

US Spacesuit Knowledge Capture

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The ability to learn from both the mistakes and successes of the past is vital to assuring success in the future. Due to the close physical interaction between spacesuit systems and human beings as users, spacesuit technology and usage lends itself rather uniquely to the benefits realized from the skillful organization of historical information; its dissemination; the collection and identification of artifacts; and the education of those in the field. The National Aeronautics and Space Administration (NASA), other organizations and individuals have been performing United States (U.S.) Spacesuit Knowledge Capture since the beginning of space exploration. Avenues used to capture the knowledge have included publication of reports; conference presentations; specialized seminars; and classes usually given by veterans in the field. More recently the effort has been more concentrated and formalized whereby a new avenue of spacesuit knowledge capture has been added to the archives in which videotaping occurs engaging both current and retired specialists in the field presenting technical scope specifically for education and preservation of knowledge. With video archiving, all these avenues of learning can now be brought to life with the real experts presenting their wealth of knowledge on screen for future learners to enjoy. Scope and topics of U.S. spacesuit knowledge capture have included lessons learned in spacesuit technology, experience from the Gemini, Apollo, Skylab and Shuttle programs, hardware certification, design, development and other program components, spacesuit evolution and experience, failure analysis and resolution, and aspects of program management. Concurrently, U.S. spacesuit knowledge capture activities have progressed to a level where NASA, the National Air and Space Museum (NASM), Hamilton Sundstrand (HS) and the spacesuit community are now working together to provide a comprehensive closed-looped spacesuit knowledge capture system which includes

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specific attention to spacesuit system artifacts as well. A NASM report has recently been created that allows the cross referencing of history to the artifacts and the artifacts to the history. NASA's formal spacesuit knowledge capture efforts now draw on the NASM preservation collection and report to enhance its efforts to educate NASA personnel and make more spacesuit history. Be it archiving of human knowledge or archiving of the actual hardware knowledge, the joining together of spacesuit system artifact history with that of development and use during past programs will provide a wealth of knowledge which will greatly enhance the chances for the success of future and more ambitious spacesuit system programs.

Nomenclature

ALSA = Astronaut Life Support Assembly
APPL = Academy of Program and Project Leadership
CDR = Critical Design Review
DCM = Displays and Control Module
ELSS = Extravehicular Life Support System
EMU = Extravehicular Mobility Unit
ESA = European Space Agency
ESSS = Extra-vehicular Space Suit System
EVA = extravehicular activity
GFE = Government Furnished Equipment
HS = Hamilton Sundstrand
HHMU = Hand-held Maneuvering Unit
ISS = International Space Station
JSC = Johnson Space Center
KC = Knowledge Capture
NASA = National Aeronautics and Space Administration
NASM = National Air and Space Museum
OPS = Oxygen Purge System
PDR = Preliminary Design Review
psia = pounds per square inch, absolute
psig = pounds per square inch, gauge
QSA = Qualification Site Approval
RID = Review Item Dispositions
SME = Subject Matter Expert
US = United States
USAF = US Air Force ()

NESC = NASA Engineering Safety Council

I. Introduction

The United States (US) has led the world in the scientific exploration of space for nearly 50 years.¹ This year in particular, many changes have come about for National Aeronautics and Space Administration (NASA). NASA's administrator, Charles F. Bolden, Jr. introduced NASA's 2011 Strategic Plan stating that, "In 2010, the President and Congress unveiled an ambitious new direction for NASA, laying the groundwork for a sustainable program of exploration and innovation."² Given this rich 50-year history combined with the new direction identified in NASA's 2011 Strategic Plan, NASA will be envisioning the future of spaceflight by capturing and benefiting from the knowledge of the past. For example, NASA's 2011 Strategic Plan, additionally states, "The commercial crew initiative represents a new way of doing business in human spaceflight and is based upon knowledge gained from prior NASA vehicle development programs."³

NASA's Strategic Plan was not the first time that "knowledge" was reference as an important pursuit. Seven years earlier, in June 2004, Aldridge, Jr. E.C., published the "Report of the President's Commission on Implementation of United States Space Exploration Policy, A Journey to Inspire, Innovate, and Discover".⁴ In this report, "knowledge" was cited throughout the document in critical statements. The excerpts reveal the importance of taking the knowledge and using it to influence our leadership in technological advancements in space exploration. The commission recommended to "Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration...". Additionally, the document states, "The vision will require incessant innovation, excellent management, and a persistent focus on a series of missions that collectively and iteratively build the body of knowledge needed to explore. This is not one mission, but many. It is not a government program, but a national journey." And finally the documents states, "The Commission finds that sustaining the long-term exploration of the solar system requires a robust space industry that will contribute to national economic growth, produce new products through the creation of new knowledge, and lead the world in invention and innovation. This space industry will become a national treasure."

The United States (US) spacesuit has become an international icon for the NASA and is one of the space industries iconic national treasures. Without spacesuits, humans could not have ventured into space, explored the moon, constructed space stations, or maintained and upgraded the Hubble Space Telescope that has provided millions of images that have amazed and educated mankind. These historical accomplishments of US spacesuits are reflected in Fig. 1 as they have been captured realizing those legacy breakthroughs of space exploration.



Figure 1. Legacy Spacesuit Montage

The spacesuit is a unique form of personal life support system that combines a pressure suit with a life support system to allow survival and performance of tasks during various phases of a space mission. Challenges such as mass and volume restrictions coupled with the need for pressurized mobility have made spacesuits one of the most difficult space systems to develop, certify and implement in support of space missions. The knowledge gained from space exploration has influenced spacesuit development. As space missions have become more complex, so have spacesuits.⁵ Many spacesuit technologies have been described as "Black Arts." A combination of engineers at NASA along with companies such as Hamilton Sundstrand, ILC and David Clark have developed the spacesuits that have left a legacy of knowledge and hardware over the years which can ignite future development with the knowledge captured benefiting future exploration to make traveling into, working in and returning from space safer.

Knowledge capture is a natural process. It may happen at many levels in a product system. It may be a planned and systematic activity or a periodic response to the recognition that knowledge is being lost. Typically, knowledge capture is conducted within an organization for the benefit of that organization. In industry, businesses develop areas of expertise to successfully compete in offering products and services. The resulting “corporate knowledge” or intellectual property is captured and disseminated internally but guarded from external release. In space exploration, NASA is tasked with management to obtain safety, reliability, and optimum performance of space programs within its financial constraints. The more effectively NASA sets the requirements, the better the resulting quality and schedule performance at minimum cost. This requires product understanding that comes from years or decades of experience. Technical understanding coupled with effective program management is the key to NASA carrying out our national goals. Given NASA’s new direction, capturing knowledge and experience gained over the years becomes even more important now more than ever. It is paramount that it is accomplished in order to preserve experiences so a legacy can be passed on for future spaceflight knowledge transfer. Therefore, this paper discusses the philosophy and background of knowledge capture, provides a discussion of elements of spacesuit knowledge capture in particular, expands on a new approach in harnessing the past of spacesuit knowledge, and articulates the involvement of the National Air and Space Museum (NASM) entrusted with the preservation of aerospace artifacts and history. What is unique about spacesuit knowledge capture is that the synergy of common interest and related needs has formed a multi-organizational loop knowledge capture system that is described in the discussion that follows.

II. Philosophy and Background

A. Philosophy

There is a temptation to think that “knowledge capture” is an end goal; an indivisible ultimate state. But what is “knowledge”, and what use is “capture?” There are possibly as many definitions of knowledge as there are definers. There are, it seems, three main sources of experience worth capturing: (1) recollections, conclusions and recommendations of veterans; (2) information in written, video, and audio formats; and (3) hardware items representing not only flight items and flight configuration items, but mockups, advanced prototypes and training hardware. Here is one approach by which one might base an investigation of knowledge; its capture and ultimate utilization.

First, let’s start with a proposed hierarchy: at the bottom of the structure is RAW DATA – instrumentation readings; numbers of people doing this or that; observations which, of themselves, have no meaning other than that they are just observations. We take these raw data and through some sort of mental exercises, turn them into something called INFORMATION, that is, data with an interpretation leading to something meaningful to the observer. Next, this INFORMATION is transformed and collated into a broader context, into a body called KNOWLEDGE, which extends the range of information over a broad field of investigation. From an analysis of this knowledge, extrapolating it to other realms should come WISDOM, which is a step-change in progress. Wisdom is the application of knowledge to not only the field under investigation, but also other fields, even life experience in general, be it in the world of science or human behavior. The last step in this progression, in the example chosen, is GOODNESS, which is the application of wisdom for the benefit of human endeavor as a whole. For the purposes of this paper, we limit the discussion to the concept of KNOWLEDGE, leaving it to those who choose to use this knowledge to tread the path leading to wisdom and, ultimately, goodness.

At all levels of the above treatment of knowledge and its antecedents and results, there are “hard” and “soft” records. Examples of hard records are written or filmed reports of tests, failures and hardware usages; analyses; data printouts and charts; accounts; hardware items themselves – the list goes on and on. These records and physical hardware and software items are preserved in a number of ways – some are organized and cataloged; many are not. Soft records are made up of the recollections of those who participated in programs and projects – sometimes these are preserved as video and audio recordings, but what serves to make them less concrete is the inevitable inclusion of personal analyses and conclusions which may be presented as fact.

Having gone this far, let us explore the other half of the dyad – “capture.” What is covered under the aegis of “capture” is the organization of the body of knowledge, as referred to in the hierarchal treatment mentioned above, in such a way as to make it identifiable and accessible to those who are undertaking projects which bear a relationship to previous endeavors. The term “capture” is really an oversimplification – what is really meant is the detailed organization of previously acquired knowledge of all forms – records and hardware - in an accessible fashion which facilitates its application to a new endeavor (Fig. 2).

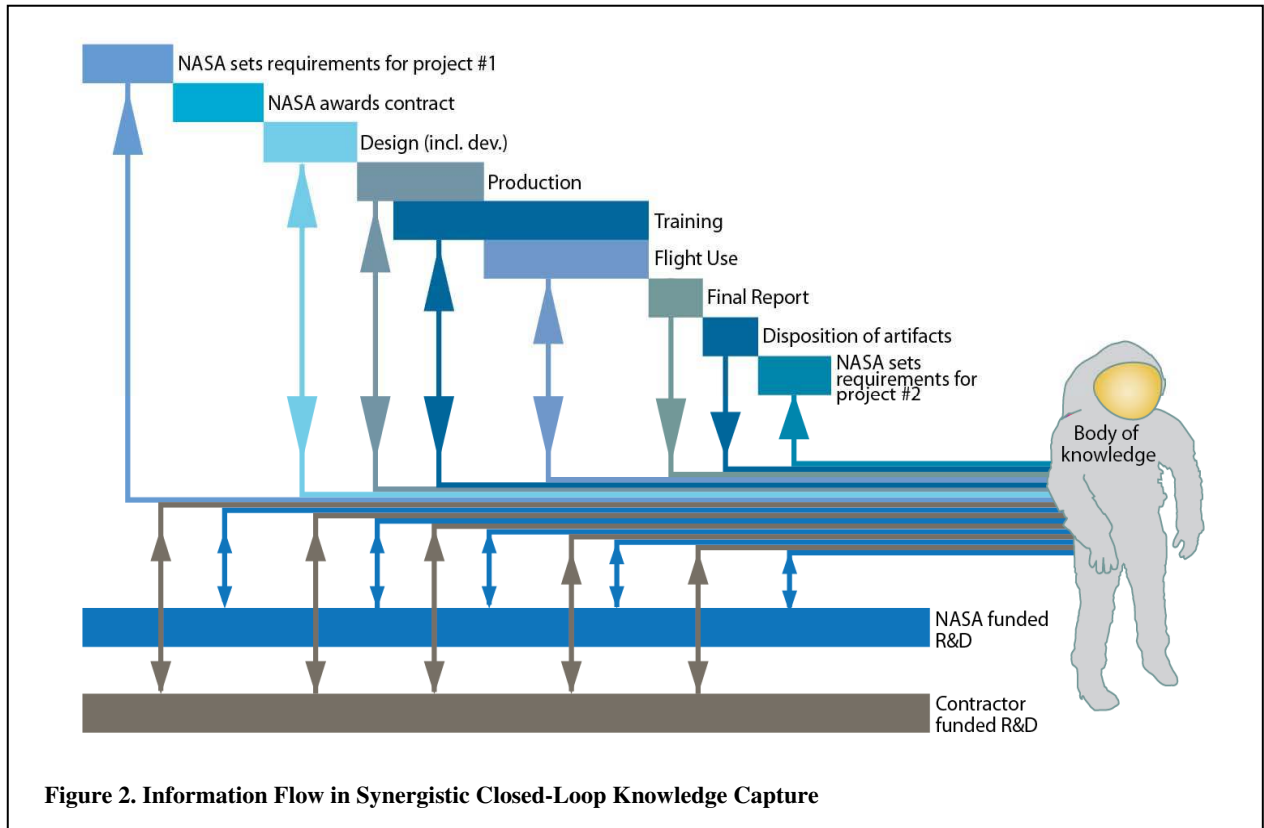


Figure 2. Information Flow in Synergistic Closed-Loop Knowledge Capture

When approaching the recounting of experiences, the tendency is to focus on the negative aspects of technical items – significant and dramatic instances of failures or miscalculations which wrought havoc on hardware and/or people. However, those who have acted in the past have, on occasion, actually experienced successes, and some effort is usually valuable in ascertaining just why they were successful.

In addition, there are elements of program history other than those dealing strictly with hardware development and use from which important knowledge and conclusions can be drawn. These typically receive less analysis and scrutiny as the more numerous and, in some cases more interesting, failures. As examples, one might choose project or program organizational structure; methodology used in analyzing and rectifying failures; cost estimating; methods of implementing so-called “soft” disciplines like configuration management; quality assurance; reliability; safety; performance measurement, and other non-technical areas.

The sense of the value of knowledge capture is intuitive; it is, in the vernacular, a “no-brainer.” The history of any technology area which has seen development and repetitive usage is replete with examples of what can happen when important lessons, painfully learned, are ignored either through ignorance or by intent. In the area of spacesuit technology, with its intimate connection with human beings, learning from the experiences of the past is not only cost-effective; it can be life-saving. Spacesuit history, unfortunately, has some examples of lessons not learned, or at least, not applied.

B. Background

1. Genesis of Knowledge Capture

In the past, formal knowledge capture has been largely left to industry. In industry, businesses develop expertise in many areas to successfully compete in offering products and services. The resulting “corporate knowledge” or intellectual property is captured and disseminated internally but guarded from external release. The common term is “proprietary” information, i.e., that which has been gained by internal processes and development, rather than information gained by direct contract funding. There is often dispute about where the line between proprietary information and information developed under contract (particularly with the government) occurs.

NASA has used a blend of standards and specifications, developed over time, and various types of workshops, seminars and interviews with veterans to try and achieve some sort of reservoir of knowledge to aid future programs.

There have also been many post-program reports and analyses, carried out at various levels, e.g., final reports on specific hardware developments and usages; chronologies of programs; books on Apollo, Gemini, Mercury, and other aspects of space flight. The NASM is entrusted with the preservation of aerospace artifacts and history. In that latter role, NASM has had difficulty obtaining the support needed to capture the history of the spacesuits in its care, thus compromising one's ability to fully evaluate and appreciate the items themselves.

2. Accessibility and Provenance of Captured Knowledge

Knowing about and evaluating previous experience is intuitively perceived as important; no one wants to make a mistake that could have been avoided by simply looking at where someone else had already been. The first problem arises when one tries to find that knowledge - be it written experiential text; hardware objects; histories, or other representations of experience. No one in an ongoing project has the luxury of time needed to sift through final reports; failure histories; hardware catalogs (if they exist); standards and criteria; or other documents, if this information is not easily accessible. The second problem arises when, after finding sources of applicable information, one may find conflicting opinions as to what history has taught, i.e., two different people experiencing the same series of technically significant events may reach different conclusions as to what were the lessons learned based on their specific point-of-view.

A case illustrating the importance of point-of-view has to do with the choice of ~4 psia pure oxygen for the Shuttle EMU versus 8 psia. The former case, which was ultimately chosen, required development of two different pre-EVA protocols - one for EVA from a 14.7 psia Shuttle cabin, and the other from a 10.2 psia cabin. These pose an undeniable operational penalty. Use of 8 psia would have allowed rapid egress from a 14.7 psia cabin without special procedures. Those at Ames Research Center and advanced technology personnel at the Johnson Space Center (JSC) who have advocated the latter approach for as long as the Shuttle has been flying will point out the advances made in suit technology and the obvious operational benefits of the higher pressure suit; those at JSC who have lived through the operational ups and downs of the 4 psia system are quick to point out the successes of that approach. Anyone looking at a new system must weigh the opposing experiences in the light of their new, unique set of circumstances.

3. Knowledge Gaps and Missed Opportunities

In order to fully appreciate the real value of comprehensive knowledge capture, and its appropriate utilization, it's worth the time to look at some examples from the past where critical knowledge, though available in various forms, was not organized and used effectively.

High-Pressure Oxygen

So what types of past experiences might be particularly valuable to spacesuit system program planners, designers and users in the future? One area which immediately comes to mind is that of the use of oxygen. No spacesuit system of the past or any contemplated for the future will avoid the use of oxygen, and the attendant hazards associated with its storage, distribution and use. In order to economically use it, high-pressure storage will undoubtedly be utilized.

The usage of high-pressure oxygen storage in spacesuit systems in the US started with the Gemini program, in late 1963. Excess Project Mercury environmental control system pressure vessels, rated for oxygen use at 7500 psig, were designated for use in the initial concept for the Gemini extravehicular activity (EVA) life support system. The approach involved the use of the stainless-steel spherical pressure vessels with aluminum-bodied regulators. Although this initial concept never was developed, the follow-on system, the Gemini Extravehicular Life Support System (ELSS) had a 7500 psig Inconel 718 cylindrical storage vessel, and an aluminum regulator. A fill check valve with a non-metallic seat was also included. During pre-flight checkout for Gemini X at McDonnell Aircraft in St. Louis, in the spring of 1966, a fire was experienced in the high-pressure check valve of an ELSS chest pack. The only result was leakage, caused by combustion of the valve seat. A few weeks later, during late-stage flight readiness checkouts for Gemini-IX-A at KSC, a similar failure occurred. Again, no personnel were injured, and hardware damage was limited to the check valve itself. Steps were taken for Gemini IX-A, focusing on reduction of fill rate (and resulting temperature); removal of thread sealant, and cleanliness. For Gemini X, a new sapphire-to-metal ball and seat configuration was employed. Cause of the failures was postulated to be ignition of thread sealant materials and seat material, with the energy being supplied by the cyclic "hammering" occurring during fill operations.⁶ The results of a fire in a 7500 psig oxygen system could have been catastrophic; the fact that two such fires occurred in the matter of a few weeks without serious incident bred a false sense of safety. The immediate problems were "fixed"; there was no need specified to begin searching for a systemic root cause. In short, things hadn't gotten bad enough yet.

Later, during laboratory operations supporting the Apollo Oxygen Purge System (OPS), there was an explosion of the 5800 psig oxygen system. Hardware was destroyed, and a technician injured. Cause was postulated to be either inadequate cleaning of regulator orifices after machining, or sharp edges left after machining causing heating and providing a fuel and ignition during blowdown tests. Remedial actions along these lines were implemented.⁷ Even though a technician had been injured and hardware destroyed this time, the severity of the problem had not crossed the threshold of significance warranting a penetrating look at all aspects of designing for and using high-pressure oxygen. Things still hadn't gotten bad enough.

The Apollo 1 fire of January, 1967, occurred during ground test operations at about 16 psia oxygen pressure.⁸ Although the ignition cause was never officially determined, the aftermath of this catastrophe served to focus the agency's attention on materials selection, cleanliness, safety procedures and design; however, there was not a follow-through involving extension of the corrective action to include high-pressure oxygen systems. There was no forcing function to assure that the growing body of experience in oxygen-related mishaps was incorporated into the body of knowledge available to designers and users of both high and low-pressure oxygen systems. More negative experience was apparently needed to force this to happen.

In April of 1980, during pre-chamber test readiness operations, a technician activated the 6000 psig oxygen system of the Shuttle Extravehicular Mobility Unit (EMU), initiating a flash fire which destroyed most of the EMU, the suit mounted to the backpack, and, most importantly, burning a technician severely over a large part of his body. Fig. 3 and Fig. 4 show the resultant hardware. The fire originated in an aluminum bodied housing containing a surge chamber, regulator and shutoff valve assembly when 6000-psi oxygen was released through the valve into the regulator. It was postulated that the fire was probably caused by one or a combination of the following:

- the rupture of a thin, internal section of the aluminum body
- the ignition of a silicone O-ring by compression heating of the oxygen, or
- particle impact⁹

Redesign of both the high pressure and lower pressure (1000 psig) oxygen systems was carried out, substituting Monel for the aluminum regulator bodies; and eliminating both the surge chamber and the high-pressure shutoff valve (the regulator served as the shutoff).

Perhaps the most far-reaching change was the generation of an agency specification, "Safety Standard for Oxygen and Oxygen Systems", NSS 1740.15, January, 1996, which covers materials selection, design, testing and cleanliness for oxygen systems.

Need for this specification and, more important, its mandated use should have been evident from the first incident recounted above (or, more probably, from other non-reported incidents). Why weren't steps taken earlier? Answers – actually excuses – abound. The immediate problems, e.g., poor check valve designs, inappropriate material selections, sharp edges, cleanliness of parts, were solved. But root causes remained unidentified and unaddressed, and thus the likelihood of repetition was increased because corrective action was limited to the instance and experience at hand. One root cause definition which one could derive from this area of experience would be the following: "Root Cause is the lack of or defect in the underlying process which controls not only the area of activity for which failure has occurred, but all related areas of activity under the control of the organization."¹⁰ Things finally got bad enough for NASA to generate an oxygen specification to address the full gamut of issues attending oxygen use. This small example illustrates the potential impact that knowledge capture,



Figure 3. EMU PLSS after 1980

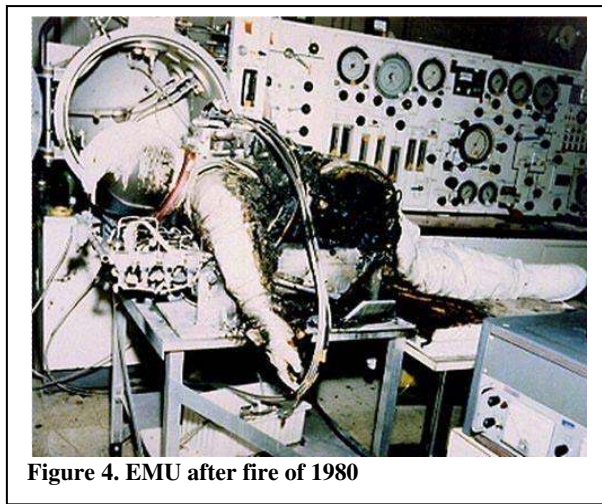


Figure 4. EMU after fire of 1980

analysis and expansion can have on the agency as a whole. The only lamentable aspect is that it took so long, and that is what knowledge capture, carried out as it should be, could and should prevent.

The Apollo Inertial Measurement Unit Temperature Control Problem

There are other, less dramatic areas in which hard-won knowledge and experience were not inculcated into the culture. One of these has to do with really scrutinizing and questioning requirements which turn out to be design drivers.

In the early 1960's, when the Apollo environmental control system was in design, the temperature control requirement for the coolant loop servicing the Command Module's Inertial Measurement Unit, or IMU, was stipulated by Massachusetts Institute of Technology (MIT), the associate contractor, to be 45 +/- 2 deg. F. for all mission phases.¹¹ With the immense variation in environmental and equipment heat loads imposed on the coolant system during the various mission phases, this posed an almost insurmountable control system problem for the environmental control system designers. A complex, electro-mechanical control system for the water boiler heat rejection device was developed, and was fraught with problems. Finally, after years of struggle, MIT was approached and relief from the tight tolerance was requested for short periods of time. As it turned out, the IMU could tolerate sizable coolant temperature excursions for short periods of time. Why wasn't the requirement re-evaluated before so much time, effort and expense were expended? The blame for allowing the program to struggle for so long before requesting relief can probably be ascribed to a number of factors including a possible reluctance to probe MIT and lack of communication between entities.

Shuttle EMU Front-to-back Dimensional Constraint

When the requirements for the Shuttle EMU were being formulated, one requirement imposed a severe size limitation on the front-to-back dimension (19-3/4 inches) of the EMU. This requirement was for a suited, pressurized crewmember to be able to traverse the inter-deck hatch (between the mid and flight decks) in order to be able to operate an unpressurized Orbiter in the event of loss of cabin pressure. As the scenario was presented, a rescue Orbiter would be outfitted with a rescue kit and launched to affect the rescue of the disabled orbiter. Two crewmembers of the disabled Orbiter would don their spacesuits, and the remaining crewmembers (up to five) would enter three-foot diameter, insulated fabric "balls", which would be strung like beads and transferred to the rescuing ship. The disabled Orbiter, assumed to be depressurized, would be operated by suited, pressurized crewmembers and landed. The program dutifully started designing the Personal Rescue Enclosure (PRE), and studying the overall program impact. As it turned out, the time necessary to prepare and launch a rescue Orbiter (assuming that an Orbiter on the pad had to be returned to the Vertical Assembly Building, relieved of its payload; outfitted for rescue; checked out; returned to the pad) could be on the order of a year. The requirement quietly died, but the impact on the Shuttle EMU design lingered on. The Portable Life Support System, or PLSS, was designed in modular fashion, with many valves clustered in a module, so it was not susceptible to further "trimming." The Hard Upper Torso, or HUT, had its size determined by the size of the astronaut candidates, so there was essentially no room for shrinkage. The principal victim of this requirement was the EMU's Display and Control Module (DCM). The DCM was "mashed" to fit the 19-3/4 inch dimension, with the result that displays were located close to the body and difficult to read, and some controls had to be mounted on the front of the DCM; located by means of a wrist mirror, and operated with difficulty. The requirement was finally questioned and lifted during the engineering review following the Challenger accident – at least four years after it was known that the requirement was not valid. Although the DCM had been designed, it had gone through a redesign, during which a more user-friendly configuration could have been implemented at little or no additional cost. Why didn't the community "push back" on the dimensional constraint when the rescue requirement became demonstrably impossible to meet, and thus allow at least the consideration of a more user-friendly DCM design? The answer is difficult to pinpoint, except to say that the culture in place at the time largely resisted questioning requirements, and everyone was hesitant to take a requirement off the books.

Shuttle EMU Man Loads

In the area of requirements generation, it is critical to understand the source of the requirement. Some requirements are engineering estimates. However, many are incorporations of lessons learned. Knowing the source can save time, expense and possibly catastrophic error. For example, loads imparted into the Shuttle EMU pressure suit by the user became an issue in 1984 as a result of an astronaut post flight debrief. Some wanted to explore if the man-load requirements might be underestimated. Others were opposed because they felt the existing requirements were all ready overly conservative. At the time, the source of the requirement was not adequately documented.

Discussions and the disagreement continued for years consuming personnel time without resolution. In 1991-92, instrumented testing was conducted. The data resulted in moderately higher man-load requirements, and caused a strengthening of the suit's restraint system.

Two years later in a passing conversation, one of the engineers involved learned that the original man-load requirements had been based on actual testing of a suit subject. The subject was a pilot in a U. S. Air Force (USAF) space program in the 1960s, thus outside the NASA experience base. Had that knowledge had been available a decade earlier, there likely would have been no expenses associated with technical discussions spanning years or of a manned spacesuit test program.

Program Support Organizational Alternatives

The tendency may be to focus on just “what” went on, i.e., the accounts of tests, in-flight experiences, failures, and looking at actual hardware items. Of equal or perhaps greater significance, is knowledge of “how” the programs were carried out, e.g., the development approach philosophy; how people were organized; how programs were managed. For example, during the '60's, the then Crew Systems Division was supporting Apollo and Gemini EVA programs simultaneously. There were at least two main ways of organizing. One would be around function. As an example, Gemini and Apollo EVA systems could be supported out of the same organizational element. Thus, engineers could be shuttled back and forth between programs as the need dictated, and communication would be facilitated. All test activities could be carried out by a specific organization, and so on. Another approach would be to dedicate specific offices to support each program: an Apollo Support Office, and a Gemini Support Office, with engineers focused only on their individual program. Flexibility and rapid response without priority conflicts would result. Each element would control its own testing. There was no knowledge reservoir to which those charged with making the decision could refer.

What was chosen was the two support office approach, but centralized testing. Veterans of the Apollo and Gemini Support Offices can recount their experiences in detail, and those seeking to organize for a new program could judge for themselves the merits of this approach.

Shuttle EMU Program Management Alternatives

Another example of the “how”, was the program management approach taken for the Shuttle EMU. At the start of the contractual effort, Crew and Thermal Systems Division managed both the technical and fiscal aspects of the contract. After a severe overrun prediction, management of the contract was assumed by the Orbiter and GFE Office. Those present during both phases of the program can present their experiences and conclusions as to the benefits and liabilities of both approaches, thus providing future programs with the benefit of their experiences.

Pros and Cons for Having a Development Unit

Another “how” was the headquarters-mandated decision that, as a cost-saving measure, the Shuttle EMU program would not have a development unit; they would go straight from design to certification (controlled configuration) hardware. What happened was that the certification unit underwent a series of test equipment failures, which induced a considerable amount of damage to the certification hardware, and it also experienced the unrelated but inevitable series of design failures. Since the unit was of controlled configuration, all activities required much more formal paperwork than would have been required of a development unit. Again, the program veterans can describe at length their experiences, and an engineer about to plan a new program can make his (or her) own conclusions about the wisdom of this approach.

C. Importance of Systematic Knowledge Capture and Utilization for the Future

Why wasn't action taken when the first high-pressure oxygen fire occurred, or even when the first injury to personnel occurred? Why wasn't the true root cause, i.e., lack of an overarching oxygen specification, exposed sooner? Why did the Shuttle EMU live with an obsolete requirement for so long? Why didn't the community know of the USAF man loads data? The knowledge dealing with all these events was “captured” in failure reports, in scientific reports, presentations and briefings, but was obviously never analyzed; made available and accessible and made part of the culture. Where was the knowledge base for those investigating how programs had been organized; experiences of operating without a development unit, and other areas? This type of information typically was not addressed in knowledge capture practices.

The stakes for future programs are much higher now than in the past. The successes of the Apollo, Skylab, Shuttle and ISS programs establish a new “baseline” for future space endeavors. We have already seen the lukewarm reception that return to the moon has experienced – simply stated the criticism, warranted or not, is

embodied in the phrase “We’ve already done that.” Voyages to Mars are so costly (and so long) as to render them unappetizing to a culture accustomed to rapid gratification. No matter what projects are finally pursued, some of the challenges to spacesuit systems will be very close to those experienced in the past – not identical, but similar. It is very important to realize that along with the successes of the past comes a tacit, but very real, expectation that things will go better in the future. In Gemini, there was no standard of comparison for EVA systems (little, if anything was known in any detail about the Russian system). Apollo EVA was likewise unencumbered with a basis of comparison. In ISS, the US Shuttle EMU and the Russian Orlan spacesuit systems exist side-by-side; each with advantages and disadvantages with no clear “winner.” The Shuttle EMU, for the most part, has been a reliable and flexible piece of machinery; however, this has come about after many early problems – notably, the fire in April of 1980 which burned a technician and destroyed hardware, and the STS-5 experience of unrelated failures occurring on each of the two EMU’s in flight. Many dollars and much re-engineering went into rectifying these and other failures occurring throughout the years. The plain truth is that although much was forgiven in the past, the reality is that we must be better in the future in tackling and resolving spacesuit system challenges than we have done in the past. The challenges will be greater, because the programs will be forced to impose them – challenges either technical or fiscal or (probably) both. One of the surest ways to mitigate the risk inherent in meeting these challenges is to make good use of the hard-won experience of the past.

The challenge facing NASA at present is both unique and familiar. It is facing a time of re-evaluation of strategic objectives, similar to that following Apollo. The fiscal hurdles are probably more severe than in the past, and the construction of the International Space Station and the repair and servicing missions pertaining to the Hubble telescope have set the bar very high for any future program. In order to have the best chance of successful achievement, the next program must not only have access to knowledge and experience gained during past programs, but this knowledge and experience base must be made a part of the daily regimen of designers, planners and managers. It is not enough to gather knowledge; this knowledge must be made universally accessible, and, further, it must be made a part of the new NASA culture.

D. Going About the Business of Systematizing Knowledge Capture

The practical mechanics of knowledge capture (and utilization) are just now really being investigated and structured by NASA in an organized fashion. In addition to the problems of identifying the types of knowledge already existing and/or obtainable, is the problem of organizing it, cataloging and indexing it, making it accessible, and, perhaps most important, communicating its existence to the engineers, managers and others who will be staffing the next agency projects. The information cannot be forced on the populace, but must be made attractive and shown to be advantageous to them.

There is an insidious aspect of any new structured enterprise put into practice by the government. There are people who positively salivate at the prospect of forming a bureaucracy which will implement and control activities in a given area. There is a fine line (too often crossed) between providing a service (which this knowledge capture system really is) and creating a self-serving, paper-work shuffling, metrics-evaluating black hole which will ultimately relegate a once-promising idea into a non-productive, circular eddy current, which will not fulfill its intended function, and merely siphon off resources.

There is a certainty that how future programs are to be structured and managed will assume more importance in the planning stages than they have in the past. In short, the tolerance for error and miscalculation, both in hardware design and in program execution will be much less than in the past. Although all errors are costly, the earlier errors are detected, the less the overall impact. As Richard Feynman said: “We are trying to prove ourselves wrong as quickly as possible, because only in that way can we find progress.” Making sure that the knowledge from those lessons mean something in future endeavors is the challenge facing NASA’s knowledge capture program.

III. Discussion

In the US spacesuit community, there are many organizations engaging in knowledge capture. Each organization performs the function to support its own needs. In the past, these activities were separate. However, the need for support from other organizations has transformed those formerly separate activities into an inter-related, closed-loop system that leverages spacesuit knowledge for mutual benefit of all. The four elements of this synergistic system are:

1. Establishing Requirements
2. Usage Experience

3. Physical Preservation
4. Knowledge Capture

1. Establishing Requirements

Establishing Requirements is the first step in the evolution of a program to develop and implement a spacesuit system. NASA creates the technical requirements for a suit-system with help of contractor community. As the initial technical requirements can have profound impacts on usability, safety, development cost, recurring program costs, implementation time, durability and reliability of a spacesuit system, this phase of a program has the greatest opportunity for improving quality while reducing cost and schedule. However, how effectively initial technical requirements are set is really a resultant of how effectively knowledge is captured and used, this topic is addressed later in this discussion.

2. Usage Experience

Usage experience is a term which we shall use to “capture” that body of knowledge during a program. With the Shuttle Extravehicular Mobility Unit (EMU) (Fig. 5) having supported US space exploration for over 30 years, it would be easy to think of this experience in terms of the low Earth orbit (LEO) operations of the Shuttle EMU. When the Shuttle fleet retires, there will have been 175 US spaceflights. Over 77 percent of those flights were Shuttle. Seventeen configurations of spacesuit saw space use supporting those flights. Each configuration provided thousands of experiences worth being retained for future reference. However, before a spacesuit system reaches flight, there is development. At least 150 development configurations were manufactured and evaluated in preparation for the flight configurations that followed. Each prototype provided lessons. More than 79 percent of that development was more than a quarter century ago.



Figure 5. 1984 Bruce McChandless Using a Rocket Pack (Untethered) Called A Manned Maneuvering Unit (Courtesy NASA)

Historical Perspective

Spacesuit experience started with adapting high altitude pressure suits for space. What triggered the development of the first space-specific spacesuit system to see flight was Cosmonaut Aleksey Leonov's extra-vehicular activity (EVA) or "spacewalk" of March 18, 1965? This galvanized the fledgling U.S. EVA community led by NASA. The next US flight was Gemini IV. The pressure suit originally scheduled for Gemini IV was a David Clark G3C, which was an intra-vehicular only suit. The US had no EVA ready pressure suit or life support system. The US had been planned for EVA much later on the Gemini program. Yet, Gemini IV US Astronaut Ed White performed a successful EVA on June 3, 1965 (Fig. 6). In less than three months, NASA developed, launched and successfully used a spacesuit system. Imagine the lessons that could be learned from that one feat.



Figure 6. The First US “Space Walk” (Courtesy NASA)

Humans have not ventured beyond the micro-gravity of LEO for more than 38 years. As we prepare return to deep space exploration and progress to other locations in our solar system, the exploration will have to address significant gravitational forces on spacesuit and crewmember mass, particulate and potentially biological contamination, plus a host of other challenges. As a result, NASA and contractor engineers/scientists are studying the Apollo surface missions (Fig.7). The conclusions from Apollo experience is already flowing into next generation development (Fig. 8).

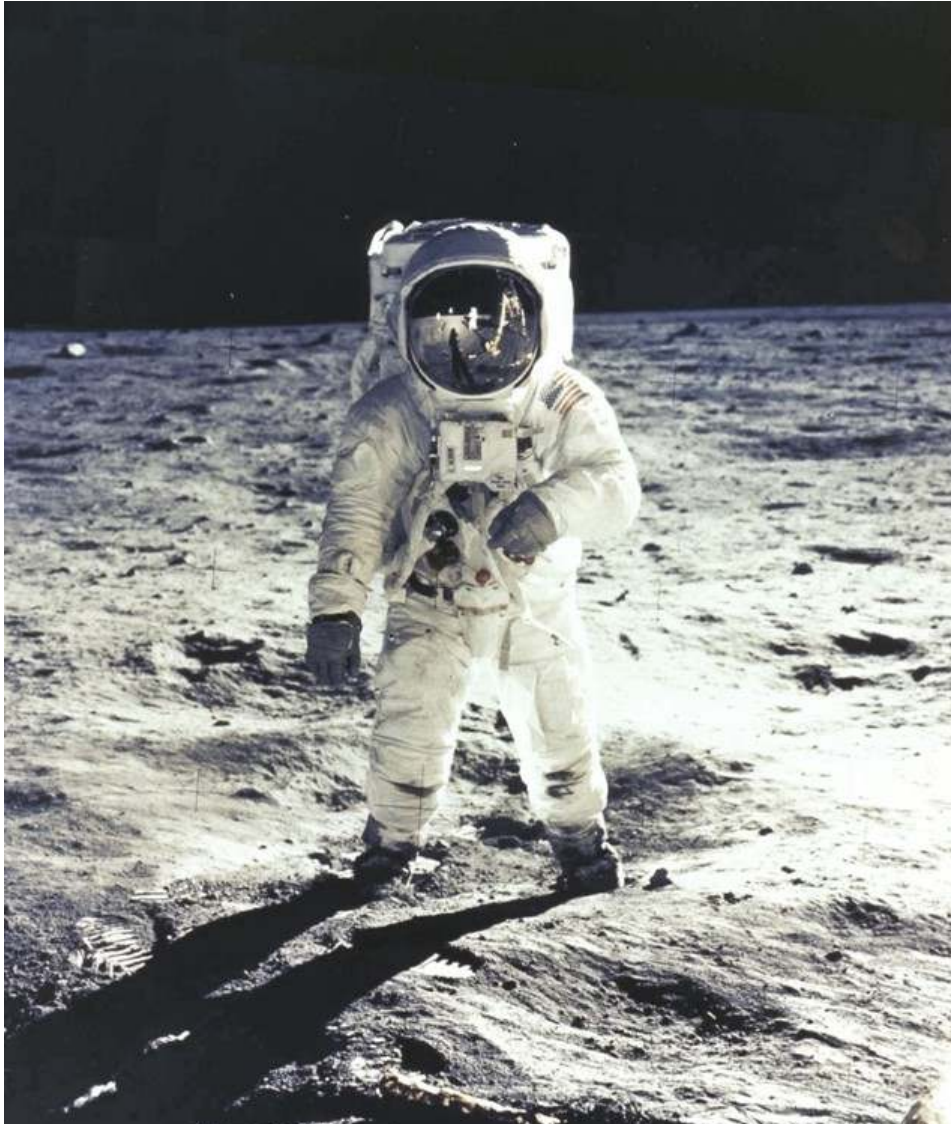


Figure 7. Apollo 11 - First Human Exploration of Another Celestial Location (Courtesy NASA)



Figure 8. HS's 5th Mars Concept in a 2009 Analog Arctic Evaluation (Courtesy Hamilton Sundstrand)

Another interesting facet of the US experience is that it has been not exclusively with US spacesuits. NASA has had dialog and joint projects with the Russia Space Agency (RSA) since the Apollo Soyuz Test project. As the "Cold War" was fading, US and Soviet space businesses additionally established dialogs. In 1992 under internal funding, HS began evaluating the RSA technology and systems in cooperation with numerous Russian space enterprises. In 1993, HS was allowed to lease an Orlan-DMA, which was the first example of then current Russian spacesuit technology to be brought to the U.S. for evaluation. In parallel, the Space Station Freedom program was revised for RSA participation to form the International Space Station (ISS). ISS was premised on any nationality using either Russian or U.S. suit-systems, whichever was the most programmatically convenient. Subsequently, NASA selected HS to certify the Orlan to NASA safety requirements and provide real-time mission support whenever US Astronauts are operating in Russian spacesuits. The first occurred was with the debut of the Orlan M

(Fig. 9) on April 29, 1997. This had the distinction of being the world's first Russian/US crewmember EVA off the Mir Space Station (Russian EVA #78, U.S. EVA #77).



Figure 9. First Orlan M & First Astronaut/Cosmonaut EVA (Courtesy NASA)

Another factor in differences between knowledge bases is that no contractor has been a system or sub-system provider in all spacesuit programs. Conversely, not all spacesuit efforts have been NASA programs. The Manned Orbiting Laboratory (MOL) program was a United States Air Force (USAF) effort in the 1960s. The USAF took

some fundamentally different approaches to spacesuit programs, to which NASA only had a secondary exposure. HS won all the contracts for MOL pressure suits and was suit life support systems provider for all MOL Spacesuit efforts.

Another example is the European Space Agency (ESA) Space Station Freedom (SSF) spacesuit program (Fig. 9). This WAS a 1987, 7.2 psi suit effort called the Extra-vehicular Space Suit System (ESSS). Dornier was ESA's prime contractor for the ESSS. Dornier selected a US contractor, HS, as a consultant on ESSS design and creation of program management systems. HS was also contracted to provide key life support subsystems.



Figure 2. The European Space Agency ESSS Concept (Courtesy Dornier)

Economic pressures caused ESA to downsize its space plans in the early 1990s. One of the consequences was that ESA reevaluated the ESSS program in 1992. This resulted in a new program under the name of EVA Suit 2000 that drew ESA into partnership with the Russian Space Agency (RSA). Dornier and Zvezda became co-contractors for the EVA Suit 2000 program. In 1993, SSF was expanded to include the RSA under the name of International Space Station (ISS). ESA and the RSA lobbied for US support for EVA Suit 2000 to become the one common space suit system for ISS, to be jointly developed by US, Russia and Europe. However, the U. S. "Enhanced" EMU was already too far along for such consideration. EVA Suit 2000 progressed to a prototype level before faltering due to budget pressures. ISS was consequently built with minimum-cost upgraded NASA and RSA suits.

Yet another factor behind differing spacesuit knowledge bases that different organizations or facets of organizations have different knowledge capture needs, depending on the functions of the organization. The historical portions of the community have to provide and update an overview to support public interest. NASA's engineering and administrative functions need top-level technical wisdom to effectively establish requirements, make judgments and provide program oversight. NASA or major spacesuit contractors require system and interface level insight to successfully conduct system design and integration. Supporting contractors must draw on their knowledge bases to effectively establish subsystem requirements and execute designs. Also, contractors conduct internally funded research and development, which creates intellectual property that cannot be shared without dissemination protections.

However the first challenges of any U.S. spacesuit design clearly fall on NASA. The importance of generating and establishing realistically valid requirements cannot be overstated. The critical time for this is during the early phases of a program, because the impact of a “bad” requirement can linger throughout the program, even though it may be “scrubbed” later on.

Knowledge Capture During a Project

Initial Information Flow in the Project Design Phase

Once a realistic set of requirements is generated, the design process can begin. Any worthwhile design process will generate a number of concepts for fulfilling requirements, and conduct a “shakeout” process to eliminate all but the most promising. One aspect of design which turns out to be important throughout the life of the item is the margin built into the design.

The ability of the Shuttle EMU to not only meet original requirements but to surpass them is reflected in the system’s design margin. For example, the life support system had a design life of 15 years, but life extension testing and analysis have extended the life of certain components to 20 years or more. Originally slated for three EVA’s between ground servicings, the life support system was proved to be capable of 25 EVAs between ground servicings, with the water loop good for 50. EVA time was originally set for 7 hours, and we now routinely see EVAs of more than 8 hours. The original battery had a guaranteed wet (serviced) life of 90 days. Extensive testing of “life expired” (so-called Class II) batteries allowed this to be extended to 270 days. These kinds of margins have paid huge dividends for the Shuttle and ISS programs. Much of the testing was done on items which had exceeded their design life, but was conducted with the same rigor as would have been the case for certification or production items. The careful documenting of supporting testing and analysis of component and system materials and configuration has provided the program with a solid technical basis on which decisions could be made.

Typically, the early phases of design will culminate in some sort of early review, for example, a Preliminary Design Review (PDR), conducted at roughly the ten percent design completion phase. Leading up to the PDR, there should be mockup evaluations; breadboard or schematic testing; analyses, and design iterations. The tendency is to keep fairly good records of the favored (and ultimately selected) concepts, but it is important to keep a record of those concepts not selected, and why they did not find favor.

The PDR, or its equivalent, will generate findings – usually in the form of review item dispositions (RIDs), and action items. The tracking and closeout of these two classes of items is crucial to assuring that all those valid requirements mentioned earlier are met. A careful record of not only the review item itself, but its ultimate disposition is important.

Knowledge capture during design is critical not only for the project at hand, but as a historical resource. Making these types of information available to future designers and planners would be a valuable resource in providing a template for a design philosophy, and for uncovering latent margin in a design.

Information Gained from Early Testing and its Importance to the Project

The testing which goes on in the early stages of a program is critically important to the ultimate selection of a final design. This is also true for the components used in both successful and unsuccessful breadboard and component testing.

The testing should not only explore the capabilities of the hardware to meet the specified (required) operating parameters and ranges, but also to determine the margin which exists in terms of such things as cycles, overpressure, over-temperature tolerance, and ultimate strength.

As important as this early testing is, in the case of crew equipment such as EVA items, the crew interface is just as important. Seemingly minor things like the size, shape or coloration of labels; the shape and location of handles; the ease of donning and doffing – all these must be investigated, and documented. Crewmembers are people; and people differ in their likes and dislikes. Written as well as visual records are crucial not only in documenting selections, but also in providing in-depth information as to why a particular approach was found acceptable or unacceptable. Being able to access this type of knowledge could be extremely important to those investigating approaches for a new project.

Another early important milestone in the design process is the design and fabrication of a development or prototype unit. This should be the “best guess” at what a production unit might be in terms of size, shape, component layout, controls, displays, crew interface, weight and volume. There must be a faithful configuration definition and record, even though this portion of the program is not typically subject to the rigid configuration

management requirements found after final design is established. A common practice is to use “red-lined” drawings and some sort of written configuration record, including changes made. A common complaint against this kind of rigor is that it is not official, and therefore cannot be used in any sort of formal process. The Quality Assurance organization can be contacted and their help sought in making the best type of record of development hardware configuration.

The first value of a development unit is not to acquire test data, but to prove that the ultimate product can actually be built. Testing comes next, and once again, exploration of not only the ability to meet required ranges but the inherent margin is critically important. There is a tendency to want to test rapidly, and avoid time-consuming documentation. There are certain requirements for even the simplest test which, if met, will render that data essentially timeless and useful for critical decisions later in the program. The requirements may be stated simply, and met with uncomplicated measures. The requirements are simply to:

- 1) Have a definite set of requirements for the test, with expected outcomes. These need not be pass/fail criteria, although that may be valuable.
- 2) Have a concrete, retrievable definition of the design which is undergoing test. This may be in terms of red-lined drawings, sketches, photographs, etc., but it must be intelligible enough to be able to relate the test item to a later flight configuration.
- 3) Have a definite procedure as to what was actually done during the test. There should be a baseline procedure, changes to which are documented during the test.
- 4) Have detailed records of what actually happened – data sheets; observations; photographs; videos; and any other means of detailing what transpired. This includes unexpected occurrences, failures, and other types of anomalies, along with analyses of why they happened.

Being able to collect flight-applicable data without the use of actual flight hardware is valuable. During the Gemini ELSS development, the development unit chestpack was put through dynamic testing which it passed, and provided assurance that the flight configuration would pass. Previously mentioned was the life extension obtained by the test of Class II Shuttle EMU batteries. In another example, during STS-51I in August, 1985, Astronaut James “Ox” van Hoften, while positioned in fixed foot restraints, attempted to stop the slow spin of the LEASAT (US Navy LEASed SATellite) by grasping and releasing a bar on the satellite. When he remarked that he “felt it down to his toes”, the EVA community was concerned about possible overloading of the suit’s restraint system. Post-flight testing conducted on the ground by a number of subjects in flight-like training suits indicated that the restraint system should be redesigned to provide higher margins of safety. The fidelity of training suits to flight was indisputable, and thus the data was directly translatable to the flight case. Upgrading of training and flight hardware was subsequently carried out.

Perhaps the most glaring failure to carry out flight-applicable development testing is illustrated by the EMU secondary oxygen pressure regulator module testing which ultimately determined its appropriateness for flight. Testing concentrated on the regulator internal parts, with the principal concern being the suitability of the Vespel seat for oxygen compatibility, and the ability of the two-stage design to satisfactorily regulate pressure. Unlike the component development test configuration, the actual configuration for flight use included the expansion chamber, which, along with other manufacturing features discussed earlier, are judged to have contributed to the ultimate catastrophic fire which severely burned a technician, and essentially wiped out a set of EMU hardware. The data relating to this incident and the subsequent redesigns is a “must see” for anyone contemplating a high-pressure oxygen system.

Most programs typically show a development test “bar” ending before the final design review, and, just as typically, many programs encounter delays in development testing, but no schedule relief for the final design review, sometimes called the Critical Design Review (CDR). The final design is not really “final” until, like an election, all the precincts have reported. Development testing is an important “precinct.”

The CDR, like the PDR, will generate findings. As an example, the Shuttle EMU Life Support System CDR portion generated over 400 RIDs. This magnitude of paper demands a system of cataloguing, organizing, tracking, and recording disposition. Although these types of reviews are resource “hungry”, the alternative is chaos, and the danger that significant deficiencies will go unattended.

Many times, the PDR and/or CDR will not be accomplished at a single point in time. In that case, a Delta review is held, and this, too, must be documented.

These records have application for the project itself, and for potential future use.

Gathering Information on the Final Design

Once the baseline design has been established, flight-configuration hardware is fabricated and assembled. Inevitably, changes occur which alter the baseline, and a careful record of authorized configuration changes must be kept. One way is by use of what is called a Master Authorized Change Record (MACR), which depicts the approved flight configuration. Each end item (contract deliverable) has its own Authorized Change Record (ACR), which shows how far out of configuration it is.

The hardware selected for certification testing is, ideally, identical to that which would fly if all tests were passed successfully. Documentation requirements for certification are extensive – there must be a clear path from requirements to test results, with information on configuration, test requirements and procedures, results, failure reports and disposition, and final results carefully documented in an organized and intelligible fashion. There is generally a tremendous time lag between the completion of certification testing and issuance of the report, not to mention the tedious process of multi-level review and approval. Without eliminating the need for the final report, there have been systems evolved which allow certification approval before completion of the final written report. One technique is the conduct of a Qualification Site Approval, or QSA. The approach is brutally simple. A team travels to the site of testing; secures the help of contractor employees from test technicians and engineers to Quality Assurance personnel and company managers. An intense “boiler room” operation is conducted over a few days, with review of test requirements and procedures; hardware configuration including examination of the item itself; test equipment and facilities; test data in both raw and reduced form; any non-conformance records and dispositions, including failure reports; analyses and conclusions reached. Interviews may be conducted with test technicians, engineers and inspectors. Minutes, including required actions, are taken and signed off by authorized representatives of NASA and the contractor. From this exhaustive, concentrated review, a determination is made as to whether or not the hardware item or items are considered certified, with whatever caveats are deemed appropriate. As previously mentioned, the requirement for a final report is not negated, but, hopefully, becomes a formality. QSA records are particularly crucial, since they are the foundation for approval prior to approval of the final report. Being able to review past QSA records can be of tremendous use to future program personnel.

Knowledge Capture on Flight Hardware

The production phase of a program brings with it unique needs for knowledge capture. Of primary importance is the status of the hardware vis-à-vis flight authorized configuration, as well as the status of failure applicability and non-conformance disposition. The build history is important, particularly in determining potential causes failures encountered later in the item’s life. Traceability of lots or batches of parts and materials is crucial in failure analysis and rectification. Traceability is two way: (1) ability to find the lot, batch, etc. of a particular item or material which is used in a particular end item, and (2) ability to identify all the end items in which a certain lot or batch has been used.

Hardware pre-delivery acceptance tests are an important source of data, starting with component acceptance testing at a vendor and culminating with contractually binding testing by the supplier. These data usually form part of the acceptance data pack, and are invaluable in failure analysis of the items itself or like items.

Once delivered, production items undergo a series of tests designed to show acceptability for activities along the way to ultimate flight. Often called Pre-Installation Acceptance, or PIA, testing, this family of tests covers a wide breadth of requirements. There are tests for chamber test readiness; for spacecraft interface testing; and tests conducted in flight prior to use. As program formality increases, so does the formality of test documentation and recordkeeping.

Actual flight usage is documented in extreme detail, including video, charts, and personal records. An important area of records is post-flight de-briefings, both general and specific. Being able to review flight usage records can be of immense value in constructing new programs.

Wrapping up – Knowledge Captured at the Conclusion of a Program

At the end of a program, it is usually very valuable to have a final report specific to a particular system. The Skylab ALSA had a comprehensive, two-volume report with content including: program structure at the contractor; definition of products with technical information and outline drawings; program history including design and development, problem areas; qualification test program with failures discussed; field and plant post-delivery support; mission summary; final disposition of hardware; and some conclusions. Admittedly, the relatively short duration of the program (from January, 1970 till the end of March, 1974) made this a relatively easy task compared to that facing the Shuttle EMU, which started in January 1977 and is still in progress.

Although hardware disposition was an item covered in the ALSA final report, it actually extended only to the status of the hardware from the contractor's viewpoint – some was left on orbit to be consumed when the Orbital Workshop reentered in July of 1979. The remainder of the hardware found various homes at NASA and elsewhere. The next section addresses physical preservation, and its importance to the knowledge capture process.

3. Physical Preservation

The Smithsonian Institution's National Air and Space Museum (NASM) is the caretaker of over 1200 spacesuit artifacts of the US space program. Included in that number are nearly 300 pressure suits, and their component gloves, helmets, boots and attachments. Calling the collection a spacesuit collection is a bit of a misnomer. Suits in the collection range from an early deep-sea diving suit that weighs several hundred pounds to the components from the Space Shuttle/International Space Station Extravehicular Mobility Unit in which astronauts build the space station while orbiting the Earth. The collection includes pre-space age pressure suits designed to protect life at high altitudes. These include pressure suits that B.F. Goodrich and David Clark Company designed for the United States Navy (USN) and the US Air Force (USAF). When the nation first began to send humans into space fifty years ago, engineers adapted these high altitude flight suits to serve as temporary lifeboats for this new breed of explorer. Flight suits were retrofitted with life support systems and connections to spacecraft. Mercury and Gemini suits were born out of these adaptations.

It was President Kennedy's challenge of the Apollo program that brought about changes in the approach to spacesuits. For Apollo, a suit would no longer be the backup or a precautionary system, but would be the only source of life-support as men first explored the Moon. The Apollo spacesuits are true artifacts of the Apollo program in that they exhibit the engineering, innovation and adaptation of the materials, science and technology that were required to send men to the Moon. And they are unique in the personalized way in which they had to be manufactured in order to do their job. Among the most famous spacesuits in NASM's collection are the twelve Apollo spacesuits that astronauts wore on the surface of the Moon. No less fascinating for visitors and historians are the developmental test and training suits that did not fly to the Moon, but tell an equally important story. These suits and their components represent the fossil record of suit development during the 1960s and early 1970s. Each suit documents an engineering idea or challenge. During the fast pace of the Apollo program, little or no paper documentation remains on the discussion that motivated these innovations. Today the curatorial department must rely on the suits themselves and the memories of the participants to tell this story.

NASM obtained the suits, parts and components in its collection largely through an agreement between the museum and NASA. The NASA Administrator James E. Webb, Secretary of the Smithsonian S. Dillon Ripley and Director of the newly inaugurated National Air and Space Museum S. Paul Johnston signed the "NASA-NASM" agreement in March 1967. This agreement granted the museum the right of first refusal of artifacts once NASA had finished with them for programmatic purposes. The agreement granted the museum the collection and responsibility for preserving the artifacts of the space age and relieved NASA of the responsibility of negotiating loans and travel schedules for exhibits, while maintaining a national and international public visibility of their programs. The museum also inherited the NASA loan program that had begun in 1961. Through the agreement with NASA, it was able to collect a suite of Mercury and Gemini spacesuits, and also samples of the high altitude pressure suits that NASA tested and adapted in preparation for these missions. As the Apollo program drew to a close, NASM received a second wave of artifacts from NASA from that program. Under the auspices of the agreement, NASA transferred many objects to the Air and Space Museum while they were on display at third party museums.

During the peak of collecting from NASA, both it and the museum considered their greatest mission to be collecting for exhibition. During the mid-1970s was the peak era of demand for Apollo and other human spaceflight artifacts. In the rush to share precious spacesuits with the public, NASA had often sent out spacesuits with mismatched parts, affixing gloves and helmets that were on hand without complete verification that they matched. Property officers not spacesuit technicians handled these transactions—a fact that even the museum did not understand immediately. In addition, both NASA and NASM considered that the wide temperature ranges that the suits were designed to operate in was indicative of the relative rigor of the materials of the spacesuit. It seemed that if the suits could withstand wide ranges of temperatures in a vacuum over a short period of time, they could withstand almost indefinite display to the public here on Earth.

The relative fragility of spacesuits became apparent to NASM by the mid-1980s. At that time, the visible light damage to Ed White's Gemini IV spacesuit was obvious to the casual observer. The light damage was so extensive that the Nomex in the cover layer had become yellow and brittle. What was not as obvious upon external inspection was that other suits were suffering from similar materials breakdown from the inside out. From the dawn of human spaceflight American spacesuit engineers had drawn from the latest existing materials to fabricate suits. The ILC

Industries design for the Apollo A7-L spacesuits included among others manufactured textiles that DuPont had created for the consumer market. DuPont had to provide materials scientists as advisers to assist ILC in the fabrication and sealing of these materials. Although all parties involved were confident about the short-term performance of multiple materials for the course of the Apollo program, no one had considered the long-term performance of multilayered spacesuits. Closest attention was paid to the performance of individual layers. Even in the case of the acknowledged vulnerability of the neoprene in the pressure layer, the solution was to add Age-Right-White to the neoprene mixture to maintain its suppleness.

In 1994, when Amanda J. Young took over the spacesuit collection, she immediately set out to resolve the long-standing accounting problems that had plagued the spacesuit collection since it had come to NASM. Armed with the original transfer papers with serial numbers and the Archer lists that documented which component flew on spacecraft, Young set out to compare all suits and components with their official documentation, visiting borrowing museums throughout the nation. Along the way, she discovered that there were wide disparities in the condition of all spacesuits in the collection. Wrist connects on training suits were far worse condition, exhibiting more corrosion in the anodized aluminum than those flown in space. Apollo suits from Apollo 15 on seemed to be much more resilient than their predecessors. In 1999, she applied for and was granted a “Save America’s Treasures” grant from the White House Millennium Council and the U.S. Department of Interior. That grant, along with generous matching funds from Hamilton Sundstrand allowed Young to hire a spacesuit conservator, specializing in synthetic materials and to convene a materials advisory group that drew on individuals from the spacesuit community and materials scientists. The primary goals of this interdisciplinary project were to preserve the 12 moon walking spacesuits in the NASM collection and to share the results of the research on the deterioration and preservation of spacesuits with other museums. This project had four phases:

- Phase I: A materials advisory group was organized and maintained to assist and advise the project team on issues related to the deterioration and preservation of spacesuit materials. Apollo spacesuits are composed of 20 to 24 layers of modern materials including Dacron, Mylar, nylon, Teflon-coated fiberglass textiles, polyvinyl chloride, natural and synthetic rubbers, plastics and metals. Extensive consultation with these individuals was deemed necessary due to the scarcity of reliable, published information on this subject.
- Phase II: Each Apollo spacesuit in the collection of NASM was thoroughly documented and examined. Non-destructive analysis was performed in order to establish a condition baseline and permit monitoring of future changes. CT scans of a single suit were undertaken so that the 3-d morphology of the interior layers could be examined and recorded. Conservation professionals and experts in the field performed analysis of specific materials and their degradation products.
- Phase III: Storage and handling systems have been designed and implemented for use with the spacesuit collection at NASM. Environmental parameters have been established for the storage of these modern materials based on research undertaken during the project. Unlike previous cold room storage conditions, these standards called for relatively warm (60-65 degree Fahrenheit) and low humidity (less than 30% rH) to best stabilize the suits and retard materials interaction. This was established at the Paul E. Garber Preservation, Restoration, and Storage Facility, located in Suitland, Md.
- Phase IV: The group established and published guidelines and standards of practice have been produced summarizing information and research assembled during the project. These guidelines form a blueprint for further research, and serve as the most up-to-date guidelines for the preservation, storage, and display of spacesuits.

A by-product of that SAT effort was the NASM report that will allow preservationists and NASM volunteers alike to cross reference the history historical context of an artifact before them in seconds. Over the course of four years, Young documented, collated multiple records and recruited a legion of experts. One of the many by-products of her work in investigating the suits and their materials is her book: *Spacesuits: The Smithsonian National Air and Space Museum Collection*. The book published the photographs of NASM staff photographer Mark Avino and the pioneering x-rays that Ron Cunningham, senior conservator at the Smithsonian Museum Conservation Institute made. The book offers the non-specialist public a view of the spacesuit collection that has never been available before.

Following the Apollo spacesuit portion of SAT, Young secured funding for improved NASM preservation facilities in the Steven F. Udvar-Hazy Center near Washington Dulles International Airport, which is the companion facility to the Museum on the National Mall. Before her retirement in June 2009, the move was in motion. Under the leadership of her successor, Dr. Cathleen Lewis, the NASM spacesuit collection made the transition to the new

storage facility at the Udvar-Hazy Center and the NASM spacesuit physical and historical preservation continues as the museum establishes new standards that will preserve the collection for at least another fifty years.

A byproduct of NASM's preservation efforts is knowledge re-capture. Some of the contractor organizations that produced the suits in the collection left the spacesuit business decades ago. Most of the spacesuit's designers are no longer available to educate today's spacesuit community. Thanks to NASM's preservation efforts, NASA and contractor engineers who have a need to study past spacesuit technologies can, by arrangement, travel to the Udvar-Hazy Center and analyze first-hand the past attempts at solving challenges that still confront the spacesuit community.

Knowledge Capture

There are many types of knowledge capture needs relating to spacesuits. An overview has to be provided and updated to support public interest. NASA needs top-level wisdom to effectively establish requirements, make judgments and provide program oversight. NASA or major spacesuit contractors require system and interface level understanding and insight to conduct system design and integration. Supporting contractors must draw on their knowledge bases to effectively establish subsystem requirements and execute designs.

a) Knowledge Capture from Gemini EVA

The importance of documenting work has been generally understood by all and accomplished when the opportunity permits. For example when the Gemini Program was drawing to a close in late 1966, there was time to do some reflection on certain aspects of the program; particularly those which had failed to meet early expectations. One of these aspects was EVA, and in particular, the ELSS used for EVA's on Gemini missions IX-A, X, XI and XII.

NASA publication SP-149, "Summary of Gemini Extravehicular Activity", chronicled in exacting detail the developmental and operational successes and failures of the Gemini EVA Program. On the plus side, EVA was proved to be feasible and, as long as workload was controlled, was able to demonstrate that useful work could be done in space by a suited crewmember. Very limited evaluation of a maneuvering device, the Hand-Held Maneuvering Unit (HHMU) shown in Fig. 10, was carried out; equipment was retrieved from another vehicle; and the importance of body stabilization and tethering of equipment was demonstrated.



Figure 3. HHMU

On the negative side, the difficulty of working in the suit was grossly underestimated. The design approach selected for the ELSS - astronaut cooling by a ventilating gas stream - was inadequate to accommodate the workloads encountered. Lack of adequate body restraints added to the difficulties with the life support system, and as a result, the plans for evaluating the Astronaut Maneuvering Unit had to be scrapped for both the Gemini IX-A and XII missions. Lack of adequate training environments compounded the problem.

The findings on Gemini EVA, as documented in this report, were instrumental in assuring the program implementation of neutral buoyancy as a mainstay of future EVA training. Also, the importance of body stabilization was not lost on future mission planners. Most important, from a life support system point of view, was the

implementation of circulated cooling water through tubes sewn into a garment and worn close to the skin. This concept had been around since the early 1960's, but neither Gemini nor Apollo had baselined this approach. While stopping short of stating the future EVA systems should use water cooling, SP-149 did state (page 11-1): "(6) In future Extravehicular Life Support Systems, consideration should be given to cooling systems with greater heat removal capacity than the gaseous cooling systems used in the Gemini Program."

There were other findings related to the ELSS; non-technical findings which had their own significance. These had to do with the cost growth of the program, and the lessons which were there for the learning. However, for this avenue of exploration, there was no official post-mortem analysis of findings; no NASA-issued report which encapsulated the history and use, and drew meaningful conclusions which could be disseminated.

To put it bluntly, but accurately, the ELSS program grew from an initial estimate of \$133,000 in 1963 to a run-out total of \$3,583,471 by the time the contract was closed out in 1967. Thus, the final cost was almost 27 times the original estimate. In a masterpiece of understatement, then Deputy Director of Johnson Space Center George M.

Low remarked on a note jotted on the cover of an informal report on the ELSS cost history that if they had known that it would have cost that much, they might have gone about the program differently.

Naturally, the cost growth didn't happen all at once. The program grew in spasmodic leaps as changes in requirements, deficits in planning and inevitable problems encountered during development and use made their contributions. When the agonizing review of why the cost growth had been experienced was undertaken, both the contractor and the NASA element responsible for the development produced documentation which tried not so much to escape blame as to spread it. Perusal of both of these documents indicates several main drivers for cost growth: (1) changes in requirements: system was changed from a simple, self-contained open loop system good for 15 minutes to an umbilical-supplied semi-open loop system good for over an hour; spacecraft stowage requirements caused changes in configuration and stowage technique; interface with the Air Force Astronaut Maneuvering Unit; and other changes; (2) Gemini IV impact: ELSS umbilical was modified to support Gemini IV, and the rest of the program delayed; (3) schedule pressure when program resumed; (4) failures; (5) problem vendors; (6) lack of planning (and cost estimates) for ground support equipment, field support, spares and repair. These documents were never released or otherwise made available other than to the parties directly involved, and their management. This is an example of knowledge un-captured. In retrospect, the SP-149 document, to really have told the whole EVA story, should have included the cost histories and growth explanations for the suit, as well as for the ELSS.

b. Knowledge Capture for the Skylab Astronaut Life Support System (ALSA)

This is not to say that the programmatic knowledge gained on the ELSS program was lost. Some of the same technical team members on the NASA side, as well as at the contractor side, were assembled for the Skylab EMU program. The EVA life support system for that program was called the Astronaut Life Support System, or ALSA. The system configuration again had an umbilical supply for oxygen, but used water supply and return lines to provide cooling via a garment laced with tiny tubes. Oddly enough, the initial cost estimate for the program was about \$3,500,000 which was close to the final cost of the Gemini ELSS program, and the run-out was \$15,520,000, which meant that growth had slowed to a factor of 4.4 versus 27 in Gemini. Once again, field support, ground support equipment and other items, though not omitted, were severely underscoped. Changes and failures once again made their presence felt. The success of EVA in saving the Skylab vehicle, and the program itself, perhaps served to mitigate the scrutiny of cost growth which might have otherwise occurred.

This time, a comprehensive final report was published, which included developmental histories, pictures, change history, mission results, hardware descriptions, and field support as well as plant activities. Cost numbers were not included, but were easily obtained from the required financial reports gathered during the program. It is not known whether or not this report, T74-10332, is available in the NASA archives, but even if it does reside there, the chances are slim that many know of it. There was no real forcing function to make the Skylab teams aware of the previous Gemini history, and to show that they had learned from it; and no system in place to assure that both the Gemini and Skylab EVA life support system program results are readily available to future system planners.

c. Some Conclusions about Past Experience with Captured Knowledge

The point of the above examples is that, captured or not, past knowledge is of little use unless it is made available and its study incorporated into the process of planning a program, including not only the design of hardware but also the programmatic aspects.

With the Shuttle program drawing to a close, and the demise of the ISS within the foreseeable future, it is reasonable to ask what has been learned about the spacesuit systems of these programs. Books such as "US Spacesuits" (Praxis Publishing) can provide some insight into Shuttle and ISS EMU development and usage history, as well as Gemini, Apollo and Skylab, but their treatment is largely technical, and focusing on high-visibility occurrences and features.¹² The real knowledge of the development and usage experience pertaining to the Shuttle EMU, and its derivative, the ISS EMU, resides in a vast array of reports, presentations, photographs, analyses, audio and visual media, and the logs and memories of the actual participants.

Some attempts have been made to start collating spacesuit system information. For example, Hamilton Standard (now Hamilton Sundstrand), put together in 1992 a document entitled "EMU Requirements Evolution" (SEMU-66-017A). In the Introduction, the authors state that "Although a fair representation of personnel remains dating from the contract inception, this representation is disappearing at an increasing rate and leaving a void in the "history" or "unwritten" aspect of system knowledge. This is compounded by an assumed average engineering lifetime on the job of five years. The EMU has experienced at least three generations of personnel (both at NASA, HS and ILC), and could reasonably be expected to host at least six more in the future. Although design criteria are well documented in specification or drawing format, there is no formal record of "why was that requirement set?" Bear in

mind that this was written no later than 1992; the contract was let in 1977, you are reading this in 2011; and the EMU is planned for use until 2020. The book on EMU requirements evolution was a recognition that the aspect of knowledge relating to the genesis of EMU requirements is worth preserving, since the presence of experienced personnel is fleeting.

Another attempt to capture history in the EMU program was the generation of a one-page developmental/flight history chart. Months and years were shown across the top; as were flights. Significant program activities and events were shown as bars and diamonds or triangles throughout the page. The last update showed flight history through 1993, and planned activities through 1997. On one sheet, information could then be gained about how long it takes to design, certify, produce, and fly hardware for those phases.

The above mentioned efforts, instead of being ongoing, were one-shot enterprises. To be of the most value, they should be maintained, and made accessible to engineers and managers.

Another type of knowledge capture, as mentioned earlier in this paper and explained in more detail later, resides in the recollections of veterans. NASA's oral history project has captured a vast number of these records – both on audio and video – for posterity. These records, though voluminous, are interesting and educational as well as entertaining. As well, the NESC, the JSC Chief Knowledge Officer, and the JSC Engineering Academy have hosted a series of lectures and seminars featuring veterans addressing various topics, ranging from failure analysis, program experience, management – the list goes on.

The challenge is to catalog and organize all the material in such a way that a potential user can quickly access a specific area of interest. If the system is not easy to use, it won't be used. Everyone is always busy, so if the information is buried, few will take the time and effort necessary to find it.

As has been stated previously, the importance of avoiding past mistakes, programmatic as well as technical, is even more critical today than in the past. Avoidance and/or mitigation of risk in resource utilization, schedule maintenance and technical performance have never been more important than now, when future programs are being planned. One way to accomplish this is to use the hard-won lessons of the past. Mentoring by experienced persons is a valuable way to accomplish this, but there seems to be less and less personnel residence time on projects, and the projects themselves now in the planning stages are multi-year. This makes the retention, organization and dissemination of all types of historical records, what we have chosen to call knowledge capture, vital to future success.

Previously, the knowledge capture to support public interest, to satisfy NASA's needs, and to sustain contractor spacesuit activities occurred separately. Until recently (see Section IV), NASA's knowledge capture efforts were funded sporadically when there was recognition that significant knowledge might be lost. These characteristics of spacesuit knowledge capture would change.

In the decades before space programs, HS (then Hamilton Standard) implemented closed-loop knowledge capture systems to flow "lessons learned" back into design reference systems to facilitate new design and system integration. These flowed into the first space programs in 1958 and into the procedures of Space Systems when it was founded in 1962. From 1952, HS's Communications Department methodically retained copies of its public domain publications. HS Space Systems additionally had periodic initiatives, coupled with less formal mentoring, to educate newer engineers on the accumulated technical understanding of products and technologies. These separate efforts provided the foundation for HS spacesuit knowledge capture efforts that followed in the 1990s.

In 1990, an internal engineering effort was initiated to capture spacesuit system level and pressure suit knowledge as these were found to be too specialized to be adequately captured by HS's generic product line knowledge capture systems. Separately in 1992, the HS technical community founded a Space Hardware Heritage Team. The goals of this volunteer group were and are to restore space related hardware and do historical documentation to promote appreciation for human space exploration. Public domain type elements of internal reports, coupled with drawing upon HS Communications Department resources, soon produced a series of external reports supporting public and academic requests for information. Starting in 1994, internal HS spacesuit documentation began to influence internally funded HS Lunar-Mars spacesuit development initiatives. This dynamic has supported six configurations for field evaluation and continues to the present.

In 1994, one of the HS Heritage Team documentation and public support functions grew into active support of the National Air and Space Museum (NASM) Space History Department. To aid NASM, the team provided identification and historical context for Apollo spacesuits and components in NASM's preservation collection. This HS/NASM collaboration expanded to the HS funding of the industry portion for the spacesuit Saving America's Treasures program in 2000-2001. In this period, it became apparent that a method of linking of artifact and history was needed. Initially, this was addressed by NASM databases supported by HS and its links to the spacesuit and historical communities. However, a more user friendly overview was needed. Also, NASA needed a reference

cancelled. When the Chinese started their next program, they elected to purchase proven Russian technology for their Shenzhou and Fei Tien suit systems. The Europeans initially attempted an internal designs but progressed to teaming with the Russians to develop a new, better EVA spacesuit for the International Space Station (ISS). This lost funding and never reached space. The Japanese chose to start by using American spacesuits as part of the NASA Shuttle and ISS efforts. To maximize knowledge gain, Japan built dedicated neutral buoyancy facilities and purchased essentially two Shuttle/ISS training EMUs. From this experience base, many in the Japanese space community hope to design and build their own spacesuit system once the need and funding arrives.

As the scope of the NASM Report is significant, the coverage of any effort was limited to one through three pages depending on historical significance. Every attempt was made to include a picture or an illustration of the suit system. Two report appendices provide cross reference between artifact and history. One permits NASM historians and volunteers to access the historical context while in the presence of an artifact via its NASM catalog number. The other appendix provides NASA or someone in the spacesuit industry the opportunity to easily determine if there is a surviving example of a configuration in NASM preservation for possible examination and consideration. The aforementioned efforts contribute to yet another knowledge capture resource in the form of NASA's new knowledge capture system.

NASA's knowledge capture initiatives (discussed in Section IV) were established to fulfill NASA's needs. This system additionally draws on the earlier NASM and contractor systems. Thus, the synergy of these formerly independent efforts combined to more effectively support their respective organizations. One of the NASA knowledge benefits is expected to be greater understanding and wisdom to more effectively establish spacesuit program technical requirements, which closes the loop on this comprehensive, multi-organizational knowledge capture system.

IV. NASA JSC's Approach to KC

JSC has numerous knowledge capture initiatives which are very robust and has continued to sustain and grow over the last several years. There are initiatives that narrow in scope that are inherent to programs. Then there are those of general in nature that offer availability to a broader audience. The ones available to the technical community associated with the US spacesuit development are shown in Fig. 12 which depicts a "Systemigram" of the sources and process to achieve knowledge capture.

The process starts with an engineer or manager who has a need for technical information in order to establish the technical requirements for a spacesuit project as described in Section III.1 of this paper. In order to obtain sufficient knowledge, the engineers and managers may obtain their knowledge from a multitude of JSC knowledge-based programs. Those sources mainly include the following:

- 1) NASA Engineering & Safety Center (NESC),
- 2) Academy of Program and Project Leadership (APPL),
- 3) Knowledge Initiative & Creation of JSC Chief Knowledge Officer,
- 4) JSC EA Engineering Academy,
- 5) JSC Spacesuit Knowledge Capture Program,
- 6) System for Administration, Training, and Education Resources for NASA (SATERN),
- 7) MOD Learning Library, and
- 8) Scientific and Technical Information (STI) Center.

As the knowledge is gained from the available sources, engineers and managers can become more knowledgeable, productive, and can create the requirements that define future programs. As the programs mature, they develop experts in particular disciplines. These experts can then share their knowledge with the knowledge-based programs. This shared expertise can be in the form of lectures, videos, or documentation. The documentation can be in the form of reports, video, audio, personnel records, post-flight debriefs, interviews, and lessons learned. The documentation can then be provided to the engineers and managers. Likewise, the documentation can be archived with the knowledge-based programs and then available to educate the engineers and managers thereafter. An additional aspect is the Smithsonian where the physical preservation of the US Spacesuits takes place. The Smithsonian can then also become a source of information back to the engineers and managers as they have a need to acquire about the hardware that has been retired. The Smithsonian also becomes the ultimate source for the public to learn about the US Spacesuit history. Section III.3 described the physical preservation in more detail.

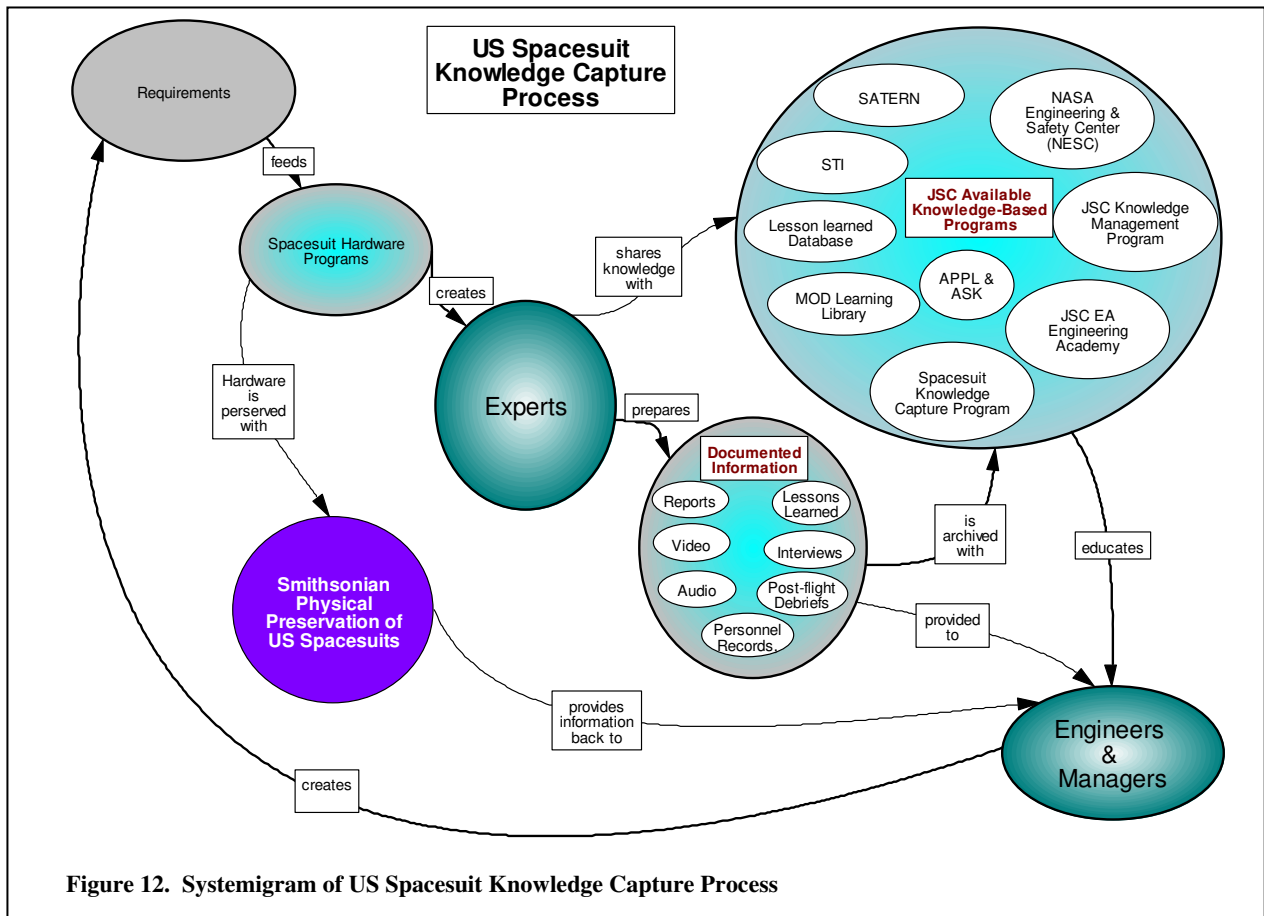


Figure 12. Systemigram of US Spacesuit Knowledge Capture Process

A. NASA Engineering & Safety Center (NESC)

The NESC is a unique resource that is agency-wide and offers a forum for reporting technical issues. It draws on the knowledge base of technical experts from across NASA, industry, academia, and other government agencies to help resolve NASA’s highest risk challenges. The NESC has an Academy that also captures the experience of the NESC experts and passes that experience along to NASA’s next generation.

B. Academy of Program and Project Leadership (APPL)

APPL is a NASA Headquarters program that provides continuing education for NASA’s project practitioners with a matrix of courses from which project team members choose a curriculum based on their individual NASA assignment, professional aspirations, and prior knowledge. APPL offers an electronic journal entitled, ASK the Academy, issued bi-monthly to share knowledge about project management and system engineering.

C. Knowledge Initiative & Creation of JSC Chief Knowledge Officer

In response to the General Accounting Office report released in January 2002, JSC embarked on the development of a center-wide lessons learned (LL) process and repository. At that time and in preceding years the Boeing Company was tasked to collect lessons learned for the ISS. Boeing developed a repository for the storage of these lessons. A decision was made to leverage the Boeing repository and turn it into a center-wide repository. As such, a center wide process was created, supported by the new repository, and released at the end of 2002. At that time the JSC Office of Primary Responsibility for the lessons learned was the JSC Office of the Chief Engineer (OCE).

In 2003 the Columbia accident occurred. Priorities and responsibilities shifted within the JSC OCE office. As such, the care-taking responsibility for the LL process was handed over to the Safety and Mission Assurance

(S&MA) organization. The JSC OCE still remained the OPR of record. However, all day-to-day activity was handed off to S&MA. During this time period the emphasis on the center-wide LL process waned and the process became essentially dormant.

In response to the growing need for a focused knowledge management and organizational learning initiative at JSC, Director Michael Coats created the office of the Chief Knowledge Officer (CKO) in October of 2006. In the spring of 2007 the JSC OCE was dissolved and the ownership of the LL process was transferred to the JSC CKO. Jeanie Engle was named JSC's first CKO and was chartered with developing a world-class knowledge management and organizational learning program. JSC's goal is to create better knowledge sharing and organizational learning across the center.

The JSC CKO maintains a very robust knowledge management program.¹³ It is essential to capturing and retaining more than 50-years of human spaceflight expertise. The tenets of the robust program include:

- 1) JSC Voices
- 2) Storytelling
- 3) Lessons Learned
- 4) Lean Six Sigma
- 5) JSC Taxonomy
- 6) Quality Management System

Additionally, the program maintains a website where recorded events can easily be archived and referenced for those personnel having access to the JSC website.

The JSC Voices includes a process whereby participants are can produce their own movie or be video-taped by the CKO to record their experience and knowledge. These stories are then made available to the community thereby passing on their legacy.

The storytelling events showcases former employees sharing their experiences in a "live" setting initially and then it is recorded and made available to the community. These events are held live approximately once a month centerwide.

The lessons learned are captured by JSC organizations across JSC via a center-level coordinating function using a Center Data Manager. Due to the diverse nature of JSC's communities work, the infrastructure mechanisms are tailored to the JSC organizations. The CDM links the local, agency, and program data altogether to facilitate sharing lessons learned.

Lean Six Sigma (L6S) is an approach to improvement. In 2009, collaboration between the CKO, the Quality and Flight Equipment Division, and quality management was initiated to integrate principles and practices into JSC Quality Management System. Additionally, Human Resources and Engineering joined to provide training, mentoring, certification criteria, checklists, and other tools for a successful program. Partnering is also occurring with the local contractors to hold L6S events.

JSC Taxonomy has been developed to capitalize the benefits of yesterday. A tool has been developed to allow JSC users to suggest terms, images and websites, and can comment on other's ideas. The goal is to connect information stovepipes and present a unified view for information and knowledge across JSC.

Quality Management System (QMS) is a collection of management principles, people and policies into one system in order to manage the work at the center. The JSC QMS is certified to ISO 9000 standards since March 1998.

D. JSC Engineering Academy

The Engineering Directorate (EA) Engineering Academy was established in January 2006 to coordinate and focus learning resources within the Engineering Directorate (EA). The EA Engineering Academy works in partnership with the Office of the Chief Engineer, the Human Resources Training and Development Office, the University and Research Affairs Office, and other organizations at JSC to accomplish its mission and objectives.

The EA Engineering Academy is:

- A virtual establishment that uses existing resources to foster and develop the technical and leadership skills of the JSC Engineering community to meet today's missions and tomorrow's challenges.
- A clearinghouse to focus and communicate information about training, development, and learning resources.
- A collection point for training, development, and learning resource needs.
- The leader in developing instructional material for Engineering Directorate processes, and
- Will adapt to evolving needs for knowledge sharing, training, and development.

The vision of the JSC Engineering Academy is to provide a culture of Engineering Excellence in which engineers learn continuously, inquire constantly, and share openly within and beyond the engineering community. The EA Engineering Academy's mission is to enhance the technical and leadership skills of the JSC Engineering community to meet today's missions and tomorrow's challenges. The objectives are to provide a learning environment for professional development and technical training directed at increasing the breadth and depth of engineering discipline knowledge. The Engineering Academy focuses on developing leadership skills at all levels of engineering, developing engineering project leadership maturity through career development processes and programs, preserving and sharing technical knowledge, skills, and experience throughout the JSC engineering community and serving as resource of world-class expertise for engineering teams.

C. Spacesuit KC Approach

In 2007, a knowledge capture initiative was launched in the Space Suit and Crew Survival Systems Branch. It was created as more of a mini-EA Engineering Academy for spacesuits. Collaboration was launched with the EA Engineering Academy from multiple avenues. The spacesuit knowledge capture manager collaborates with both the Office of Chief Knowledge Officer and the Dean of the Engineering Academy so as to stay in line with center and engineering initiatives, training, and opportunities. Likewise, as products and knowledge is captured for spacesuits, they are archived with the Engineering Academy and shared with the CKO. Additionally, spacesuit knowledge capture requests are periodically submitted to the EA Engineering Academy for obtaining retired experts to share their lessons learned. Additionally, an agreement was reached with the Mission Operations Directorate (DA) and EA so that the DA astronaut training facilities could be used on a space available basis so EA Engineering Academy and spacesuit events could be recorded.

The Spacesuit knowledge capture has proven to be vital in keeping important and pertinent knowledge at the forefront and timely as a new spacesuit is currently being designed assembled, and components are being tested and the architecture is being established. The knowledge is being shared and learning is being encouraged in order to help improve performance, facilitates innovation, reduce future redundant work, potentially reduce "training time", and help adapt to a changing environment in space exploration.

The tenets of spacesuit knowledge capture include:

- Lunch-N-Learns
- Training Courses
- Expert Lectures
- Formal Interviews

For spacesuit knowledge to be useful to others, and benefit the organization as a whole, it must be shared. Knowledge can be transferred from one person to another in a multitude of venues and mediums, but the key is to capture the information that makes spacesuit knowledge valuable for future use. Aside from the written word, verbal communication is the most common form of knowledge transfer. For spacesuit knowledge capture endeavors, valuable technical information is successfully captured by providing a venue for subject matter experts (SME) to lecture and present their tacit knowledge of spacesuits and topics relating to spacesuits to both a live audience and in formal interviews. Much of this spacesuit knowledge is in the form of storytelling. This provides an insightful view of the workings of historical NASA on past spacesuit development. The experiences shared by the SMEs are historical in nature on how the spacesuit came to be what it is today, and how engineers worked through obstacles, such as management and budget issues to produce a working spacesuit on which the current spacesuit development efforts are modeled. These experiences lead to the valuable lessons learned by the SMEs and what these lessons can teach the engineers and managers. The knowledge can help prevent negative history from repeating itself, and use it to create positive events in the future by learning what key factors helped to make successes in the past. All of this information incorporates extremely technical information on the spacesuits, including how certain mechanisms function, how and why certain hardware was designed, and the technical reality of why the spacesuit is designed how it is today and why certain failures occurred in the past. The hard work, research, and expertise of these individuals working together as a whole, unite to create a vast record of spacesuit knowledge, which could not be shared on a wide scale without the use of knowledge capture efforts. Each of these methods has major benefits to providing both current and future engineers with the knowledge they need to be successful in future spacesuit progress.

When the SME has the opportunity to lecture in front of a live audience that is eager to learn, a very unique learning environment is created, providing a real connection between the audience and the presenter. The spacesuit knowledge the SME has gained over years of experience, including the lessons learned from both successes and failures, trial and error, logic and reason, observation, witness testimony, argument from authority, i.e., the tacit

knowledge he/she possesses, is easily transformed into explicit knowledge through verbal communication and descriptive knowledge through historical narratives, all of which the audience internalizes during the lecture. This internalization of spacesuit information by the audience is reinforced by the opportunity given to the audience to ask the presenter questions real-time during and at the end of the lecture. This connection between the audience and the presenter provides a very deep and rich relationship in which spacesuit knowledge is shared and comprehended. The benefit from this type of lecture is that any audience member has the opportunity to ask the SME any question relating spacesuits and can obtain an immediate answer. This cannot be accomplished with formal interviews, as the student does not have access to the presenter.

The formal interview is a much more intimate lecture style. The SME sits with only a single person or very small group/panel of interviewers who ask the questions. It allows for more in-depth discussion since there is not a live audience to consider. The lack of audience also allows a platform for questions and answers which can be very candid in nature. Very detailed information can be revealed if the right questions are asked by the interviewer(s). The same tacit knowledge possessed by the SME can be revealed, shared, and internalized by the audience, but the effect may be different. As stated above, the student does not have access to the presenter during an interview because the interviews are usually taped events which are viewed by others (the students) at a later time. There are instances where a student can contact an SME via email and get questions answered in a relatively short time frame, but this is not always an available option. What information the student gains from watching a previously taped interview largely depends on the environment in which the interview is viewed and the goals of the particular student. This is not necessarily the case with the live audience lectures, due to the fact that a learning environment is created when many people gather to listen to a lecture, i.e. the environment creates itself, in a sense. However, if the interview is done well, and very detailed information is extracted from the particular spacesuit topic, a student watching a taped interview can learn a wealth of information, just as if it were a live audience lecture.

In order for both utilized formats of Knowledge Capture to be useful to others, the live audience lectures are taped, just as the interviews are. The same principles can be applied to those watching a taped live audience lecture. It does depend on the environment in which the tape is viewed and the goals of the student. In both cases, taping adds an extremely rich dimension to spacesuit knowledge capture efforts. The benefit of taping all Knowledge Capture spacesuit events is that each event will be available for others to view at their leisure for educational purposes for years to come. These taped events add to the legacy of spacesuit education because each event will be catalogued/archived and saved, creating a recorded educational spacesuit collection. A useful tool is that taping can be stopped and edited as needed to ensure a quality lecture or interview is distributed to the future audience. Proprietary information that the SME deems not suitable for taping can be discussed in front of a live audience, but will not be available for viewers watching the recording. If during an interview, the SME needs a moment to think of the best way to answer a question, or needs to take a break, taping can be paused until the interview can resume, and those viewing this at a later time do not have to spend their time waiting. It is also important to record the actual questions being asked from the audience. This is valuable because a learner listening to the lecture already recorded will have the same effect as being there.

Whether the student sits in a lecture or watches a recorded lecture or interview, over time, the knowledge transfer between SME and student comes full-circle, as the student begins to build onto her existing tacit knowledge base and converts the knowledge into procedural knowledge, by applying it directly to a specific task, which allows others to learn from it, and the knowledge capture cycle continues indefinitely. This is the main goal of knowledge capture: to significantly increase the number of spacesuit education resources for engineers and managers to be able to promote a continuous knowledge capture cycle of spacesuit knowledge.

E. System for Administration, Training, and Education Resources for NASA (SATERN)

SATERN is NASA's learning management system. The tool offers online courses along with a mechanism to sign up for JSC offered courses, HQ offered courses, or offsite courses such as university classes. Anyone across the agency can access the site.

F. MOD Learning Library

This is a learning resource of information and training on line for engineers at JSC can access. The specific audience in which this educational resource is focused is for astronauts and flight directors.

G. Scientific and Technical Information (STI) Center

The STI Center, houses a sizeable collection of JSC, NASA and other government documents, a small collection of reference books, journals and a variety of electronic resources that assists JSC employees and contractors in their work.

V. Conclusion

All of knowledge capture is to frame “knowledge” in time and in a venue by means of archiving those who learned before us so those who come after us can continue to explore, to push the envelope, live in space so we can go farther, do better, and know more in the process. This paper gives the reasons why knowledge capture is important, it gives examples where lessons learned can be valuable, but learned harshly if we are not diligent enough. There exist formal activities that are ongoing across JSC that allow for a robust process to capture valuable knowledge. In particular, with regard to spacesuits, there currently exists a closed-looped systematic process whereby the knowledge and the hardware is archived in a manner for those current and in the future can retrieve and learn what, why, and how spacesuits were designed, developed, and tested. There is ongoing effort to assure that experiences from Shuttle and ISS are captured and archived before the programs end and valuable knowledge is lost. Perhaps the greatest challenges facing our knowledge capture system consist of first making sure that those who could benefit from it know of its existence, and second, know how to use it. Knowledge capture’s value was best expressed by the parent of an elementary student: “We don’t always reach our expectations and we don’t always win; it’s the lessons from the journey that we carry with us and mean the most over time.”

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