46th International Conference on Environmental Systems
10-14 July 2016, Vienna, Austria
ICES-2016-138

A Tale of Two Chambers: Iterative Approaches and Lessons Learned from Life Support Systems Testing in Altitude Chambers

Gianluca Callini[1]
Jacobs Clear Lake Group at NASA Johnson Space Center, Houston, Texas, 77058

With a brand new fire set ablaze by a serendipitous convergence of events ranging from a science fiction novel and movie ("The Martian"), to ground-breaking recent discoveries of flowing water on its surface, the drive for the journey to Mars seems to be in a higher gear than ever before. We are developing new spacecraft and support systems to take humans to the Red Planet, while scientists on Earth continue using the International Space Station as a laboratory to evaluate the effects of long duration space flight on the human body. Written from the perspective of a facility test director rather than a researcher, and using past and current life support systems tests as examples, this paper seeks to provide an overview on how facility teams approach testing, the kind of information they need to ensure efficient collaborations and successful tests, and how, together with researchers and principal investigators, we can collectively apply what we learn to execute future tests.

Nomenclature

< = Less than
APIST = Ambient Pressure Integrated Suit Test
ARS = Air Revitalization System
CAMRAS = Carbon Dioxide and Moisture Removal Amine Swingbed
CEO = Chief Executive Officer
CH_4 = Methane
CHC = Carbon Dioxide and Humidity Control Swingbed
CHX = Condensing Heat Exchanger
CO_2 = Carbon Dioxide
COO = Chief Operating Officer
CTSD = Crew and Thermal Systems Division
ECLSS = Environmental Control and Life Support System
Ft/ft = Foot (unit of measure)
HCTD = Human Certified Test Director
HESTIA = Human Exploration Spacecraft Testbed for Integration and Advancement
HMS = Human Metabolic Simulator
iPAS = Integrated Power, Avionics and Software
IPIST = Interim Pressure Integrated Suit Test
ISRU = In Situ Resource Utilization
ISS = International Space Station
JSC = Johnson Space Center
kPa = Kilopascal
m = Meter
O_2 = Oxygen
Pa = Pascal
PI = Principal Investigator
PIST = Pressure Integrated Suit Test

---

[1] Test Director, NASA Johnson Space Center – Crew and Thermal Systems Division; 2101 NASA Parkway, Mail Code: EC4, Houston, Texas 77058

PM = Project Manager
psia = Pounds per square inch absolute
RP-LiOH = Reactive Plastic Lithium Hydroxide
TCRS = Trace Contaminant Removal System
TBD = To Be Determined
TD = Test Director
UPIST = Unmanned Pressure Integrated Suit Test
VPIST = Vacuum Pressure Integrated Suit Test
WBS = Work Breakdown Structure

I. Introduction

TO the untrained eye, it may look like this all began yesterday, but the truth is that we have been going to Mars for a while. The journey that development hardware takes before its final incarnation in a fully integrated spacecraft can take years – sometimes decades or more – as is the case for the Orion environmental control and life support system (ECLSS) that has been in development for the better part of a decade.

Life support systems are not just for when everything goes according to plan. What happens when things go wrong? Through the Pressure Integrated Suit Test (PIST) series, NASA personnel at the Johnson Space Center have been characterizing the behavior of a closed loop system for life support in the event of cabin depressurization, with test subjects wearing developmental space suits. This is a very exciting time, as we are now faced with many “firsts” – testing hardware and people in ways that have not been tested before This must be how the Apollo era engineers and scientists felt. Not since then have there been so many “firsts” in the area of human in the loop vacuum testing. This kind of crewed testing – one of the most hazardous activities we perform on the ground at JSC – requires an iterative approach, as each new iteration increases in complexity (and often, hazards). One does not simply trust an uncertified life support system to keep test subjects alive in a vacuum chamber, while donning a modified space suit used in a way it was not initially designed to operate. Steps were taken to characterize the system, protocols were written, hazards were mitigated, and lessons were learned. The PIST series, conducted in the Crew and Thermal Systems Division (CTSD) 11-Ft chamber, started with unmanned test precursors before moving to a human-in-the-loop phase, and continues to evolve with the eventual goal of a qualification test for the final system that will be installed on Orion.

Much “younger”, but in many ways related, is the fledgling Human Exploration Spacecraft Testbed for Integration and Advancement (HESTIA) program: an effort led by the JSC Engineering Directorate to research and develop technologies that will eventually work in concert to support habitation on an extraterrestrial planet, such as Mars. September 2015 marked the first unmanned HESTIA chamber test, which integrated three proven technologies into the CTSD 20-Ft chamber simulating a habitat, with the goal of characterizing how each affected the other in a closed environment. Like PIST, HESTIA will eventually culminate in crewed testing, but it is important to approach this effort rigorously. Unlike PIST, HESTIA can benefit from the lessons learned from a modern-era large scale crewed test that is farther ahead in its development and operational life cycle. PIST will help us get to Mars. HESTIA will help us live there. Both test series are now ongoing.

Human-in-the-loop testing is a very high-stake undertaking. CTSD has developed checklists, guidelines and and overall approach overtime to ensure successful tests. When processes are not followed or are modified, problems may arise down the line. Let’s take a look at the two test activities chosen for this paper, and discuss what we have learned from them to make future tests even smoother.

This is a tale of two chambers.

II. The Setting - Chambers

A. 11-Ft Chamber

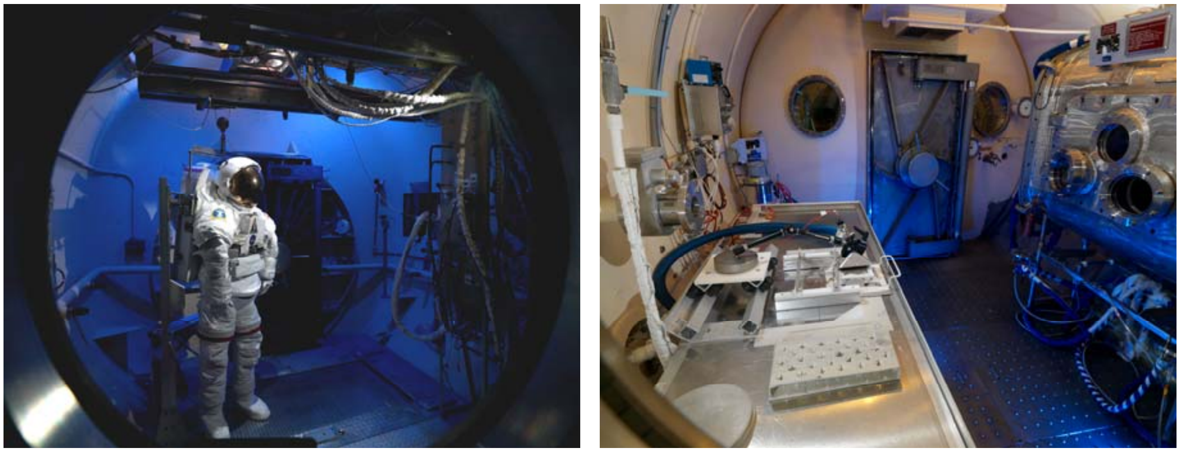

Figure 1. 11-Ft Chamber. Inner Lock (L) and Outer Lock (R)

The 11-Ft chamber (Figure 1) is a 11.0 ft x 19 ft (3.3 x 5.8 m), dual airlock pressure vessel used for human testing at reduced pressure, and space suit development and certification at vacuum. It features a treadmill and a weight relief system for suited operations. The outer lock of the chamber is home to the Dual Glove Box/2-Ft chamber complex, a thermal vacuum chamber used for extravehicular activity tool development and verification. The 11-Ft chamber was selected to house the PIST for a number of reasons: its ability to be depressurized to vacuum, the existing test infrastructure to support a hazardous human-in-the-loop test, and its approximate volume to that of the Orion capsule for the cabin-mode tests where that is a desired variable.

Figure 2. 20-Ft Chamber

B. 20-Ft Chamber

The 20-Ft chamber (Figure 2) is a large, three-level vacuum chamber that has been used over the years for a number of crewed habitability tests. It has served as a sea-level test bed for Space Station and advanced environmental control and life support systems testing. This chamber was chosen for HESTIA due to its size, ability to accommodate people and hardware and, for future iterations of this test, its ability to be depressurized.

III. The Storylines – Tests

While extremely different in scope and technologies used, and at very different points in their life cycle, both PIST and HESTIA have many commonalities: both are large-scale tests utilizing development hardware, both are multi-year iterational test series, and they both require (or in HESTIA's case, will require) human test subjects for the more realistic scenarios.

The actual data analysis and test results are outside the scope of this paper, which aims at capturing the processes and pointing out lessons learned from a facility test standpoint. However, shortenened overviews of the tests are discussed in the following sections, for better awareness.

A. PIST Background and Overview

The Orion Program baselined the Carbon Dioxide and Moisture Removal Amine Swing-bed (CAMRAS) as the technology for atmospheric carbon dioxide (CO_2) and humidity removal for the Environmental Control and Life Support System. In August 2006, personnel at the NASA Johnson Space Center Crew and Thermal Systems Division began testing CAMRAS units through a number of tests under different metabolic loads and cabin pressure environments. Following these initial tests, the PIST test series began in 2011 with the Ambient Pressure Integrated Suit Test (APIST) manned test, followed by the Intermediate Pressure Integrated Suit Test (IPIST), and the Unmanned Pressurized Integrated Suit Test (UPIST). APIST was conducted to evaluate the performance of the CAMRAS when humans were introduced in the loop by incorporating up to two test subjects wearing pressure suits. IPIST tested the CAMRAS with human test subjects in pressure suits at sea level and 10.2 psia (70.3 kPa) cabin pressure and varying suit pressures. The series progressed with UPIST, which tested the CAMRAS with unmanned suits at full vacuum. VPIST (Figure 3) then merged the lessons learned in the prior tests series, and conducted manned testing at vacuum cabin pressure (300 microns/40 Pa or lower). While at vacuum pressure, the test evaluated the new development Carbon Dioxide and Humidity Control (CHC) swingbed (in place of the older CAMRAS unit), and new Orion hardware, such as a development fan to circulate breathing gas, a development regulator to supply oxygen as needed to make up for pressure decreases and leaks, a development heat exchanger, and the current closed-loop suit design. A new iteration on VPIST, planned for late 2016, will test the system with more advanced flight-like hardware, and four test subjects in suits at vacuum cabin pressure. The benefit of VPIST being ahead of the Orion ECLSS design is the opportunity to recommend design changes based on test results.

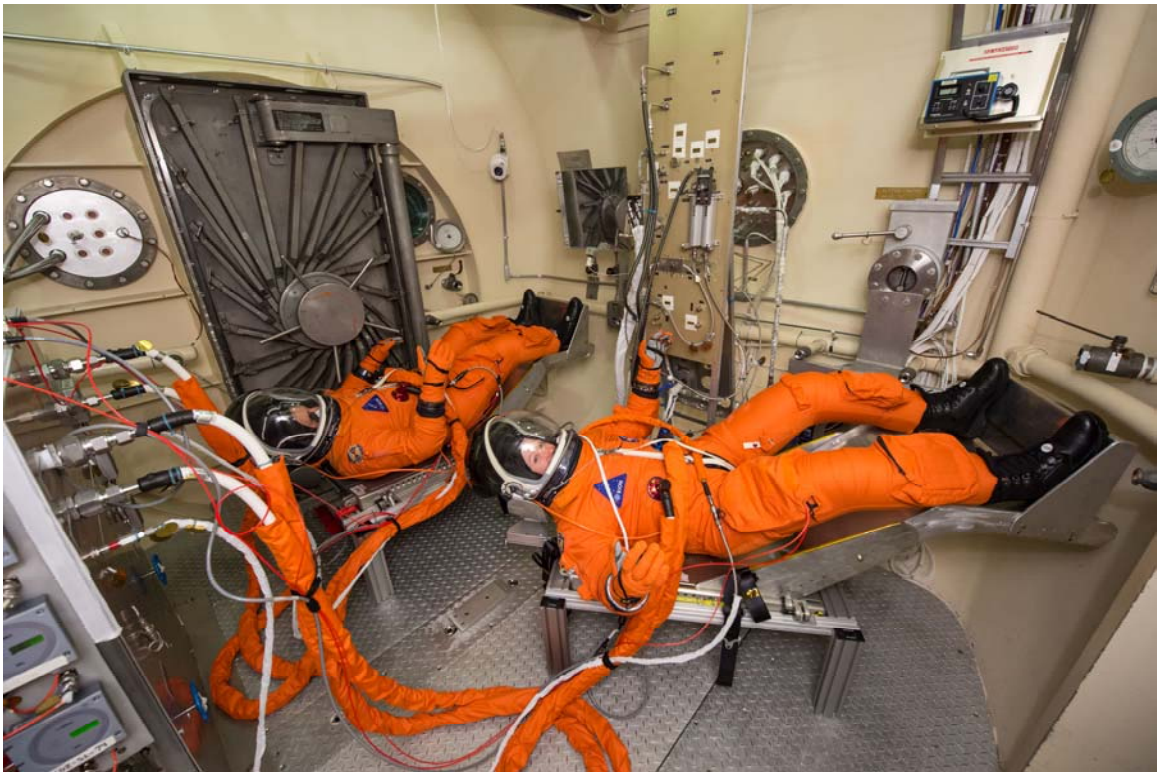

Figure 3. VPIST Test Setup in 11-Ft Chamber Inner Lock

B. HESTIA Background and Overview

We have a need to advance the capabilities that will support long-duration human exploration missions beyond low earth orbit. NASA has supported short duration (< two weeks) human space missions since 1961. The International Space Station (ISS) has been in continuous operations with crew aboard since 1998, with a regular resupply of consumables and maintenance items. For ISS, in the event of a catastrophic condition on-board the spacecraft, there is always an emergency option for crew to evacuate back to earth within hours. For longer missions beyond earth orbit, the human exploration spacecraft architecture must ensure crew survival for hundreds of days, and emergency resupply and a quick return to earth are not viable contingency options. These long duration missions will be enabled by both the advancement of key technologies and an efficient approach to system design, in order to reduce mass, provide capability with margin, make efficient use of consumables, and have a balanced approach to reliability and spares.

The management of a life support system for a long duration is one of the most complex challenges for human exploration missions. Recycling and reuse of consumables is required for a viable mission, and the very presence of humans in the loop makes the process much harder. Humans and the spacecraft generate waste and contaminants, which can be hard to fully characterize in advance. It is also difficult to predict the impact of contaminants on system components.

Current Mars architectures include the use of liquid oxygen (O_2) and liquid methane (CH_4) for spacecraft propulsion; this is due primarily to the commonality between oxygen and other spacecraft systems like life support, and the potential for making methane on the Mars surface using In Situ Resource Utilization (ISRU) for the return vehicle. A system architecture that exploits these commonalities sounds great in theory, but key integration issues have not yet been examined to evaluate consumption and production rates, purity of commodities, and interplay between components.

The goal of the HESTIA program is to provide the means for NASA engineers to develop, integrate, demonstrate, and test capabilities that are needed for long duration human exploration missions. An initial ECLSS portion of HESTIA is what was evaluated in the 20-Ft chamber in 2015.

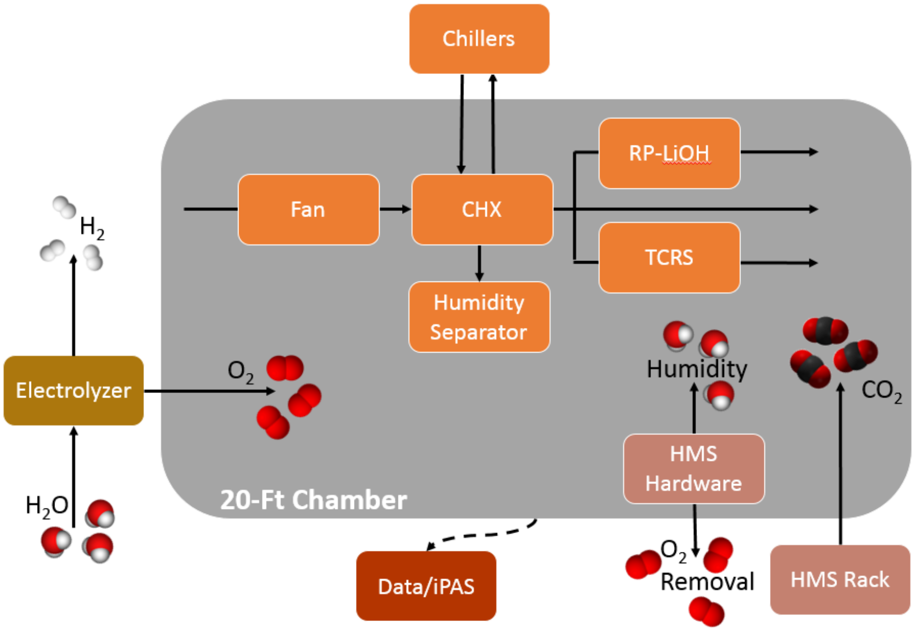

Figure 4. HESTIA Phase I Integrated Schematic.

The objective of this first "Phase I" test (diagram on Figure 4) was to evaluate a number of technologies which could one day be part of a closed loop habitat. Test buildup and instrumentation were located on all of the three levels of the chamber, as well as the ground level and platform outside the vessel. These initial technologies are described below. The Electrolyzer splits water molecules into molecular oxygen and hydrogen. Oxygen is injected into the chamber (for breathing for the crew in a future manned scenario). At the time of the Phase I test, hydrogen was vented outside the building through a roof vent. In future iterations of HESTIA testing, hydrogen may be used as an input to another life support system or ISRU technology.

The Air Revitalization System (ARS) is a collection of different subsystems aimed at maintaining "good quality" air that the crew can breathe. A fan circulates the air, while a condensing heat exchanger (CHX) pulls humidity out of the air. Parallel flow paths then include a Trace Contaminant Removal System (TCRS), consisting of two trace contaminant filters used in in the VPIST test, and a Reactive Plastic Lithium Hydroxide (RP-LiOH) unit, which removes carbon dioxide (CO_2).

Since this first phase of testing was unmanned, a Human Metabolic Simulator (HMS) was used to simulate the human production of CO_2 and humidity, and the removal of oxygen.

As another proof of concept, select data from this test was sent to the Integrated Power, Avionics and Software (iPAS) laboratory in a remote location, with the idea of integrating data from different facilities in the future, for integration and modeling purposes.

IV. The Plot Elements - The Ideal Test Process

In order to allow a facility test team to perform at its best and have as much time and resources as possible dedicated to tackling the technological challenges that a test presents, there needs to be a strong foundation, both in terms of the information needed to get started, and a clear organizational set-up with defined roles. It is in these two areas that we will look at our two chosen tests, to identify improvement areas. First, however, it is important to delineate the elements of an ideal test process.

Based on experience and lessons learned over literally decades of testing, there is a generally accepted approach to human-in-the-loop testing of life support systems in altitude chambers. This approach spans from a defined organizational structure, specific information, and a structured process. This is to ensure not only success of the project and test, but also safety of the test subjects.

A. The “Smart Start” – The Backdrop

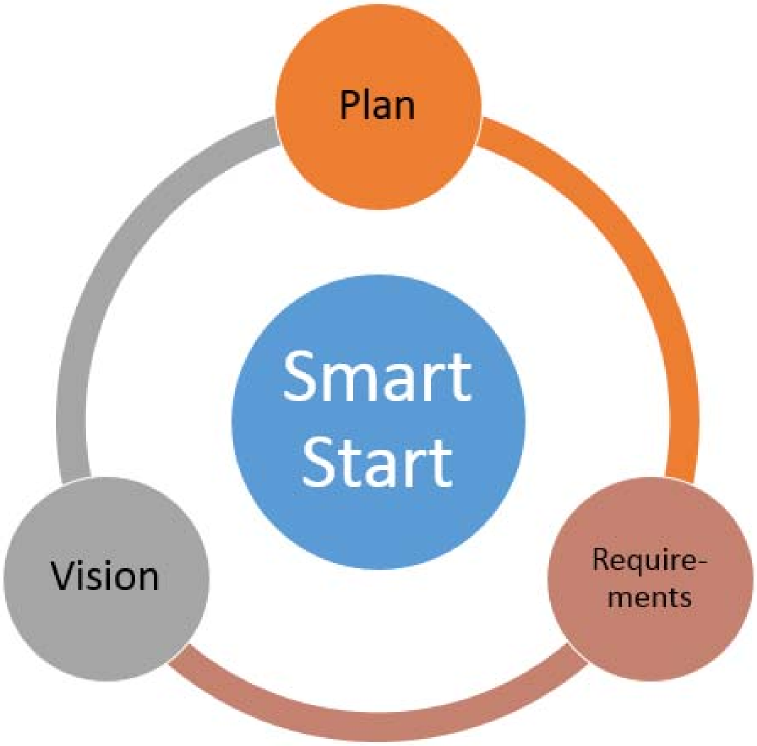

Figure 5. Key Elements for a Test. *These elements represent the foundation of required information for a successful test, or “Smart*

When a Principal Investigator (PI) decides to perform a test, a number of basic items of information must be obtained by the test team. Creation, design and execution of a test are the direct result of the collection of a number of key elements that are coordinated, managed and distilled successfully into a test. As shown on Figure 5, these key elements are:

1. Vision – what is the ultimate goal for the test or tests? It is important to have a clear vision for the ultimate purpose of a project or test to be able to map out a strategy to arrive at it, which in some cases, may result in a change of scope or breakdown into phases.
2. Plan – taking the vision to a more concrete level, what does the PI plan on testing, and how? What hardware/software/operation is being tested? What values and variables will need to be monitored, and recorded? Quite simply put, when the test team arrives on test day, what will they be doing?
3. Requirements – breaking down the plan to quantitative details results in requirements. These are the quintessential “shall” statements that dictate what the test team will be required to meet in order to build the test apparatus and execute the test procedures as required by the PI.

B. Organizational Structure of a Test Team – The Cast

Once the Smart Start elements are defined, and a PI reaches out to a testing organization such as CTSD's Systems Test Branch, a test team is assembled. At the inception of a test of any size, a test director (TD) with a test team are assigned to the task. The test director may also act as the project manager (PM) or, depending on the activity's scope, be flanked by a full-time PM to allow him/her more time to focus on integration and operations. The PM also facilitates the collection and redaction of the information from the Smart Start elements and organizes it (see Figure 6). This is especially crucial in the case of a test with multiple PI's and multiple sets of requirements. As with any project (and it is important to emphasize that a test is a project and should be run as such), communication is extremely important. However, it is also important to follow the hierarchical structure for actions such as performance of work, requirements vetting and approval, and scope, budget and schedule management. In the case of distinct PM and TD roles, it is important that both roles are well demarcated and operate over their respective juridisdictions with authority, much in the way that a company's CEO and COO would.

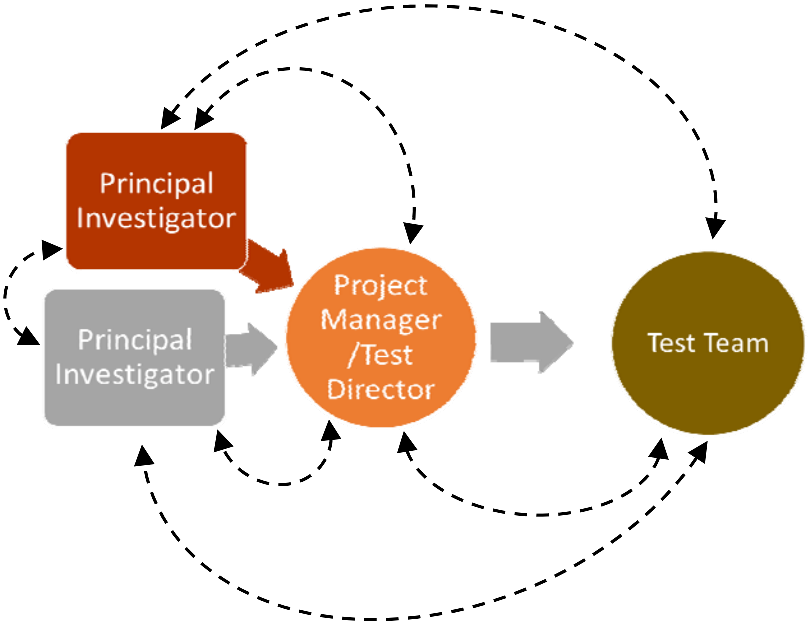

Figure 6 – Organizational Structure of a Test Team. *Communication is key in every project: the graphic illustrates the communications channels with the dashed line, according to the N(N-1)/2 formula*[1]*. However, the organizational hierarchy (marked with the large solid arrows) must be followed for proper management of the project.*

C. The Iterative Test Process – The Script

Helped by a solid Smart Start, the first task of a TD and Test Team is to gather information on the vision, plan and requirements from the principal investigator(s) and distill those into test products (see Figure 7). These products are:

- Work breakdown structure (WBS)
- Schedule
- Cost estimate
- Design
- Buildup
- Test procedure and documentation (which includes design reviews, protocols, hazard analyses, etc.)

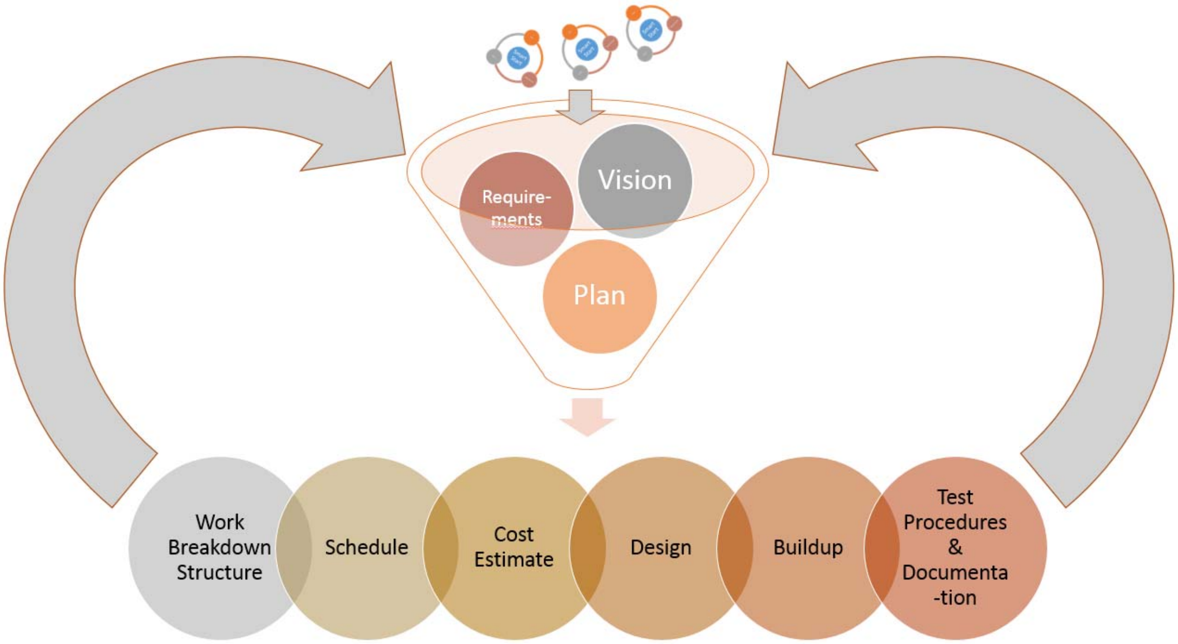

Figure 7 - Distillation of Smart Start Elements by the Test Team. *This graphic highlights the direct correlation of inputs (vision, requirements, plans) to test products and the iterative process that occurs in the development phase.*

The direct elements correlation illustrated on Figure 7 indicates that the quality of the output is only as good or comprehensive as the quality and comprehensiveness of the input. Lack of requirements directly reduces the fidelity of a cost estimate, and affects the ability to create an accurate design and test procedure. An unfocused vision and plan directly affect many of the procedures and protocols, if the test team does not have a clear idea of the end goal or the daily operations needed to achieve it. As represented on the diagram, this is an iterative process and may require a number of iterations, particularly for complex tests. Any of the test team's products, especially the earlier ones such as WBS, schedule, and estimate, may indicate the need for the entire team to revise requirements, plans, and even the vision. On the latter in particular, a need may become apparent for a re-scoping, or de-scoping based on factors such as cost, schedule, and feasibility.

It should be apparent by now that the better delineated and solid the initial three key elements are, the higher the chances for a successful test. A lack of requirements immediately affects a test design and test procedure.

With this framework in place, we can now look at how certain aspects worked well under PIST and HESTIA, and how others could use improvement.

V. The Cautionary Tales

A. PIST – A Story About (Mostly) Smart Starts

1. Smart Starts

If there is one key element that PIST had locked in from the start, it was vision: the ultimate vision for PIST was always to test developmental ECLSS hardware with humans in a vacuum to provide input to the final Orion design. From the onset, the PIST team took the incremental approach (Figure 8) that its predecessor test series, CAMRAS, employed successfully. Because of the quantity of developmental hardware involved in the use of a new life support system with humans in the loop, it was decided early on to split the test into large stand-alone tests, and be able to characterize the hardware in a manned environment before adding hazards such as reduced pressure and, eventually full vacuum.

Figure 8. VPIST Iterative Approach.

In true iterative fashion, vision scoping and planning processes continued through the lifecycle: although smaller in scale than its counterparts, UPIST did not initially exist as a stand-alone test activity. However, with the data gathered from APIST and IPIST, the team decided to add one more step before the human-in-the-loop vacuum test. This breakdown approach also helped reduce initially daunting undertakings into more manageable ones. One particular example is the writing and submittal of the human testing protocol to the Institutional Review Board (IRB), prior to subjecting any human subjects to any potentially hazardous condition. A new protocol was written and submitted for each PIST manned test series, eventually culminating into VPIST. By that point, a lot of the knowledge base was already in place, familiarity with the IRB process had been acquired, and the team was aware of the documentation required to satisfy the IRB's questions and concerns, rendering the process increasingly smooth, despite the increasingly complicated test.

While vision was almost laser focused from the beginning, requirements and planning were not quite as defined; the first of the PIST tests, APIST, had a rather fast-paced development process, and the TD acted as the project manager. Because of its fast cycle, the test plan and requirements document were not fully developed prior to the test procedure, but rather almost concurrently. This caused difficulties with ironing out a final design and accompanying procedures. As a major lesson learned from APIST, the inefficiency of this approach was improved for further tests, particularly with VPIST, where a draft test plan and requirements documents were circulated and eventually completed before test procedures were written. Figure 9 graphically illustrates the different outcomes from APIST to its successors. As an additional example of how important this distillation process is and its effect on the test, even the few "to-be-determined" areas left in the VPIST requirements document eventually caused a few design/redesign issues, which affected both cost and schedule.

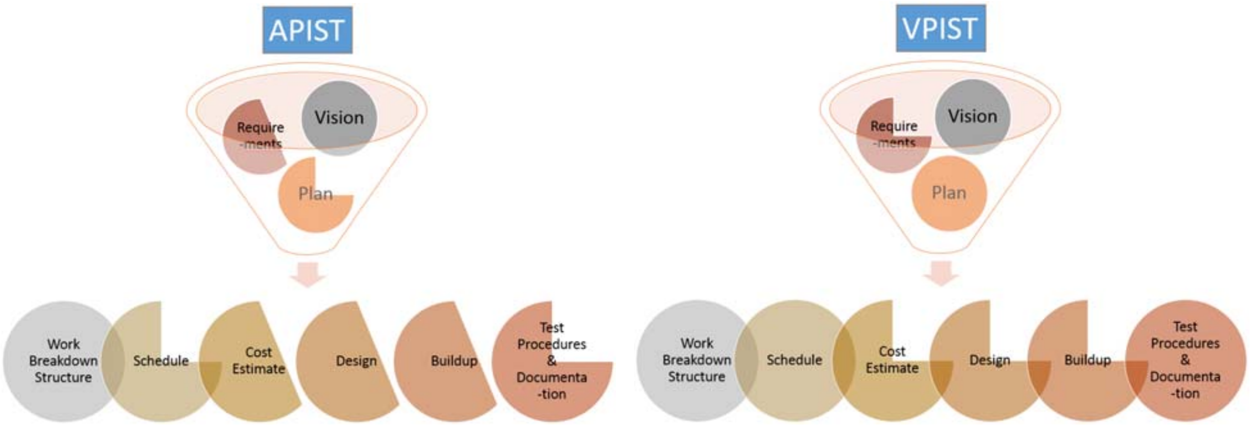

Figure 9. Smart Start Elements in the PIST Series. *From APIST (left) to its successors (right), a better definition of the key elements resulted in higher quality deliverables from the test team. It is important to note, however, that while this graphic focuses on a number of fundamental elements, complex tests may have been affected by technical challenges as well.*

2. *Organizational Growth*

Organizationally, as the complexity of the test grew, starting with VPIST, the TD was flanked by a dedicated PM, with the direct mandate to collect the PI's requirements and manage schedule for deliverables to the TD, track and manage budget, manage stakeholders, and act as liaison between the requesting groups and the facility team. This allowed the TD and the rest of the test team to focus on the hardware and software integration, engineer and technician leadership and management, test design buildup, and operations.

3. *Moral of the Story*

Large, multi-phased tests are going to increase in complexity and hazards. It is important to have a clear vision of the endgame, and break down the endeavor into manageable pieces with a reasonable scope. It is also important to re-evaluate the scope, as was the case for UPIST, in case further reassessment is needed. Concurrently, it is just as important to have a clear plan and requirements to enable a testing organization to assess feasibility, cost, and schedule and avoid rework due solely to lack of information. In terms of the Smart Start elements, the PIST series has become smarter and smarter with each iteration, rendering the realization of the vision and implementation of the plan smoother with each test, despite the rising challenges.

Organizationally, the addition of a PM as the test grew helped alleviate the burden on the TD, and also provided a point of contact between the PIs and the testing organization, with the TD still acting as a "gate keeper" to the test team.

B. HESTIA – A Story About A Missing Cast Member

HESTIA's vision was rather well defined from the start – integrating existing and emerging technologies to create a closed loop habitat for human habitation and running a human-in-the-loop evaluation.

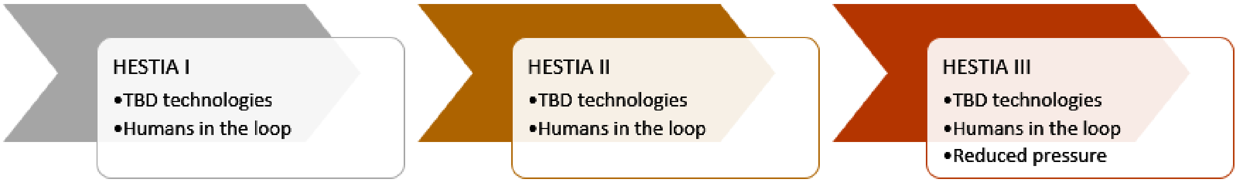

Figure 10. HESTIA Initial Vision Breakdown. *While the "TBD technologies" may be what jumps out the most, the hidden risk here is actually the first phase that jumps into a manned test with untested technologies in this scenario.*

A large number of PIs came to HESTIA with their respective technologies, making the first challenge deciding which of these technologies would be feasible to integrate into the chamber for a first test, within the budget and scheduled allotted. While that was definitely an issue to resolve, the hidden risk lay in the initial demarcation of the various phases, which was delineated as shown on Figure 10. While a non test director PM was assigned to the test, there was initially no human-certified TD (HCTD) with the knowledge of risks and protocols for this type of testing. The lack of a human testing subject matter expert resulted in the PIs communicating requirements, operational information, desires and other type of information directly to the test team engineers (Figure 11).

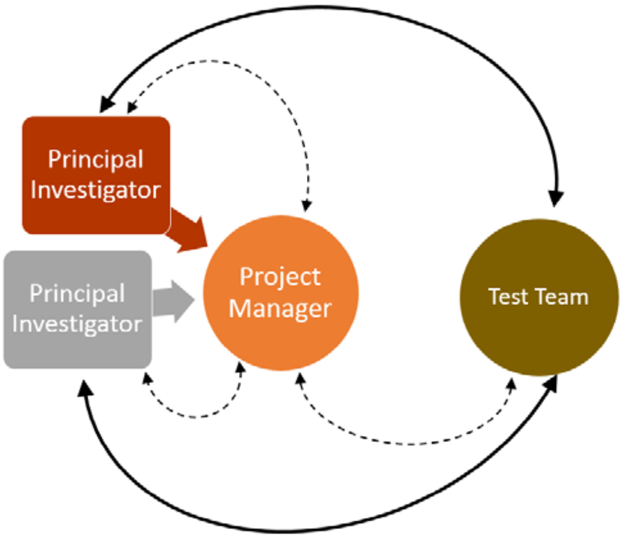

Figure 11. Organizational Structure Without a TD. *The lack of a test director caused some of the communication lines to "solidify" into organizational lines, making the project hard to manage by a sole PM.*

What would normally be considered communications channels, became conduits for establishing requirements, and directing work, without the PM necessarily being in the loop. Also lacking was a focal point to educate and extract the Smart Start elements of vision, plan, and requirements into deliverables. In essence, the distillation process described on illustration Figure 7 was not occurring as necessary. Requirements were being captured but not in an integrated fashion: the big picture of how these systems were going to work together was missing, resulting in a lack of a test plan describing the goals of the test operations as a whole, and the absence of a discrete test matrix outlining test points and configurations.

This situation presented itself shortly after VPIST was concluded, so some of the key personnel from that test became available and were assigned to HESTIA. The first organizational change was to restore structure to match the optimal test team structure (see Figure 6). This restored the communication and organizational lines and jumpstarted the distillation process. Based on the desired phased approach to achieve the vision, the TD and test team returned a WBS, cost estimate and schedule that far exceeded the initial expectations. A rescope was clearly needed. Taking a page out of UPIST, a further phase breakdown occurred, which allowed the team to tackle a more manageable task within a reasonable timeframe and budget (Figure 12). A major change was to keep the first newly-formulated phase of HESTIA unmanned, to first evaluate these technologies without the added variable of a human in the loop.

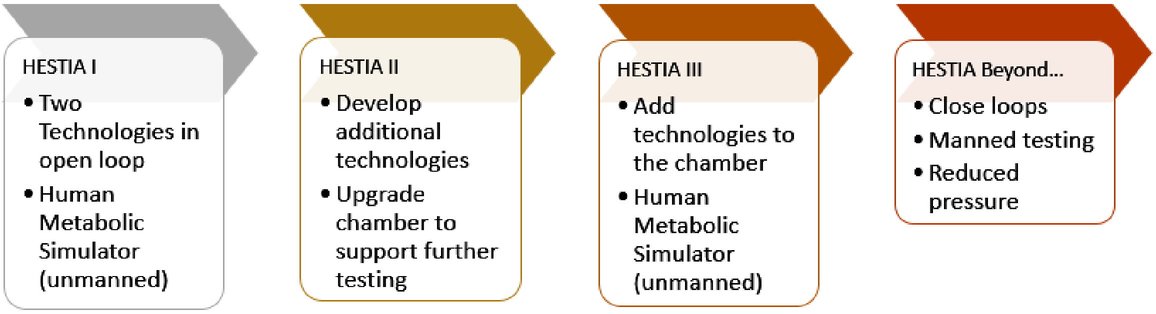

Figure 12. New Breakdown of HESTIA Phases.

With a new approach and a functional team in place, the HESTIA team restarted a requirements aggregation process and assisted the PIs in formulating a test plan which, with the assistance of the PM, included a clear test matrix that allowed the test team to create a concept of operations and produce appropriate test procedures.

A perfect example that reaffirms the need for a designated person to aggregate and distill plan and requirements was the creation of the test point matrix. One of the systems had a requirement to keep the chamber door closed for the first few days of testing to achieve a high CO_2 level without reconditioning the chamber each day. Meanwhile, another system had a requirement to access the chamber at the end of each day to retrieve and measure the amount of condensated water from the air. This kind of conflict would normally be identified early on when creating a test plan and comprehensive matrix. In the case of HESTIA, this conflict was identified by the TD (who was not in the original team make-up) rather late in the process, during the test procedure creation. Fortunately, in this particular case, this conflict required a fairly easy solution. However, it is a valid example of an issue that could have been caught and resolved much earlier in the process.

The team went on to complete the HESTIA Phase I test successfully and within the budget and schedule generated during the restored distillation process. The follow-up phase, consisting mostly of chamber upgrades to support future tests, is underway at the writing of this paper.

1. *Moral of the Story*

The idea behind HESTIA is no-doubt cutting edge: using existing and emerging technologies to create highly integrated and interdependent systems to support missions to other planets. In the life support and in-situ resource utilization arenas, this means utilizing the same fluids and raw materials, as well as byproducts to provide the functions needed. In and of itself, this is an extremely ambitious, long term goal. In addition, HESTIA initially employed a new methodology for collecting and cataloguing requirements in an online Sharepoint-based repository, in an attempt to eliminate traditional plan and requirements documents, which was a rather large paradigm shift. Combined, the broad vision and the new approach resulted in a very large undertaking.

As in any project, it is important to start by setting up the proper organizational structure, with clear roles to encourage communication and efficiently manage work assignments and stakeholders relationships. While creating a more streamlined team, the initial absence of a HCTD during the requirements collection proved to be a detriment by not infusing the team early on with the necessary expertise, the ability to integrate the requirements and create a holistic view of the test, and easily identify any “holes” in the information provided. While the Sharepoint site provided a place to collect the requirements, it did not integrate them and interpret them into a solid idea of what a test would look like, therefore it was not a replacement for a person with the right skill set. Furthermore, a different breakdown of the vision, as was done post-reorganization, would have likely occurred earlier had there been a fully staffed team in place that included a HCTD.

VI. Epilogue

Conceiving, structuring, managing, and executing a test is like telling a story or writing a book (or a multi-part saga). Whether it turns out to be a fairy tale or a horror story depends on many factors, but for it to be compelling there are certain elements that need to be in place.

There need to be solid plot elements, starting with the foundations of the elements of vision, planning and requirements. A Smart Start. There needs to be a complete cast of characters (preferably, no villains) that include not only the PIs, but also the managers and leaders (PM and/or TD) with the appropriate background and experience, as well as the test team. There needs to be an efficient and comprehensive distillation process of the Smart Start elements by the team to create efficient and complete test products; the weaker any one element is, the weaker the rest of the story.

All these elements result in what the Crew and Thermal Systems Division at NASA JSC considers the basic tenets of out human-in-the-loop accepted test process. These tenets are virtually non-negotiable. Reductions or shortcuts have a history of causing issues.

Ironically, VPIST added a PM in its later iterations to tackle increased complexity, whereas HESTIA started without a human-certified TD, and then added one. In both cases, the teams had the courage to reassess and make changes which immediately resumed the Smart Start distillation process and resulted in better functioning teams and successful tests. While HESTIA certainly learned from VPIST by immediately adopting the phase approach, it attempted this breakdown exercise without all stakeholders on the team to point out any weaknesses or issues.

Both tests showcased in this manuscript showed that an issue with any of the these elements resulted in one or more problems downstream that required revisiting, often at the cost of budget, schedule, and/or technical objectives.

Although two test cases were used from two neighboring chamber tests, the lessons learned from running large scale tests (manned or unmanned) can be applied to many similar operations of all sizes. Usually, activities such as these have a large number of technological challenges and unknowns, which are enough for a team to focus on within the usual constraints of budget and schedule, so any work that can be done in the beginning to set a strong base, will help result in a smoother execution. From a programmatic standpoint, the lessons learned from PIST and HESTIA can be summarized as follows:

- Principal Investigators should strive to have as clear a vision as possible for the activity they want to test, coupled with clear requirements (the "what") and a plan (the "how"); the end result is highly dependent on the information provided in the beginning
- Testing organizations should identify key team players and stakeholders early on;
    - At a minimum a test team should be composed of a TD (acting as the project manager) and the test team, composed of engineers and technicians as appropriate for the task
    - Based on complexity and scope, it may be advisable to split the leadership/management role by flanking the TD with a PM. One can focus on the technical management and operations, while the other provides the outward interface to the PI's and overall programmatic management.
    - TD qualifications are unique. While it is possible for a TD to pull "double-duty" as PM, the opposite is not necessarily true due to the very specific training required to be a certified HCTD. The TD should be present early on in any activity that is going to culminate into a test.
- All processes should always be open to revision and improvement. The test process is no different. However, major changes (such as the document-free Sharepoint approach) should be implemented carefully and incrementally, especially when there are other complexities at work. Additionally, at a minimum they should provide the functions of the process they are replacing.

The road to Mars is long and arduous. Large-scale, multi-year test operations are the way to get there. It is important to continue evaluating our processes, delineating key elements for smooth execution and ultimate success, and formalizing them within the technical community. It is imperative for PIs to understand what test teams need, so that we may be, and continue to be, on the same page, as we write the next chapter in space exploration together.

Acknowledgments

The author would like to thank the Crew and Thermal Systems Division and all members of the PIST and HESTIA teams for many years of exciting experiences in the field of life support testing, with hopefully many years – and many lessons learned and applied – ahead.

References

[1] *A Guide to the Project Management Body of Knowledge (PMBOK® Guide)*, 5th ed., Project Management Institute, Newton Square, Pennsylvania, 2013, pp. 291, 292.