U.S. Spacesuit Legacy: Maintaining it for the Future

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The history of U.S. spacesuit development and its use are rich with information on lessons learned, and constitutes a valuable legacy to those designing spacesuits for the future, as well as to educators, students, and the general public. The genesis of lessons learned is best understood by studying the evolution of past spacesuit programs–how the challenges and pressures of the times influenced the direction of the various spacesuit programs. This paper shows how the legacy of various spacesuit-related programs evolved in response to these forces. Important aspects of how this U.S. spacesuit legacy is being preserved today is described, including the archiving of spacesuit hardware, important documents, videos, oral history, and the rapidly expanding U.S. Spacesuit Knowledge Capture program.

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Nomenclature

ALSA = Astronaut Life Support Assembly
AMU = Astronaut Maneuvering Unit
CIL = Critical Items List
CKO = chief knowledge officer
CM = command module
CTSD = Crew and Thermal Systems Division
DCC = David Clark, Company
DCS = decompression sickness
EMU = Extravehicular Mobility Unit
EVA = extravehicular activity
FMEA = Failure Modes and Effects Analysis
FRR = flight readiness review
HQ = Headquarters
HSD = Hamilton Standard Division
HUT = hard upper torso
ILC = International Latex Corporation
ISS = International Space Station
JSC = Johnson Space Center
KC = knowledge capture
KSC = Kennedy Space Center
LEO = low-Earth orbit
LM = lunar module
LSU = life support umbilical
NASM = National Air and Space Museum
NTRS = NASA Technical Reports Server
OPS = Oxygen Purge System
OWS = Orbital Workshop
PCU = Pressure Control Unit
PECS = Portable Environmental Control System
PLSS = Primary Life Support System
psi = pounds per square inch
psid = pounds per square inch differential
PTFE = Polytetrafluoroethylene
RCU = Remote Control Unit
SOMA = Skylab Oxygen Mask Assembly
SOP = secondary oxygen package
SR&QA = Safety, Reliability and Quality Assurance
SSA = Spacesuit Assembly
SSF = Space Station Freedom
STI = Scientific and Technical Information
TMS = The Museum System by Gallery Systems, Inc.
UV = ultraviolet

I. Introduction

THE U.S. spacesuit is a critical piece of NASA's history and legacy. The heritage is rich and grounded with magnificent accomplishments. As use of the current Extravehicular Mobility Unit (EMU) ends and as a new spacesuit is developed, a critical juncture exists to preserve U.S. spacesuit heritage. The U.S. spacesuits and their legacy is one of America's most precious possessions. If this spacesuit knowledge were lost, it would be catastrophic to future scientific achievements.

The U.S. Spacesuit Knowledge Capture (KC) program is capturing and storing valuable stories, lessons learned, and knowledge about legacy spacesuits. In addition, it is of utmost importance to preserve the historical physical elements of the spacesuits to adequately design future spacesuits. The most significant physical elements include the

"hard" documentation and the spacesuit hardware. These physical elements exist in many venues and must be preserved and made easily accessible to educate those who are eager to learn and to allow engineers to develop future spacesuits. These repositories of knowledge become paramount in preserving spacesuit legacy.

Along with the "hard" documentation and spacesuit hardware, it is important to consider some of the most valuable lessons from NASA's spacesuit history to know how to use them. This paper presents the spacesuit legacy programs that encompass manned spaceflight and the paramount lessons that are some of the most valuable that influence spacesuit legacy from a different perspective. Hardware and documents can illustrate a historical story that reflects a spacesuit design. However, there are sometimes other aspects that help achieve the final destination or design. These factors influenced past manned spaceflight programs and impacted the resultant hardware unlike those of the technological advancements. To be able to chart a reasonably planned program for future spacesuit systems, it is vital to understand how these factors interacted during past programs, and to gain insight into how to improve future hardware and the facilitating of the management and participating organizations. To do this, this paper shares lessons learned from the former programs of Mercury, Gemini, Apollo, Skylab, shuttle and, the International Space Station (ISS).

II. State of Knowledge Capture Strategy

NASA must preserve the rich history of its spacesuit program for the trove of design information, procedural knowledge, and lessons learned to inform future spaceflight engineers and historians. NASA is implementing new programs and strategies to help facilitate this endeavor and has named Dr. Edward J. Hoffman as the agency's new KC officer, and individual NASA centers have created knowledge officer positions to archive information in multiple repositories. Additionally, grass-roots efforts to document knowledge of specific disciplines have arisen throughout the agency. The U.S. Spacesuit KC program is an example of these efforts. Likewise, other programs, such as the Johnson Space Center (JSC) Oral History Project, have added to the robustness of manned spaceflight efforts. All these archiving opportunities help facilitate the preservation of spacesuit knowledge as well.

Hoffman realizes that the challenge of sharing knowledge effectively impacts all of NASA: "Developing more consistent knowledge capability across the agency was part of what motivated the Aerospace Safety Advisory Panel (ASAP), an advisory group established by Congress, to recommend that NASA 'establish a single focal point (a Chief Knowledge Officer [CKO]) within the agency to develop the policy and requirements necessary to integrate knowledge capture across programs, projects, and centers.' ASAP acknowledged good work in this area at Johnson Space Center and Goddard Space Flight Center, and also recommended that all centers and mission directorates consider establishing CKOs to 'ensure standardization.' "[1]

In February 2012, Hoffman met with the agency's knowledge community and took inventory of knowledge services and activities at different centers and mission directorates. The knowledge community, which includes center chief knowledge officers and practitioners from each center and certain NASA entities meet approximately once a month to collaborate and understand how to share information across the agency.[1]

Hoffman is forming an agency knowledge strategy by working with CKOs and knowledge leads at the centers and mission directorates. Hoffman described what NASA will provide for KC: "While the details of the strategy are still being developed, some of its core principles are already clear. It will integrate knowledge policy and requirements with those for program/project management; knowledge is inseparable from project success and should not be treated as a stand-alone discipline. It will focus on establishing both systems that make knowledge accessible and a culture that values learning and knowledge. Finally, it will respect existing knowledge practices and local customs while setting agency-wide norms for knowledge identification, capture, and dissemination."[2]
Currently, NASA centers and entities have their own individual implementation for knowledge capture (e.g., lessons learned, best practices, case studies, etc.). Knowledge capture activities include documenting and storing lectures from subject matter experts and search and tagging tools such as taxonomy, ontology, and meta-tagging. These tools add relationships between categories to enhance search capability. A knowledge map to chart agency activities was released in May 2013: http://km.nasa.gov/knowledge-map/.[3] For information about NASA knowledge mapping: http://www.nasa.gov/offices/oce/appel/ask/issues/46/46d_director.html.[4]

Jean E. Engle is JSC's CKO who manages JSC Knowledge Online, which is a resource center for knowledge sharing at JSC. JSC Knowledge Online collects and stores story telling events, case studies, historical records, and other forms of useful space-related knowledge and makes this information accessible to authorized agency users.[5] Scientific and Technical Information (STI) is NASA's central repository for technical and scientific information. The NASA Aeronautics and Space Database (NASD) is a database that NASA users and the public can access.

A new knowledge-capture program was initiated in NASA's Space Suit and Crew Survival Systems Branch in 2007. A paper entitled "U.S. Spacesuit Knowledge Capture (KC) Status and Initiatives," presented at the

International Conference on Environmental Systems in 2012, sponsored by the AIAA, provides a detailed description about the program over the first five years of its existence. U.S. Spacesuit KC manager Cinda Chullen started and leads this program. The program's main objective is to capture the lessons learned from spacesuit subject matter experts. Avenues to capture the information include lectures, lunch-and-learn sessions, interviews, and courses. Each event is digitally recorded and archived and made available to engineers designing a new spacesuit. After events are deemed public releasable, they are archived through the NASA Scientific and Technical Information (STI) Center.[6]

Other programs, such as the Johnson Space Center (JSC) Oral History Project, have added to the robustness of manned spaceflight knowledge capture preservation. Through the JSC Oral History Project, the History Office collects first-hand experiences, eliciting details of procedures, processes, methodologies, rationale, and background of operations, design, and development. Individuals participating in the JSC Oral History Project have made key contributions to the Center's history and achievement of goals. Prior to the interview, extensive research about the person and the projects, programs, and areas where the person worked is gathered to form questions specifically to extract details. Interviews feature open-ended inquiries to prevent biased answers or skewed responses. The JSC Oral History team has gathered knowledge for this ongoing project since 1996 and consists of four members including the JSC Historian, (Dr. Jennifer Ross-Nazzal) who is a proven space history scholar, receiving awards for her work and being published in numerous journals and publications. The team also has facilitated a number of other oral history projects for the Center and for the NASA Headquarters History Office, such as Columbia Recovery, Space Shuttle Program Tacit Knowledge Capture, Earth System Science, Shuttle-Mir, and gathered data from former NASA administrators and officials. More than 1000 people have been interviewed and transcripts are accessible to all via online at the JSC History Portal, (www.jsc.nasa.gov/history), a single source for all online JSC history resources that receives an average of one-half million hits per month.

The history team has worked with the JSC Space Suit & Crew Survival Systems Branch to support its knowledge capture effort in numerous ways that include conducting interviews with subject matter experts, providing these experts research support, and offering methodology techniques for gathering and sharing information.

Another critical repository is the Smithsonian.

III. The Importance of Spacesuit "Hardware" Preservation

The National Air and Space Museum (NASM) has accumulated a valuable repository of spacesuit system artifacts. The collection spans the timeframe of the earliest suits used by Wiley Post, through the early Air Force programs focusing on supersonic flight, on through the Mercury, Gemini, Air Force Manned Orbiting Laboratory, Apollo, Skylab, and Apollo-Soyuz Test Project programs, and includes artifacts from the shuttle and ISS programs.

NASM archives contain over 1200 spacesuits and related items that are preserved for present and future generations. After nearly 12 years of planning, on November 2011, the Smithsonian Institution's NASM began moving its spacesuit collection from its storage facility at the Paul E. Garber Facility in Suitland, Maryland to its new, state-of-the-art facility at the Stephen F. Udvar-Hazy Center in Chantilly, Virginia near Dulles Airport (Fig.1). The new facility has the suit collection sorted according to program, ranging in size from the hard suits from Litton, AirResearch, Ames, and JSC, through the flown, training developmental and contract suits from the Apollo program, Manned Orbiting Laboratory suit, followed by the Gemini, Mercury, and aviation flight suits.

Figure 1. The Stephen F. Udvar-Hazy Center

Now that the spacesuits are in their new permanent home, planning has turned to documenting the collection. During her years as curator of the spacesuit collection, Amanda Young collected many linear feet of hardcopy documentation on the development and documentation of spacesuits.[7] None of these resources has been digitized. NASA has posted several hundred articles concerning the spacesuits in its NASA Technical Reports Server (NTRS). The next step in preserving and documenting the collection is to digitize, index, and catalogue these resources. The Air and Space Museum's cataloguing system, The Museum System by Gallery Systems, Inc., (TMS) is housed on a secure server and only very limited information is synced to the Smithsonian's public web pages. For those reasons, the museum catalogue is not an appropriate forum for interactive and trans-institutional collaborative discussion and assessment.

During 2011, Air and Space Museum curator, Dr. Cathleen Lewis has explored some possibilities for an appropriate forum for interactive collaboration. Culling from NTRS and other academic online catalogues to collect citations and articles that provide insight on the development of the spacesuit, she has assembled almost 800 citations to date. This total excludes the user manuals and technical reports that Young had collected, but which have not yet been digitized and released through NTRS. Most of the available databases include export features to standard academic bibliographic databases. In 2011, it seemed that the best opportunities for collaborating in this literature search would be through the on-line versions of bibliographic databases. Unfortunately, the membership and access limitations to these on-line bibliographies do not meet the current needs for the U.S. Spacesuit KC program. The goal is to find a suitable way to share and collaborate on the collection and collaboration of these resources among the greater spacesuit community and to post questions and answers of interest. The U.S. Spacesuit KC program is considering solutions that would allow external collaboration.

IV. The Importance of "Hard" Documentation Preservation

The importance of "hard" documentation in the schema of KC cannot be overestimated. Although memories and recollections are valuable and instructive, the fine details are best captured in physically retrievable records. This documentation can be in the form of reports, video, audio, personnel records, post-flight debriefs, interviews, and lessons learned. It can then be made available to the engineers, technicians, and managers. In addition, the documentation can be archived with the knowledge-based programs and made available to educate the engineers and managers thereafter. Records dealing with all phases of project design, development, certification, failure reporting and resolution, in-flight use, and program closeout can be invaluable to designers and managers involved with the future spacesuit systems. It is a challenge to collect, organize, and disseminate documentation, but these functions are key to an effective KC.

The Astronaut Life Support Assembly/Skylab Oxygen Mask Assembly (ALSA/SOMA) Program Final Report, shown in Fig. 2, offers an example of valuable historical information.[8] This final report might be used to illustrate the scope of program material that was gathered and organized to preserve experience gained. The ALSA consisted of a front-mounted package called the Pressure Control Unit, or PCU, containing pressure-regulation equipment, controls and displays; a 60-foot life support umbilical (LSU), which provided supply and return coolant lines, an oxygen line, electrical cabling, and a load-bearing tether; and a leg-mounted secondary oxygen package, or SOP, which provided 30 minutes of purge flow during loss of oxygen supply from the spacecraft. The SOMA was to be used during a contaminated atmosphere inside the Orbital Workshop (OWS). It consisted of a full-face mask outfitted with a demand regulator and hose, and could supply oxygen to a crewmember through the spacecraft oxygen supply or from the SOP.

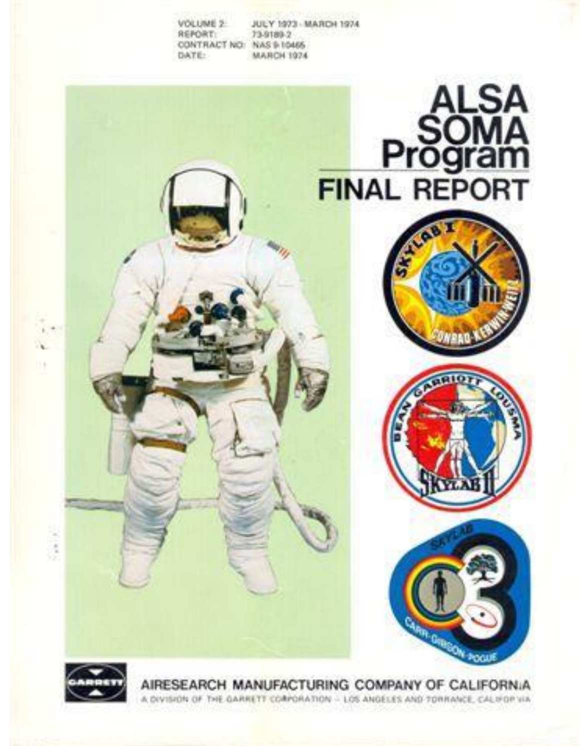

Figure 2. ALSA/SOMA Program Final Report

Because of the May 1973 near-catastrophic loss of a solar array and critical insulation for the OWS experienced during the Skylab I launch, extravehicular activity (EVA) played a crucial role in successfully releasing the one remaining jammed solar array. Without this source of power, the remaining missions would have been impossible. Also, without EVA, the replacement of the sunshade parasol with the final long-duration shade assembly would have been impossible.

The ALSA final report covers the period from January 1970 through March 1974. The report is presented in two volumes, with the first focusing on the period from January 1970 through June 1973. The design, development, testing, change history, certification testing, failure summary, and hardware item descriptions are contained in Volume I. In addition, the contractor's program structure is discussed, along with significant milestones, changes, and redirection. Volume II focuses more on flight use of the hardware, with detailed descriptions of EVA missions and their outcomes regarding the ALSA. Volume II also describes the contractor's field support effort at JSC and Kennedy Space Center (KSC), along with the in-plant effort supporting the flight hardware and field. Final disposition of flight articles is also presented.

Through a presentation of program change orders, the report gives a detailed illustration of how requirements changed through both evolution and "step" changes. Timelines showing major program events, planned and unplanned, add to the depth of understanding of how an ongoing, dynamic program evolves.

Not all programs provide such a wealth of specific information–because of their very size and duration, some make the task daunting. This makes the study of the available information all that much more valuable. People need information of past mistakes and successes to learn from them. Memory is a wonderful tool, but it can be selective, and can impart a romantic patina that objective documentation will not. It is important to gain a fuller insight into the past as a guide to the future.

V. Progression of Spacesuit Legacy

The history of U.S. spaceflight encompasses manned and unmanned programs–each with its own rich heritage of accomplishments and failures and the resultant experience gained, to be embraced or ignored by succeeding programs. Manned spaceflight carries with it the inherent need to provide humans with the ability to perform safely and reliably in a hostile environment, and it was this need that created the spacesuit systems of Mercury, Gemini, Apollo, Skylab, shuttle and, ISS.

Since radical leaps in technology were sometimes required to meet the objectives of these programs, it is tempting to suppose that the designs of these spacesuit systems were a straightforward result of specific technical requirements, generated by the application of the laws of physics, molded to fit time and budgetary constraints, and

executed during flight with computer-like precision. However, people must beware of oversimplifying the past. Technology was only one of many factors that affected the outcomes of spacesuit programs of the past.

During the U.S. manned space programs, the spacesuit systems used were a product of many–sometimes conflicting–factors. Technical requirements were a necessary part of the equation, but changing political environments, funding constraints, unforeseen events, and–perhaps most influential of all–the distinct personalities of the participating organizations and the individuals who carried out the day-to-day engineering and management tasks had as much or more of an influence on the resultant hardware that was used in manned spaceflight programs.

The laws of physics involved in these programs were the same for Wiley Post, when he flew the B. F. Goodrich suit in 1934, and they will remain the same in the future. Although the laws are well understood and documented, exactly how they apply in a given situation is often problematic. The engineers and managers of past spacesuit programs were dedicated, capable, and innovative, but chance and human error sometimes frustrated their best efforts.

The following subsections examine and analyze the program objectives, technical requirements, and other influencing factors as they occurred during past U.S. manned-spaceflight programs, with specific reference to the spacesuit systems involved.

A. Program Objectives– Pre-Mercury, Mercury, Gemini, Apollo, Skylab, Shuttle, ISS

Basic programmatic elements (i.e., objectives, goals, and requirements) are the primary foundation for what is perceived to be the U.S. space industry's grounds for establishing a "spacesuit legacy history." These basic elements help people understand how similar influencing factors will drive and determine future spacesuit system architectures. The space industry should know, however, that there are also many other underlying factors involved that tend to shape the outcome of various space programs, and correspondingly, affect the subsequent development of spacesuit hardware systems that are associated with those particular programs. The following overview in the subsections below gives some historical insight and perspective to a few of the driving factors. Insight into these factors and how they influenced the progress of spacesuit programs are illustrated by examples drawn from the history of the pre-Mercury period, Mercury, Gemini, Apollo, Skylab, shuttle, and ISS programs. A pictorial of the spacesuit legacy's progression is provided in Fig. 3.

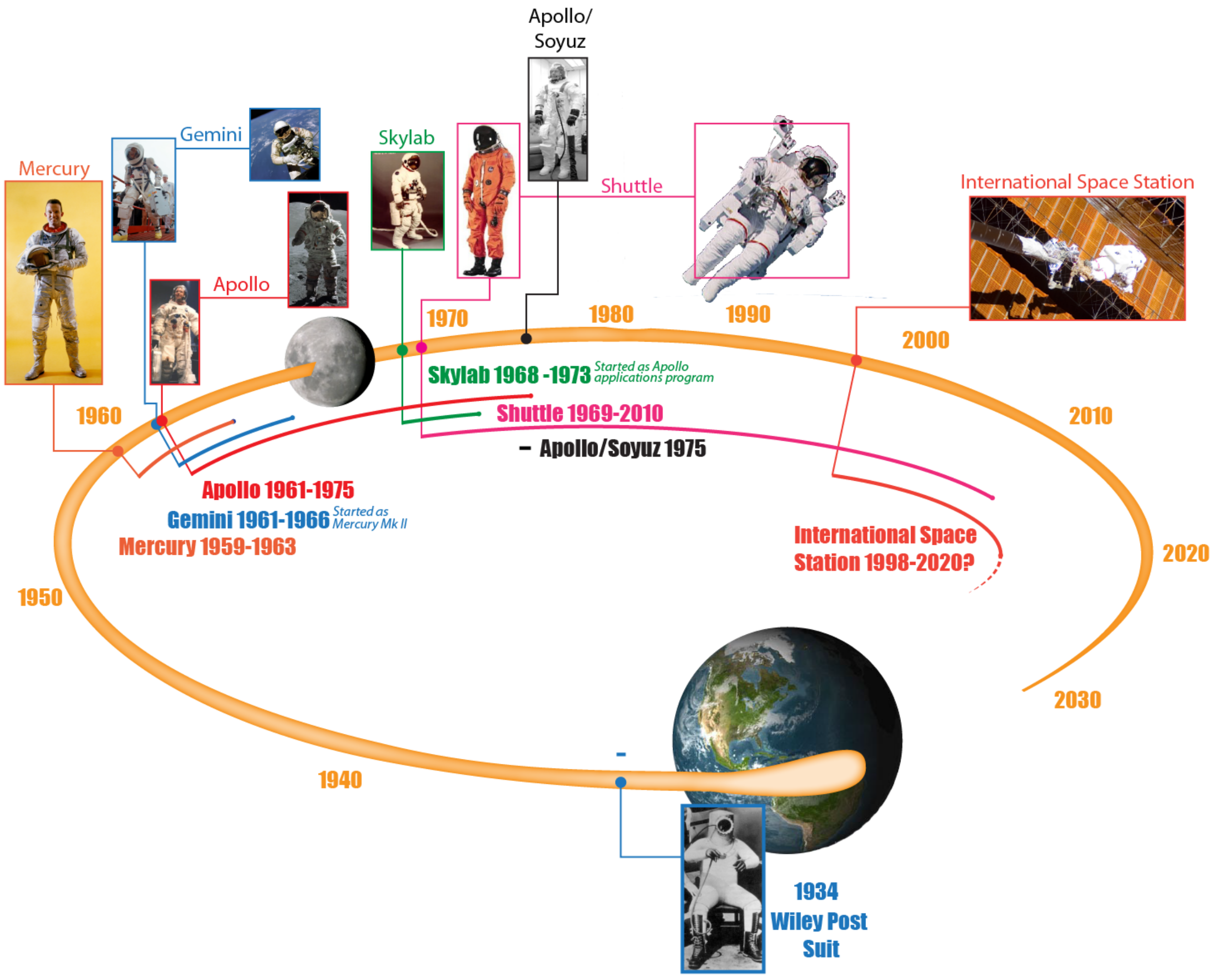

Figure 3. Progression of the spacesuit legacy.

1. Pre-Mercury

The origins of the spacesuit lie in aviation and man's quest for higher altitudes and speeds. At the beginning of the 1930s, these two human desires drove the development of high-altitude pressure suits. The quest for achieving altitude records used balloons. The pursuit of higher and higher speeds also involved reaching high altitudes to use the east-to-west wind regime, now called the jet stream, could increase the travel speed of the fastest of airplanes by an additional 50%.

The pressurized cabins required by aircraft to maintain a viable atmosphere at these high altitudes added weight, which limited speed, and added great expense. To overcome these factors, the pioneer aviator Wiley Post concepted the first high-altitude pressure-suit system to reach operational use for a coast-to-coast air-speed record attempt. Post hired B. F. Goodrich to design and manufacture the pressure garment. Russell Colley was the Goodrich project engineer. As a result, Colley oversaw the development of U.S. industry leading high-altitude pressure suits during the cold war competition between the United States and the Soviet Union.

a. Results

It was fitting that the Goodrich Mark IV military suit was selected as the basis for the Mercury Program, the first U.S. venture into space. The first pressure suit used in the United States was a Goodrich suit worn by early aviator Post in his record-setting high-altitude flights.

2. Mercury

Project Mercury was the nation's first venture into manned space flight. The Mercury program was initiated in October 1958 after the National Advisory Committee for Aeronautics (predecessor to NASA), the military, industry, and other government agencies had conducted approximately a year of combined research and studies. NASA was created by the Space Act that President Dwight D. Eisenhower signed into law on July 29, 1958.[9] The Mercury program established a broad set of objectives since humans had never flown in space before.

For the Mercury program, NASA established the following set of specific program guidelines: existing technology and off-the-shelf equipment should be used wherever practical, the simplest and most reliable approach to system design would be followed, an existing launch vehicle would be employed to place the spacecraft into orbit, and a stepwise program consisting of unmanned flights, flights with primates, sub-orbital manned flights, and, ultimately, multi-orbit manned missions would be used.

Since a new area of flight was being investigated, the United States planned to use a buildup-type of flight-test program, in which each component or system would be flown to successively more severe and rigorous conditions to first prove the concept, then to qualify the design, and finally to prove, through some repeated use, the reliability of the system. One of the basic problems that demanded a solution for the successful accomplishment of the Mercury program was providing for the physiological well-being of the capsule-confined pilot-astronaut in space during both sub-orbital and orbital mission operations.[10, 11]

The major spacecraft system that was essential for sustaining the astronaut in flight was the environmental control system, with the pressure suit being an important element of the system. However, since the pressure suit was provided primarily as a backup during the loss of cabin pressure, the suit architecture was based on the 1961 state-of-the-art operational Navy Mark IV high-altitude pressure suit to serve this role. Also, since the pressure suit was to be primarily worn unpressurized, no significant suit mobility development activities were conducted to directly support the Mercury program.

a. Results

One of the primary lessons learned from the Mercury program during its 55-month history was that humans were still needed to work in conjunction with machines. As flight director Christopher C. Kraft expressed it, "Man is the deciding element. As long as man is able to alter the decision of the machine, we will have a spacecraft that can perform under any known conditions, and that can probe into the unknown for new knowledge."[12] This statement was a profound indicator of the critical role of humans, especially humans operating in the space environment, which was to be exemplified in future programs.

3. Gemini

Project Gemini was one of the United States' early pioneering efforts that advanced the development of space operations capabilities. This program's initiation was timed to profit from the knowledge gained and lessons learned in the U.S. space program's first series of Project Mercury manned sub-orbital and orbital spaceflights.

The Gemini program's objectives, goals, and requirements included the investigations of the operations and performance capabilities of astronauts outside the confines of the spacecraft (i.e., extravehicular operations, known as "EVA") while protected from the hard vacuum and hazards of space by a pressurized spacesuit.[13] The full-opening door gave ready access to space and the Apollo program eagerly awaited the EVA experience to be gained.

Although the Gemini spacesuit was initially based on a conventional high-altitude U.S. Air Force pressure suit configuration, the necessary modifications required for EVA and the operational knowledge gained and lessons learned during the Gemini program were vital to the ensuing development of the Apollo and later spacesuit systems.

The two life-support systems used during Gemini were umbilical-based approaches. The first system was a small chestpack used by Ed White in June 1965 for a 36-minute EVA. Oxygen flowed at 100 psi through the umbilical and was throttled into the suit at the chestpack. Suit pressure was controlled by a relief valve on the outlet of the suit, that vented the effluent oxygen to space. The ventilating oxygen carried off perspired and respired moisture, along with expired carbon dioxide. The chestpack carried a manually-activated 5-minute emergency oxygen bottle.

The other system was a somewhat larger chestpack used for Gemini IX-A through Gemini XII. It recirculated part of the flow, and although carbon dioxide and moisture were vented overboard through a pressure relief valve, additional cooling was provided by evaporating stored water in a heat exchanger. A 30-minute, automatically activated emergency oxygen system was provided.

a. Results

There were numerous specific findings that were critical to the spacesuit system's continuing development, as well as the performance of an EVA itself. Two spacesuit system findings were significant:

1) The mobility limitations imposed by the spacesuit-affected-mission results, causing high workloads. Hand fatigue experienced on the 2-hour EVAs was particularly noticeable. This finding emphasized the need for low-effort joints and improvement in glove mobility.
2) The selection of crewmember cooling using chilled ventilating gas flow relied on perspiration to remove the heat generated by the crewman's workload. The inadequacy of this approach was dramatically demonstrated on two missions where the EVA crewmember experienced excessive sweating. The corrective action taken was to carefully monitor and control the workload. This finding underscored the need for a radical change in the cooling approach. As a result, Apollo and subsequent programs firmly implemented cooling using chilled water flowing through tubes woven into a close-fitting garment.[14]

4. Apollo

Regarding the future Apollo program, President Kennedy was eager for the United States to lead in the Space Race for strategy and prestige. He first announced the goal of landing a man on the Moon in the speech to a Joint Session of Congress on May 25, 1961:

> "First, I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth. No single space project in this period will be more impressive to mankind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish."

Kennedy also made a speech at Rice University on September 12, 1962:

> "We choose to go to the moon. We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too."

With these words spoken at Rice University, President Kennedy formally ushered in the Apollo program. There were five major Apollo program objectives:[15, 16, 17]

i. To demonstrate endurance of humans and equipment to spaceflight for at least eight days required for a Moon landing, to a maximum of two weeks
ii. To affect rendezvous and docking with another vehicle, and to maneuver the combined spacecraft using the propulsion system of the target vehicle
iii. To demonstrate EVAs, or space-walks outside the protection of the spacecraft, and to evaluate the astronauts' ability to perform tasks there
iv. To perfect techniques of atmospheric reentry and landing at a pre-selected location
v. To provide the astronauts with zero-gravity, rendezvous, and docking experience required for Apollo

The third objective as stated above, was the primary driving force for initiating the design and development of portable life-support system and spacesuit mobility joint technologies that would enable humans, for the first time, to explore and conduct operations on the surface of another planet.

The Apollo EMU consisted of a spacesuit and a totally self-contained, closed-loop life-support system, thus freeing the crewmember of umbilicals.

The life-support system, in its ultimate form, was designed for up to 6 hours on the lunar surface. The emergency oxygen system was manually actuated, and was designed for 30 minutes.

Cremember cooling was achieved by pumping chilled water from the backpack through a close-fitting garment into which small tubes had been woven. This proved to be an effective way to avoid the overheating caused by the inadequate ventilation-type cooling used during Gemini.

a. Results

The success of the Apollo program during six lunar landing missions contributed much to the spacesuit legacy. Some of the lessons learned are listed below:

1) Spacesuit joints, though much more mobile than their Gemini predecessors, still imposed a significant effort to bend and hold a position; the amount of work required would probably have been unacceptable for extensive lunar exploration.
2) Food and water provisioning to the suited crewmember was imperfect. The helmet pass-through port represented a significant failure point. Water bottles frequently leaked. On at least two occasions, orange juice that had leaked out of its container resulted in skin irritation.
3) The restraint cables used on the arms and legs of the spacesuit were single-failure points which, though never failing in flight, experienced several failures during manned ground testing on treadmills.
4) The need to customize suits to fit specific astronauts was the principal driver in determining suit quantities.[18]

5. Skylab

Following Apollo, the Skylab program was America's first experimental space station. It was designed to conduct long-duration missions in low-Earth orbit (LEO). The Skylab objectives were twofold.[19]

i. To prove humans could live and work in space for extended periods
ii. To expand the U.S. space industry's knowledge of solar astronomy well beyond Earth-based observations

To minimize cost of this short-lived program, most, if not all of the program hardware was based on Apollo-era technology and hardware, including the modified A7L-B spacesuits worn by the Skylab astronauts.

While the selection of the spacesuit for Skylab was relatively straightforward, the choice of an associated life-support system was complicated.

The requirements of the Skylab life-support system were varied. First and foremost, it had to accommodate multiple EVAs to service the instruments mounted on the Apollo Telescope Mount, a large structure that extended some distance from the Skylab Cluster. There was also a series of EVA simulations to be performed in the voluminous interior of the OWS. Several types of maneuvering units were to be evaluated, and this would involve providing cooling, power, communications, oxygen, pressurization, thermal control, and carbon dioxide control to a suited cremember.

Potential candidates included the Apollo Primary Life Support System/Oxygen Purge System/Remote Control Unit (PLSS/OPS/RCU) combination, the Gemini life-support system, or a new system.

As the technical specialists, Crew and Thermal Systems Division (CTSD) had been investigating an advanced life-support system called the Portable Environmental Control System (PECS). This system was a 4-hour, closed-loop system with the additional feature of being able to operate from an umbilical. For an oxygen supply, it used sodium chlorate "candles," which, when ignited, emitted oxygen, and left sodium chloride as the residue. At one time, NASA planned to use the PECS on the latter Gemini flights, but it was ruled out because of the cost and the problems faced by the Gemini EVA program. NASA thought of using the PECS on latter Apollo missions, but the termination of the program after Apollo 17 scuttled those plans. Now, it seemed, there was an opportunity in Skylab for the PECS.

CTSC dutifully performed tradeoffs considering all the candidates that had been identified. The Skylab Program Office, however, was not interested in a system with more capability than they needed. Also, the Skylab vehicle had plenty of oxygen, a large heat exchanger, and could accommodate coolant pumps. The Skylab Program Office charged CTSD to design a system that used the spacecraft capabilities, and could perform both the EVA tasks, as well as EVA simulations in the OWS. They ultimately selected the resulting system called the ALSA.

The ALSA was an umbilical-based approach, and the umbilicals were 60 feet long. They were stowed in spherical "blisters," attached to the exterior of the airlock module, and accessed through openings in the wall.

Oxygen was supplied from the vehicle at 100 psi, and regulated to suit pressure through redundant demand regulators. Various sizes of outlet orifices could be selected to get more or less ventilating flow. Cooling was achieved by recirculating coolant to and from the suit through the umbilical. An Apollo-type cooling garment was used. The coolant was chilled by a vehicle-based heat exchanger, and pumped through the umbilical by vehicle-based pumps. A leg-mounted, automatically activated, two-bottle oxygen package provided 30 minutes of emergency oxygen.

a. Results

The umbilical-based life-support system of Skylab and the modified Apollo spacesuit were intended to be a "work-horse" assembly that would perform such mundane tasks as changing out film canisters and brushing dirt and debris from experimental camera lenses. This dramatically changed when the Skylab 1 vehicle lost much of its insulation and solar power because of a malfunction during launch. EVA was used to help recover the OWS, and with it, the Skylab program. This use of EVA was a harbinger of the extensive EVA operations used to repair and service the Hubble Space Telescope in the ensuing space shuttle program.

The remaining Skylab EVAs were all successful, but an interesting situation arose. The umbilicals required constant attention by one of the two EVA crewmembers to avoid tangling and snagging. In fact, umbilical management required almost all of one of the EVA crewmember's time.

6. Shuttle

Before the Apollo XI Moon landing in 1969, NASA began early studies of space shuttle designs. In 1969, President Richard Nixon formed the Space Task Group, chaired by Vice President Spiro T. Agnew. This group evaluated the shuttle concept studies to date, and recommended a national space strategy including building a space

shuttle. The goal, as presented by NASA to Congress, was to provide a much less-expensive means of access to space for NASA, the Department of Defense, and other commercial and scientific users.

The shuttle program was formally launched on January 5, 1972, when President Nixon announced that NASA would proceed with the development of a reusable space shuttle system. The stated goals of "transforming the space frontier...into familiar territory, easily accessible for human endeavor" was to be achieved by launching as many as 50 missions per year, with hopes of driving down per-mission costs.[20, 21] When the spacesuit system was developed for the shuttle program, it was the first time the spacesuit and integrated PLSS were primarily designed for extravehicular use and not as a backup system during the loss of cabin pressure, as did Mercury, Gemini, and Apollo suits. The design of a backup suit system was delegated to a separate “launch-entry” suit configuration whose basic design was based on a military high-altitude pressure suit.

a. Results

Skylab resulted from Apollo, but shuttle represented a new start, especially with the spacesuit systems.

Instead of the Apollo spacesuit custom-fit, multi-sized spacesuits were built to accommodate a variety of crew sizes as well as both sexes. The life-support system, though schematically similar to that of Apollo, was much more densely packaged and designed for multiple usages over a 15-year life span, rather than the single-mission use of the Apollo backpacks.

Shuttle existed simultaneously with the ISS, with space-suited men and women assembling the station, as well as servicing shuttle-based payloads such as the Hubble Space Telescope.

7. International Space Station

The evolution of a permanent space station orbiting in LEO, and subsequently the completed ISS, has had a variety of independent concepts, design studies, and development activities that began in the early 1960s and continued over the following 20 years. In May 1982, NASA administrator James Beggs formally commissioned a NASA task force to study the proposal for a space station for 14 months. A broad community of prospective users or potential customers of this proposed space-based system provided inputs to this task force. These participants included the science applications community, potential international partners, the Department of Defense, the potential commercial community, and other interested government agencies.

The early plans for a space station were embodied in the concept for Space Station Freedom (SSF). It was to be a dual-keel affair, cost $14.5 billion, and be in orbit by 1994.[22] This approach proved to be too costly and went through a series of revisions to become what is now the ISS.

The ISS is a modular structure whose first component was launched in 1998. The ISS is a microgravity and space environment research laboratory in which crewmembers conduct experiments in biology, human biology, physics, astronomy, meteorology, and other fields. The station is suited to test spacecraft systems and equipment required for missions to the Moon and Mars.

Decision makers chose the extensive use of EVA to assemble and maintain the space station. A series of advanced, higher-operating pressure spacesuit concepts (e.g., AX-5 hard suit and MK III hybrid suit) had been designed, developed, and tested to support space station activities. A severe funding shortage discontinued the advanced suit development activities. The highly successful operational capability demonstrated by the shuttle EMU spacesuit system caused the ISS program to adopt a modified form of the shuttle EMU (along with the Russian Orlan spacesuit system) to support its planned orbital extravehicular operations.

In the aggregate, the ISS program consists of a complex set of legal, political, and financial agreements between the 15 nations involved in the project, governing ownership of the various components, rights to crewing and use, and responsibilities for crew rotation and station resupply. These agreements unite the five space agencies and their respective ISS programs and govern how they interact with each other daily to maintain station operations, from traffic control of spacecraft to and from the station, to use of space and crew time. These agencies anticipate that this partnership will potentially have an impact on future spacesuit legacy factors.[23]

The ISS, which was finished in 2011, has a truss length of 357.5 feet and cost over $100 billion to complete.[24, 25]

a. Results

There were 162 EVAs performed, totaling 1021 hours, to assemble the ISS.[26] Astronauts will continue EVAs to maintain the ISS throughout its lifespan. The continuing successful servicing of ISS systems and structural components by EVA astronauts is living testimony to the successful incorporation of lessons learned from previous programs, and the accumulation of more experience will serve future programs.

B. Technical Requirements

Having identified the program objectives, detailed technical requirements follow. Program requirements define the need for a type of spacesuit system; technical requirements expand this into a system-specific functionality.

The technical requirements probably influence reliability, durability, cost, schedule, and performance of a product more than any other influence. The closer a program can get to the end-of-the-program requirements at the outset of the program, the more likely the program is to be successful. However, program requirements can result in technical requirements that can have negative impacts to meeting the program's needs.

The Apollo Spacesuit Assembly, or SSA, offered some examples of the effects of early requirements on the subsequent activities of the program. The SSA was composed of all the anthropomorphic elements of the spacesuit plus the helmet and visor. Because of the perceptionthat SSA development had to precede that of the spacecraft, the SSA became a "rapid start" requirement. Because of a set of under-developed technical requirements, the program had designed, manufactured, certified and chamber-tested an SSA before discovering the requirements were incorrect or inadequate. The most significant output of the first 17 months of the SSA contracted effort was that an acceptable SSA configuration was yet to be determined. That effort revealed SSA limitations, which resulted in multiple parallel spacesuit efforts. The eventual configurations and providers of the fundamental spacesuit technologies and flight items resulted from competition.[27]

All the desirable characteristics for a spacesuit will always exceed what can be effectively packaged in one suit-system. Also, some desirable characteristics may conflict with others or not be feasible. For example, the Apollo SSA program started with a requirement that the SSA was to protect an astronaut from lunar ejecta (falling debris from a meteor impact). NASA wanted astronauts to remain safe and operational if a meteor struck nearby. However, ejecta from a meteor impact could hurtle debris vast distances into space. The particles that failed to reach orbital velocity would be drawn back to the surface by lunar gravity. Without an atmosphere to slow the return, such returning debris would reach supersonic velocities. Early in the program, NASA questioned the ability to meet the requirement. Experimentation indicated "body armor" consisting of wrought aluminum plates 0.150 inch thick would be required to provide adequate protection.

After a well-meaning desire has become a technical requirement, it is difficult to remove. The ejecta requirement lasted over three years into the program, whose name by then had changed from SSA to Apollo EMU. The adoption of the term EMU recognized the role of the Portable Life Support System, OPS, and RCU co-existing with the SSA, which completes the extravehicular assembly. The ejecta hazard was recognized as applying to the life support elements, as well as to the SSA. Defining an acceptable probabilistic assessment of risk resulted in the acceptance of a lower level of protection.

The development process provides technical requirement validation and refinement. This process is not limited to the activities within the program. In Apollo, the challenges in developing the lunar module (LM) to reaching its launch weight, caused the LM to "shrink," thus compressing the Apollo EMU front to back dimension.

With shuttle, the selection of vehicle cabin pressure caused a significant impact. NASA wanted to avoid the expense of designing, developing, and certifying a new EMU for shuttle or to minimize the expense to the extent possible. NASA recognized the PLSS to be the greatest single expense in the EMU. NASA wanted to reuse the already designed, certified, and proven reliable Apollo schematic design to the extent possible. At the start of shuttle EMU development, NASA planned the shuttle cabin to be capable of reduction from the nominal pressure of 14.7 psid to 9.0 psid. With a revision of EMU nominal suit pressure from the 3.7 psid used on Apollo to 4.0 psid, extensive oxygen prebreathing before performing an EVA could be avoided while providing minimum risk of exposure to decompression sickness (DCS). The shuttle EMU reached certification before the shuttle vehicle was built. The vehicle program developed safety concerns regarding oxygen percentages needed to implement the 9.0 psid pressure option. The oxygen partial pressure levels were sufficiently high, which raised flammability safety concerns. The vehicle settled on a pressure of 10.2 psid, requiring the EMU operating pressure to be increased to 4.3 psid to minimize the danger of DCS (the "bends"). The implementation of this requirement occurred during EMU certification. To avoid a complete redesign of the EMU, the pressure operating requirements for all the PLSS field replaceable items were compressed toward a slightly higher pressure operation range. While this minimized the EMU program expense and schedule to complete certification, this caused scores of anomaly investigations through the subsequent decades of the EMU use with components marginally failing requirements. The costs associated with the investigations and the resulting attempts at corrective actions added expense that far exceeded the savings during certification.

In a bizarre instance of "déjà vu", the shuttle EMU front-to-back dimension was constrained, as it had been during Apollo, because of vehicle considerations. During shuttle, a requirement was added for an astronaut to be able to access the flight deck from the mid-deck in a pressurized suit.

This requirement arose from a proposed scenario during which an orbiter that was stranded in orbit would be rescued by a second orbiter. As part of this rescue, it was supposed that the disabled orbiter had to be depressurized to allow the rescue crew to enter and traverse through the mid deck to the flight deck. The interdeck opening required that the EMU be no “thicker” than 19-3/4 inches. The vehicle deck opening concept design necessitated that the EMU had to translate through this passage; therefore, the EMU had to absorb the brunt of the requirement. This resulted in the front-mounted displays and control module being compressed in thickness. This compression resulted in difficulty reading the displays and easily reaching and activating controls. Legends and labels identifying front-mounted controls were printed in mirror-image configuration, allowing the crewmember to read them in a wrist-mounted mirror. Coincidentally, the perceived need to allow pressurized access into the flight deck from the mid-deck was based on a postulated scenario involving recue of a disabled (and depressurized) orbiter, from which the crew and passengers had been removed by means of rescue performed by another orbiter. The requirement ended because NASA determined that the worst-case time required to return a “stacked” orbiter from the launch pad, destow the payload, put a rescue kit onboard, return to the launch pad, and launch could take up to a year. The deminsion requirement was challenged later because of the need to accommodate an increased capacity battery and the regenerable carbon dioxide removal canister. This resulted in the EMU program removing the front-to-back constraint

The importance of a development phase cannot be overemphasized. When the JSC CTSD managers proposed their shuttle EMU Life Support System budget to NASA Headquarters (HQ), NASA HQ rejected having a development unit. The JSC contingent argued that being able to complete the certification-type test program on a prototype unit would provide maximum assurance that certification testing on the more closely controlled (and therefore more expensive) production configuration would be successful. NASA HQ stated their belief that the certification effort would be successful without the cost of a development program. The result was that the first production unit, the certification unit, underwent a series of failures and subsequent redesigns, all with the accompanying formality that drove costs and jeopardized the development schedule. The certification unit became an expensive development unit. In retrospect, the JSC argument should have been based on the need to first prove that the item could be built, then test it.

In summary, the message received from past spacesuit programs is that program requirements and the ensuing technical requirements exert a tremendous influence–positive or negative–on both design and the conduct of the program. It is very difficult–sometimes almost impossible–to expunge the effects of an early requirement that may have been deleted. But the area of requirements definition and implementation is only one, albeit an important, contributor to the profile of a program as it progresses. There are numerous other influencing factors that exert a tremendous power over configuration and operations. The next section explores some of these other influencing factors as they have been experienced in past spacesuit programs.

C. Influencing Factors

The set of factors influencing a program can be varied. For instance, the perceived Russian "threat" to get to the Moon before the United States was probably the overwhelming reason NASA went to the Moon. The goals of increasing scientific knowledge and partaking in the adventure of exploration of an entirely new regime were minor compared to the United States’ national Cold War paranoia, which was not unreasonable at the time. [28]

In addition to national goals, there are other significant factors that influence the course of a program. These factors tend to emerge in the conceptual stage of the program and continue throughout the duration of the effort. Some important factors in past spacesuit system programs include leadership personalities and their critical decision making capabilities, conflicts among organizations, unforeseen events that often can occur during the effort, implementing reusability of spacesuit systems, the dominance of schedule adherence, and the checks and balances that a program follows.

No program proceeds as it was initially planned; factors from failures to changes in the political environment will alter not only configurations, but ultimate goals as well. The following discussions of various influencing forces is by no means the only portrayal of these factors, but these have been selected because they had profound effects on past spacesuit systems.

1. Leadership

Regarding leadership, it is tempting to stay in the stratosphere when addressing the effects of leadership on past programs. John F. Kennedy, along with early NASA administrator James Webb and others in executive positions, were instrumental in setting the goals and guiding the agency. However, there were individuals at much lower levels who had enormous impacts on the execution of past spacesuit system programs.

In the early days of Project Mercury, Richard (Dick) S. Johnston came from the Bureau of Aeronautics in Washington, D.C., and joined NASA in 1959. When he was told that NASA was going to use the David Clark Air Force suit for Project Mercury, he dissented and arranged formal, manned evaluations at Wright Patterson Air Force Base in Dayton, Ohio, and the Naval Air Crew Equipment Laboratory in Philadelphia, Pennsylvania, which resulted in the selection of the U.S. Navy (B.F. Goodrich) suit over the International Latex Corporation (ILC) and David Clark Suits.[29, 30] Johnston was a deputy branch chief in Life Systems Division (now CTSD) in 1959. In his NASA oral history interview he stated: "Working on the Mercury program was like going into a candy shop. There was (sic) so many things you could do. You just had to say, 'I'll do them'."[31] In addition to suits, he was responsible for spacecraft environmental control system, NASA's animal program, and the bioinstrumentation program. Johnston eventually became chief of the Crew Systems Division (precursor of CTSD) in 1963. Johnston was an enthusiastic and inspirational leader, and he took great interest in the development of those whom he led. He once told his project engineers that he wanted them to "take a ride" on their hardware, to gain the user's perspective.

The Gemini program was formed to prove equipment and techniques for rendezvous and docking to support the Apollo program.[32] Suits were required for the Gemini missions' safety, which were to reach a 14-day duration. NASA first investigated two partial-don versions (i.e., the B. F. Goodrich and Arrowhead suits had removable arm and leg portions to enhance crewmember comfort). However, the Gemini suit ultimately selected was one David Clark Corp. built, and did not have the partial-don feature.

John Flagg was the president of David Clark Corp., and was a dynamic leader. Under his direction, David Clark Corp. built a suit with the company's own funding. David Clark Corp. essentially came in "off the street" and easily won the competition. Flagg became quite famous among the NASA contracts personnel, since he had a practice of not claiming costs for changes to which he was entitled to remuneration.

EVA was proposed as a secondary objective for the Gemini program. As stated previously, the Gemini program's primary objective was to develop and prove equipment and techniques for rendezvous to support Apollo. The Gemini contract (NAS 9-170) was awarded after that of Apollo (NAS 9-150).

The selection of individual ejection seats with the accompanying full-opening doors for emergency escape during launch for the Gemini program was a departure from the escape tower approach of Mercury and Apollo. In those programs, the entire crew module would be separated from the booster by rockets mounted on a tower. If not used, the tower was automatically separated after the risk was over.

The full-opening doors of the Gemini spacecraft were a natural portal for accessing space. However, extensive modifications to the suit and helmet were needed including the suit's extra isolative layers and the helmet visor's protection from ultraviolet (UV) and infra-red radiation.

A life-support system was also required. NASA contracted with AirResearch (now a part of Honeywell) for an umbilical-fed chest pack. The first umbilical EVA was planned for Gemini VI (scheduled for the latter part of 1966) with the AirResearch system; however, Russian cosmonaut Aleksey Leonov's EVA, on March 18, 1965, caused NASA to revisit their previous EVA plans.

NASA planned a potential "stand-up" EVA for Gemini IV, scheduled for early June 1965. This was to be accomplished by adding extension hoses to the environmental control system, eliminating a full extravehicular life-support system. By opening one of the doors, a crewmember could stand up in the spacecraft and extend into space. However, this would require the suit and helmet changes discussed above; therefore, the necessary modifications to the Gemini suit had already been initiated.

The importance of the stand-up EVA extended to the vehicle interior systems, since they would be exposed to space, and this would be an opportunity to determine the accuracy of the test and analyses performed. Positive results would "open the door" for future EVAs. However, the Gemini-IV stand-up EVA plans were overtaken by events related to Leonov's EVA, and this exercise was never performed on Gemini IV.

In response to the challenge of the Russian EVA, James (Jim) V. Correale, branch chief of the Gemini Support Office in Crew Systems Division, convened a meeting on March 26, 1965, to investigate how NASA could perform an umbilical EVA on Gemini IV, less than three months away. Correale had come to NASA from the Navy's Air Crew Equipment Laboratory in Philadelphia. Correale was an innovator, and experienced in pressure suits. He was convinced that NASA could conduct a safe and productive EVA on Gemini IV. To this end, he selected Larry E. Bell to lead a tiger team to design, build, and test a life-support system to perform in conjunction with the suit. He was a practical engineer, with a natural ability to summon the best efforts from those under his leadership. The team successfully designed, built, and tested an umbilical-type life-support system to accommodate the suit. White successfully performed the first U.S. EVA, conducting a 36-minute sortie on June 3, 1965.

Anticipating comfort problems during the planned 14-day Gemini VII mission, the crew petitioned NASA management to let them wear standard U.S. Air Force flight suits with medical monitoring instrumentation, helmets, and oxygen masks. This configuration had been successfully evaluated in altitude chamber testing at McDonnell

(now Boeing) in their St. Louis, Missouri plant. However, the possibility of the crew being exposed to high cabin temperatures, or being exposed to a sudden cabin decompression ruled against such an approach. Correale suggested a light-weight version of the intravehicular suit, and David Clark Corp. met the challenge and fabricated a 16-lb “get-me-down” suit, as Correale and others dubbed it. The suit was successfully flown on Gemini VII.

After Gemini IV, the Gemini EVA missions were Gemini IX-A, Gemini X, Gemini XI, and Gemini XII. The Gemini IX-A mission was to feature a tethered EVA by an EVA crewmember wearing the U.S. Air Force Astronaut Maneuvering Unit (AMU). This was a backpack containing a thruster system using hydrogen peroxide, and carrying oxygen to supply the chestpack in place of the umbilical. Because of inadequate foot restraints, the crewmember was unable to release the AMU control arms, causing him to expend enormous amounts of energy, overpowering the chestpack cooling system, and partially blinding him temporarily with perspiration.

Gemini X had a shortened EVA because of too little spacecraft maneuvering fuel, and Gemini XI challenges were a repeat of Gemini IX-A. The EVA crewmember expended tremendous amounts of energy attempting to attach a collar to an antenna boom at the front of the vehicle.

Gemini XII had originally been slated to use the AMU in free-flight. Gemini program manager Charles W. “Chuck” Mathews opposed this, and the mission plans were scaled back to focus on adequate foot restraints, moderating the workload, and investigating various types of spacesuit glove-accommodating connectors and tools. Newly instituted neutral buoyancy training had been used, and NASA thought this would better prepare the EVA crewmember for what he would encounter in zero-gravity.

Mathews was deceptively low-key in manner and appearance. He would patiently listen for hours to competing ideas and presentations during the critical flight readiness reviews (FRR), and render a decision. The Gemini XII FRR was tense because this was the last Gemini mission and the last opportunity for NASA to know if challenges to training crewmembers and controlling workloads had been resolved. During one part of the briefing, an advocate of stainless-steel hook and loop fastener material passed around samples of the material while he extolled its virtues. Mathews took a sample of the hook material and rubbed it across his pants leg. The stainless steel shredded his pants, and then everyone speculated about what it might do to the pressure retention characteristics of gloves. Mathews patiently, but firmly, deleted that material from consideration. It was this ability to subjugate personal feelings to the current task that made him one of the great managers.

2. *Conflict Between Organizations*

In the early 1960s, NASA’s Life Support Division (precursor to Crew Systems Division, now named CTSD) had initiated various pressure-suit studies that lead to the preliminary prototype suits that numerous contactors developed. When the official proposal for an Apollo spacesuit was released in 1962, many teams of contactors submitted responses. One team, composed of Hamilton Standard Division (HSD) of United Aircraft Corporation, offered the PLSS, with David Clark, Company (DCC) providing the spacesuit garment. Another team was led by ILC who was the proposed pressure garment contractor, and included Westinghouse Corporation for life support.

NASA selected the concept for the PLSS from HSD and the pressure suit garment concept from the competing ILC team. NASA chose Hamilton Standard as the prime contractor for the entire SSA with the condition that they team with ILC to be the spacesuit garment supplier. Unfortunately, this forced a collaboration that created many unforeseen problems. Many times, this was complicated by NASA becoming involved directly with ILC, instead of going through Hamilton, as the prime contractor. The Apollo suit program was rife with management personality clashes, coupled with cost overruns and an extensive series of prototype spacesuit configurations from multiple organizations. While the first three years of the program produced the base configurations of the pressure suit and life-support system that were used on the Moon, the effort proved HSD and ILC were unable to work together. NASA functionally assumed the role of spacesuit integrator in September 1965. Lingering contractual issues resulted in NASA formally gaining the role in March 1966.

3. *Unforeseen Events*

Unforeseen events, especially those that are catastrophic, always cause change, and NASA has had many. The Apollo 1 fire in January 1967, caused a complete revision of spacesuit external materials. The Skylab emergency on May 14, 1973, illustrated the importance of having EVA. The shuttle EMU fire of April 18, 1980, caused a sweeping redesign of the EMU’s oxygen systems. Two unrelated EMU failures in different EMUs during STS-5 in November 1982 caused extensive redesign of the EMU ventilating fan and increased quality control in oxygen regulator assembly. The shuttle program’s Challenger disaster in January 1986, resulted in redesign of spacesuit rotating joints. The Columbia disaster on February 1, 2003, although it did not have a direct impact on spacesuit systems, it did have an indirect effect by demonstrating how EVA could be a significant benefit to spaceflight.

a. The Apollo 1 Fire

The Apollo 1 fire occurred on January 27, 1967, during launch pad testing using pure oxygen at greater-than-atmospheric pressure. As a result of this catastrophic event, which claimed the lives of all three crewmembers, all Apollo program efforts stood down for a comprehensive safety review.

Richard (Dick) S. Johnston, the chief of Crew Systems Division (now CTSD), immediately flew to Cape Canaveral, now the KSC, to aid in the Apollo fire investigation. According to Johnston's oral history account, when he returned from the Cape, he assembled his division. In his words he said, " 'Look, we're going to straighten this out. We're going to do what we have to do about new materials. We're just going to straighten this out.' And we did."[33]

While well intentioned, this was a goal without an immediate means of implementation. However, also after the fire, JSC's deputy director George M. Low managed the Apollo program. Johnston was impressed that Low sent a hand-written memo to him every morning about the investigation. Low expected more from the investigation than just materials being reviewed and less flammable replacements found. He directed that all potential failure modes be reexamined and analyzed for risk reduction. Additionally, all previous anomalies were to be reviewed to determine if their corrective actions were sufficiently robust to preclude reoccurrence. This approach to anomalies continued for the duration of the program.

The investigation of the Apollo 1 fire resulted in several key recommendations, one of which stated that: "The amount and location of combustible materials in the Command Module (CM) must be severely restricted and controlled."[34] This recommendation affected nearly every Apollo CM subsystem by initiating a search for flame retardant, non-metallic materials, including that which was used to design the suits.

This search for new materials elevated a unique personality in Crew Systems Division (eventually CTSD) to prominence. Matthew (Matt) Igor Radnofsky was an acknowledged world expert in non-metallic materials, and had a wide variety of contacts in government and industry. He had overwhelming energy and drive. He demonstrated an amazing ability to focus a variety of resources on a specific task, and ultimately achieve success.

After the Apollo I disaster, Radnofsky was the focal point for the development of fire-resistant spacesuit materials, with the necessary degree of comfort and functionality. He began this task with his customary energy, and soon had a spate of candidate materials. Radnofsky was enthusiastic about each one–there was a running joke that he had a "material of the week" to take to the weekly division staff meeting. Because of the combined efforts of government and industry, which he led, fire-resistant materials such as Polytetrafluoroethylene (PTFE) -coated glass fiber cloth and other flame-resistant spacesuit materials were developed and successfully used in Apollo and subsequent programs.

The stand-down after the Apollo CM fire and the subsequent quality reviews paid dividends. Preflight pressure suit testing for Apollo 7 went smoothly, as did the testing before Apollo 8. Unlike the Apollo EMU testing in January 1967, the complete EMU chamber testing that preceded the flight of Apollo 9 was amazingly uneventful. The first Apollo EVA occurred on March 6, 1969. It lasted 46 minutes. Russell L. Schweickart and David R. Scott simultaneously emerged from the LM and CM, respectively. Scott went EVA from the CM using an umbilical for life support. Schweickart's EMU was in lunar EVA configuration using the backpack life-support system. The absence of anomalies became the new Apollo EMU norm, which resulted in lunar surface operations being well supported.

b. The Skylab Emergency

The Skylab program is a good example of how "unforeseen factors" may affect a program's outcome. The Skylab program was the U.S. version of a modest space station. Modified Apollo suits were to be used for Skylab EVA, along with an umbilical that provided circulating water for crewmember cooling in addition to oxygen, electrical power, communication, and instrumentation. EVA was used for film retrieval and other such tasks until the near-catastrophic loss of one solar wing and insulation from the OWS occurred during the Skylab 1 vehicle launch on May 14, 1973. The vehicle's temperature rose and all of its power was robbed because of the loss of half the solar-powered electrical system and failure of the remaining solar wing to deploy. This event essentially rendered the OWS, in which the crew was to live and work, potentially uninhabitable.

A series of EVAs was proposed to free the jammed solar wing. Additionally, some means were needed to shield the uninsulated section of the OWS from direct sunlight. Failure to solve any one of these problems doomed the program. Teams at JSC, and Marshall Spaceflight Center in Huntsville, Alabama, worked around the clock for two weeks during May 1973. During these intensive two weeks, both management and technical personnel 'rolled up' their respective sleeves and worked side-by-side in the design, development, fabrication, and testing of the umbrella-like sun-shade concept that astronauts deployed on the following Skylab 2 mission. As a result, they perfected the tools and techniques successfully used to free the jammed solar wing.

During the fast-paced two weeks, the NASA head of the Safety, Reliability and Quality Assurance (SR&QA) Division, which levies a strict set of requirements for the design, development, and fabrication of space-flight hardware said, “Waive all requirements, just make the damn thing work.”

The human cost of this intense effort might best be illustrated by an example. Charles (Charlie) C. Lutz had joined Life Systems Division (now CTSD) after leaving the life support group at Wright-Patterson Air Force Base. Lutz was extremely knowledgeable, intelligent, and a self-taught expert in pressure suits and non-metallic materials. He was made a branch chief of the suits and life-support systems of Skylab–an incredible achievement for someone without a college degree. As branch chief, he could have elected to stay above the fray, so to speak, but he left his office and helped the “troops” develop the EVA tools and execute planning for the Skylab vehicle rescue. The team worked horrendous hours, and Lutz’s participation was equal to anyone’s, even though he was a much older than many of the team members. Approximately a week or 10 days into the team’s activities, Lutz was leaving CTSD Building 7A one evening. After traveling a few steps away from the door into the drive, he collapsed from fatigue. There were no lingering after-effects and he returned to his job without any loss of ability, but this graphic picture of dedication was typical of this team’s effort.

There was a bit of center-to-center rivalry involved in the Skylab recovery operations, however. JSC developed the umbrella, or parasol, deployed through a scientific airlock. Since the entire Skylab emergency had its origin in the failure of the micrometeoroid and insulation shield that swept off one solar wing of the OWS, which was a Marshall Spaceflight Center responsibility, the Marshall organization wanted a more definitive role in determining the solution to the loss of insulation, and the long-term viability of the OWS. The JSC umbrella, or parasol, was supplanted by a larger Marshall Spaceflight Center-designed twin-pole sunshade, deployed on Skylab 3 by astronauts during EVA.

Although the 84-day on-orbit stay time of Skylab 4 is perhaps the program’s best-remembered achievement, the dramatic role of EVA saving the OWS, and with it the $24,0000,000 Skylab program, is perhaps its most important legacy–a legacy that influenced the oncoming shuttle program.

The shuttle program represented a significant departure from previous programs. Initially, EVA on shuttle was considered to be optional. The necessary airlock and spacesuit systems were to be part of a “kit,” which could be manifested or demanifested at will. After the lessons of Skylab, however, EVA became firmly entrenched in the shuttle program. A presentation slide was distributed at JSC, bearing a picture of the crippled Skylab OWS with its single deployed solar array and the parasol and a caption that read: “EVA – Would You Want to Fly Without It?”

c. The EMU Fire

The examples discussed above involved events that essentially affected the spacesuit system from without; however, the shuttle EMU fire of April 18, 1980, affected the spacesuit system from within. During this occurrence, one technician was burned over much of his body, and a second technician received burns to one hand. The fire originated in a 6000-psi oxygen system, and almost completely destroyed the EMU. A sweeping redesign of the high-pressure and lower-pressure (900 psi) EMU oxygen systems was performed, and a comprehensive NASA specification for the design, cleaning, materials selection, and testing of high-pressure oxygen systems was generated.[35] As a result of the monumental effort that Hamilton-Standard (now United Technologies Corporation Aerospace Systems (UTAS)) and NASA performed, the redesigns were certified and the April 12, 1981, STS-1 launch date was held.

d. EMU In-flight Anomalies on STS-5

Another spacesuit-related event that profoundly affected the program was the occurrence of dual, unrelated failures of both EMUs carried aboard STS-5 in November 1982. STS-5 was to have seen the first EVA of the shuttle program; however, one EMU’s ventilation fan failed to reach required operating speed, thus not providing enough flow to wash expired carbon dioxide from the helmet. One other aspect of the low speed was to cause interference with the communication system. The second EMU’s oxygen regulator failed to reach required suit pressure. If an EVA to close failed payload bay doors had been necessary, it would have required mission controllers and the crew to make a difficult decision. Post-flight analysis showed that the regulator was stable at a value that would have been life-sustaining, but a slight decay of pressure in flight could have caused simultaneous oxygen withdrawal from the secondary, or backup oxygen system.[36, 37] The regulator anomaly was traced to the omission of thread-locking inserts in the regulator adjustment mechanism.

The problem with the ventilation fan in the other defective EMU was corrosion from moisture intrusion in the speed-sensing components-magnetic Hall-effect sensors. Coincidentally, some months previous, during an altitude chamber run at JSC, an identical ventilating fan had suddenly shut down, but was easily restarted, albeit attaining a lower speed than previous. The speed was still within the allowable tolerance, and it was deemed too expensive and

risky to disassemble the fan's motor; therefore, the suspect fan was relegated to non-flight service. After STS-5, this previous instance was reviewed. The fan motor was disassembled, and corrosion was found–less corrosion than in the one that failed in flight, but significant nonetheless. The warning had been given during that earlier chamber run, but ignored.

The regulator needed no redesign, only a sharpening of procedures and verification. The ventilation fan motor was eventually housed in a "can," the Hall sensors were hermetically sealed, and allowable levels of drift were periodically verified.

e. The Challenger Disaster

On January 28, 1986, 73 seconds into flight, the Challenger vehicle was lost because of failure of an O-ring seal in one of the launch vehicle's solid rocket boosters.[38] The effects of the shuttle Challenger disaster affected the spacesuit program differently from past disasters. The virtual shutdown of the flight program after January 1986, resulted in all Orbiter systems engineers performing an exhaustive review of design, materials selection, certification, checkout, and operations. For the spacesuit system, the governing repository of information resided in two critical program documents: the Failure Modes and Effects Analysis (FMEA), and the Critical Items List (CIL). The FMEA revealed whether certain levels of redundancy were present, and identified where single-point failures existed. The CIL then took those components that were in violation of the criteria, and attempted to show by design margin, certification, checkouts, and operational procedures that the item was considered to be safe, even though the strict criteria of the program were not met. The CIL essentially constituted a voluminous waiver for the spacesuit system for many single-point failures. Without the waiver mechanism provided by the CIL, the necessary degrees of redundancy to meet strict program requirements would have rendered the suits too heavy to launch and too cumbersome for the crew to operate.

When the Challenger-based re-evaluation occurred, spacesuit systems' engineers and designers decided that all rotating bearings in the suit should be redesigned to feature redundant pressure seals, rather than the single seal previously used. This would significantly reduce the number of single-point failure conditions in the suit. The EVA life-support system was also reviewed, with 1600 design changes being thoroughly scrutinized. Some "holes" in certification were also found (i.e., certain practices were being performed for which a requirement had never been levied, therefore, no certification tests were performed). An example was the practice of lifting the "short EMU"–the hard upper torso (HUT) and arms, with the life support backpack and displays and control module attached by means of a circular plate with an eye bolt latched into the neck ring connector normally used for the helmet. Fortunately, calculations and tests showed that the 200 plus pounds of weight did not overtax the connector and its junction at the HUT.

f. The Columbia Disaster

On February 1, 2003, the spacecraft Columbia disintegrated during entry, causing the loss of all seven crewmembers. The contributing cause was the loss of thermal protection tile from the left wing, caused by a piece of foam from the launch vehicle external tank impacting it during launch.[39] The Columbia accident review board recommended that NASA develop a means of inspecting and then repairing damaged tiles. While the inspection was determined to be possible by use of the shuttle's remote manipulator arm outfitted with a camera, the means of repair was demonstrated by a pair of EVA astronauts on STS-123, launched on March 11, 2008. The crew successfully squirted a repair material mixture onto some pre-damaged tile samples during the fourth EVA of that mission.[40]

g. Reusability

The concept of spacesuit system reusability was an enormous change from past programs. Apollo had featured custom-designed suits for specific astronauts. Full-body casts were used to define the exact sizing required. It was a strange sight to view an astronaut clad from neck to feet with plaster-of-paris, leaving only the extremities bare. For shuttle, the spacesuit system was to be made of various-sized suit elements, to allow a suit to be "built" by selecting the right sizes from "bins." There was to be another significant difference in the shuttle suit. Jim Correale, at this time chief of CTSD, had a vivid memory of seeing Apollo astronauts falling down on the lunar surface (e.g., astronaut Harrison (Jack) Schmitt during Apollo 17). Correale vowed that no suit would ever have exposed hoses, such as was the case for the Apollo EMU. Consequently, the shuttle EMU featured a suit that joined directly to the backpack, with all fluid passages at the junction.

Correale also determined that the upper torso of the suit was to be "hard," to provide more protection against loss of pressure because of puncture. This was a significant departure from the all-fabric construction of all flight

spacesuits to date. The HUT was first built as an aluminum prototype, and the production versions were made of multilayer fiberglass, covered with multi-layer insulation.

The life support backpack, although schematically similar to that of Apollo, featured much more dense packaging and subsystems that were designed and certified to last as long as 15 years. An unforeseen benefit emerged when many backpack components and subsystems were certified for much longer times to allow current use on the ISS.

h. Schedule Adherence

One of the common aspects of past programs was the dominance of adherence to a set schedule. President Kennedy's challenge to land a man on the Moon and return him safely to Earth before the end of the decade of the 1960s is perhaps the best known and most often quoted; however, schedule adherence and the consequences of slippage were always uppermost in the minds of engineers and managers in all past programs. The additional burden of adhering to cost and guaranteeing performance completed the triad of sometimes conflicting requirements for these engineers and managers.

This environment gave rise to a type of management style that might be termed the "Military Paradigm." The characteristics of this paradigm include a dictatorial approach to managing employees, no tolerance for failure to meet deadlines, rapid and draconian action, and a personally intimidating manner. Although successful in the short term, this management style inevitably leads to discontent and eventual loss of employees.

Both NASA and Hamilton-Standard (now UTAS) have had practitioners of this management style during the Apollo and shuttle programs. Although the present environment does not reflect a schedule-driven milieu, when a hard schedule is mandated, it is almost inevitable that the Military Paradigm will resurface.

4. Checks and Balances

In the world of spacesuit systems' design, development, testing, and in-flight use, the schedule, cost, and technical performance pressures inevitably resulted in conflict between engineering, management, safety, contracts, configuration management, and other disciplines. The emergence of program change boards became the focal point for resolution of issues between parties, as well as authorizing changes to the program. These top-level boards had authoritative representation from multiple stakeholders, such as engineering, program office, safety, quality assurance, reliability, the medical community, flight operations, and the crew.

The efficacy of the change board as a check and balance resulted from the dedication of the various disciplines to decisively represent their area, and thus present the chairman with "pure" input to make an informed decision. This made it vital that the various representatives not be unduly influenced by other considerations.

Failure to keep disciplines separate in their functions was illustrated in one change board, during a discussion about a Lithium-ion battery short-circuit occurrence for which no definite cause could be found. This battery was being proposed for the shuttle EMU. When the safety organization presented their position that the program could proceed with corrective actions, one of their findings was that the program may not be able to afford developing a battery tolerant of sorts. However, this particular configuration never flew, but when safety worries about cost, it is unclear who worries about safety.[41]

Separation of functions during conduct of a program is also important to assure an adequate set of checks and balances. During the battery program discussed above, it was discovered that a series of test anomalies went uninvestigated. Engineering controlled Quality Assurance, thus effectively destroying Quality Assurance's independence; therefore, that discrepancy paper was not written. The engineers wanted to complete the test program.[42]

In summary, these are just a few examples of past space flight program efforts that were affected by the various factors as identified. History has a way of repeating itself, especially when past lessons have not been sufficiently inculcated into the culture; therefore, it should not be surprising for some of these same, unintended circumstances to recur in future programs.

VI. Future of Spacesuit Knowledge Preservation

The U.S. spacesuit legacy is full of lessons learned that are being preserved, including information that only NASA has, but this information will be useful only if those individuals needing it are aware of its availability and location.

To help spacesuit researchers find information that can lead them to success, the U.S. Spacesuit Knowledge Capture program is gathering useful knowledge from spacesuit experts through digitally recording their

presentations of collective memories and documentation. The recordings are stored in contemporary formats for easy access.

Relying on a tool such as the U.S. Spacesuit KC repository makes it possible for future spacesuit designers, educators, students, and the general public to access knowledge that will reduce redundancy in learning and promote new ideas and knowledge built on lessons learned. It can also eliminate the knowledge gap that exists when employees leave and take their knowledge with them, when a program ends, and when new issues or unanticipated knowledge needs arise.

To fill the knowledge gap and encourage authorized users to search for and use this information, it is important that the retrieval system be easily accessible to them. The search model should tie together relative information to cause researches to find a plethora of information on any particular topic, allowing the user to collect as much or as little information as desired. To enhance information searches, the format of search engines should be considered. Search engines should include various search categories and categorize data in a consistent, meaningful way by selecting from a preset list of preferred terms (e.g., presenter's name, date of presentation, subject of presentation, key words, etc.), abstracts or synopses of documented information, and multiple ways of searching and finding pertinent information. Currently, certain information is archived without a quick and easy way to share it. It would be helpful for this information should be in the mainstream. Authorized users need to know the location of this information and have simple accessibility to it. Like that of a city library, the agency and its centers could establish a virtual library where a user could browse information in a particular discipline, similar to a physical library that has information sectioned within individual categories. Captivating graphics and links within documents that lead the researcher to additional relative information can also help spark the researcher's interest and increase his or her use of the knowledge capture repository.

Although some of the spacesuit knowledge captured includes proprietary information that is intended only for authorized NASA employees, that which is non-sensitive and relevant for outside users to have should be made available to them. Sharing this information not only benefits the person who is learning, it can also spur the much-needed support for continued U.S. scientific efforts and lead to more scientific advancements.

It appears the majority of Americans support the sciences, especially those between the ages of 18 to 49. According to a July 2009 GALLOP® article: "On the eve of the 40th anniversary of the U.S. moon landing, a majority of Americans say the space program has brought enough benefits to justify its costs. The percentage holding this view is now at 58% and has increased over time. Notably, those old enough to remember the historic moon landing are actually somewhat less likely than those who are younger to think the space program's costs are justified. Among Americans aged 50 and older (who were at least 10 years old when the moon landing occurred), 54% think the space program's benefits justify its costs, compared with 63% of those aged 18-49."[43] To continue NASA's increased popularity trend, it is advantageous to be part of young Americans' educational awareness and growth.

The knowledge capture collection is educational, and as a way of sharing this material, it could be put into an open-access format with the capability similar to a learning university (e.g., a massive open online course (MOOC)). An open-access format helps users increase their knowledge from a network of connections. NASA's Science, Technology, Engineering, and Math (STEM) initiatives and educational outreach, particularly through its science missions, have encouraged America's young students to focus on advanced studies in science, technology, engineering, and math. Using this format to give the public access to non-sensitive information can help ignite and maintain that interest. This format will augment the already existing multitude of docuements that exist and are accessable to the public.

Every piece of information that is deemed important should be shared with authorized users. Centers and outside entities can lean on each other and benefit from knowledge sharing.

VII. Conclusion

The U.S. Space Agency has achieved missions that no other country or entity has. The trove of valuable information that it has retained will be useful only if it is shared with researchers. Although NASA has had many past accomplishments, only the surface of scientific discoveries has been revealed. If this information is adequately disseminated, it will help the United States to reach extraordinary scientific goals and be a world leader in science. For next-generation scientists, engineers, educators, and histories, our nation's future history depends on this information being shared.

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