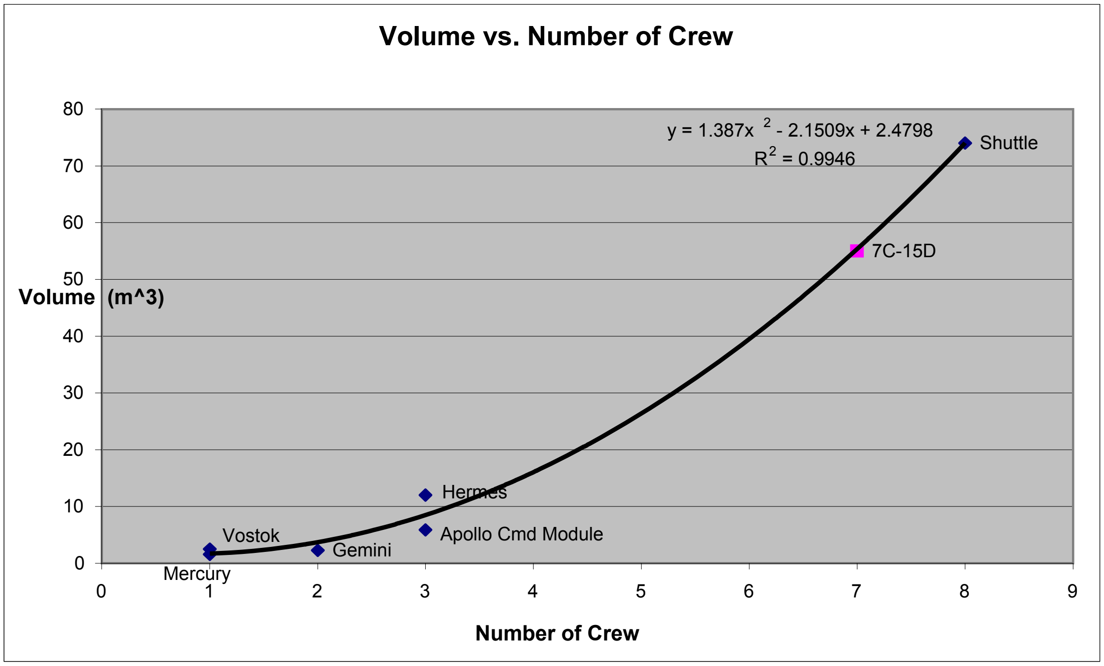

Figure 2: Volume vs. Number of Crew. This graph shows the volume vs. number of crew for transfer-to-orbit spacecraft. Note the equation for use for other total crew numbers.[3] "7C-15D" = 7-Crew/15-Day hypothetical mission.

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[3] In all our plots of historical data, we determined that a 2nd order polynomial curve fit would more accurately reflect the trends, rather than the typical straight-line fit.

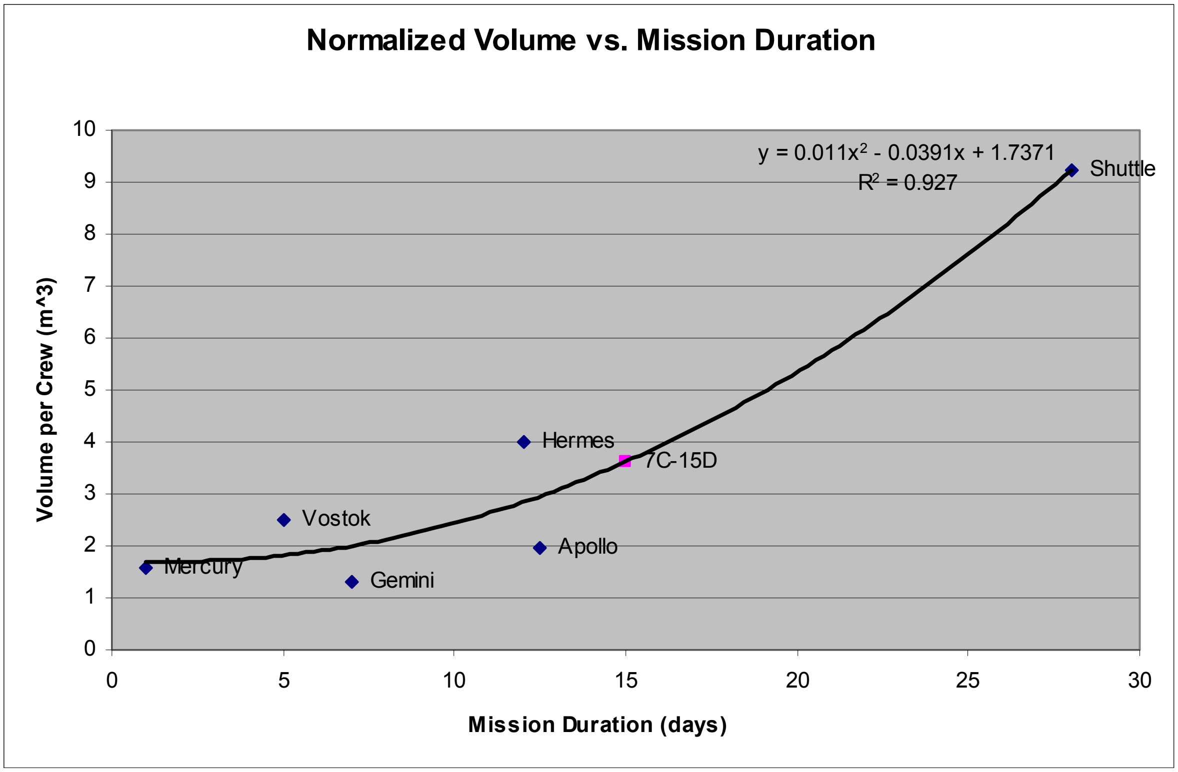

Figure 3: Normalized Volume vs. Mission Duration. This graph shows the normalized volume vs. duration for transfer-to-orbit spacecraft. Note the equation for use for other durations.[3] "7C-15D" = 7-Crew/15-Day hypothetical mission.

One of the main advantages of the activity-based approach to crew volume estimating is that it can easily be applied to diverse vehicles supporting missions of varying durations and crew sizes. To reiterate, this approach is driven by mission objectives and the associated activities to be performed to accomplish these objectives. Thus, crew volumes estimated for longer duration missions and/or bigger crews are simply a reflection of the larger set of activities associated with the longer mission and/or increased crew numbers.

Table 2 summarizes the minimum volume allowances for each functional activity area on a per-crew basis for ease of applying this activity-based analysis to missions and/or vehicles with various crew sizes. Of course, the number of crew required to simultaneously use each particular area, as well as "nesting" and "time-sharing" of functional areas, must still be expertly assessed in order to properly calculate the total required crew volumes [3].

Furthermore, results from this and any other human vehicle design process must always be verified using mock-ups and models in higher and higher fidelity as the spacecraft design progresses.

On-going work supporting such human vehicle design processes has shown that the activity-based approach to crew volume estimating proves to be justifiable in the arena of astronaut interfaces and operations.

FUNCTION	***m^3 per crew***
Command/Control	*1.06*
Payload/Science	*2.36*
Wardroom/Galley	*1.06*
Private Hygiene	*2.36*
Passive/Sleeping	*0.85*
Exercise Area	*3.06*
Health/Medical Area	*1.06*
EVA Preparation	*2.51 (minimum of 2 crew required)*
Table 2:	***Summary of minimum per-crew volume allowances for functional areas.***

REFERENCES

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BIOGRAPHIES

Ms. Leslie Wickman, Ph.D., *is currently director of the Center for Research in Science (CRIS) at Azusa Pacific University (APU), as well as a Sr. Engineering Specialist at The Aerospace Corporation, and an adjunct research scientist with the RAND Corporation. Some of her current research projects include fighter pilot training issues, future human spaceflight vehicles, human factors problems for extreme environments, and a water reclamation research project. For more than a decade Wickman was an engineer for Lockheed Martin Missiles & Space in Sunnyvale, Ca., where she worked on NASA's Hubble Space Telescope and International Space Station Programs, receiving commendations from NASA for her contributions and being designated as Lockheed's Corporate Astronaut. As director of CRIS at APU, Wickman's responsibilities include addressing the relationship between science and theology. She has lectured extensively around the world on satellite servicing, astronaut operations, mission planning, and space physiology issues. She is also a dedicated athlete who plays competitive beach volleyball and football. Wickman holds a master's degree in aeronautical and astronautical engineering and a doctoral degree in human factors and biomechanics, both from Stanford University. She graduated magna cum laude from Willamette University with a bachelor's degree in political science.*

A founder of Paragon, ***Mr. Grant Anderson*** *has 23 years experience designing power, thermal and life support systems for human rated spacecraft. He is presently the Program Manager for the Paragon Lockheed Martin Orion program. He and his team are responsible for interface control and vehicle schematics, as well as specific design responsibility for the service module radiators and overall spacecraft ECLSS tubing. He is currently the Principal Investigator for Diver Breathing and Isolation Systems that allow Navy divers to work in contaminated water. This new diving technology is currently undergoing full up dive testing. He is the PI for the development of a structurally integral CEV service module radiator technology, as well as single loop thermal control system fluids. The fluids are presently being tested in Paragon's lab. Previous experience includes being Project Design Lead and Cost Account Manager for the ISS Solar Array Program at Lockheed Martin, the largest solar arrays ever built; Cabin design and build of the first CEV mockup, now on display at Johnson Space Center; Engineering lead for experimental flight hardware on five shuttle flights, two Mir missions, a Russian Progress, and the first commercial payload on ISS; he also lead the engineering on a flight qualified Micro-gravity Cell Culture System. Mr. Anderson holds two degrees from Stanford University in Mechanical Engineering (BS) and Aeronautical and Astronautical Engineering (MS) and is a registered Professional Engineer.*