Exploration Space Suit Architecture: Destination Environmental -Based Technology Development

Terry Hill – September 2010

Abstract

This paper picks up where *EVA Space Suit Architecture: Low Earth Orbit Vs. Moon Vs. Mars* (Hill, Johnson, IEEEAC paper #1209) left off in the development of a space suit architecture that is modular in design and interfaces and could be reconfigured to meet the mission or during any given mission depending on the tasks or destination. This paper will walk though the continued development of a space suit system architecture, and how it should evolve to meeting the future exploration EVA needs of the Unites States' space program.

In looking forward to future US space exploration and determining how the work performed to date in the CxP and how this would map to a future space suit architecture with maximum re-use of technology and functionality, a series of thought exercises and analysis have provided a strong indication that the CxP space suit architecture is well postured to provide a viable solution for future exploration missions. Through the destination environmental analysis that is presented in this paper, the modular architecture approach provides the lowest mass, lowest mission cost for the protection of the crew given any human mission outside of low Earth orbit. Some of the studies presented here provide a look and validation of the non-environmental design drivers that will become every-increasingly important the further away from Earth humans venture and the longer they are away.

Additionally, the analysis demonstrates a logical clustering of design environments that allows a very focused approach to technology prioritization, development and design that will maximize the return on investment independent of any particular program and provide architecture and design solutions for space suit systems in time or ahead of being required for any particular manned flight program in the future. The new approach to space suit design and interface definition the discussion will show how the architecture is very adaptable to programmatic and funding changes with minimal redesign effort required such that the modular architecture can be quickly and efficiently honed into a specific mission point solution if required.

Exploration Space Suit Architecture and Destination Environmental-Based Technology Development

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Abstract—This paper continues forward where EVA Space Suit Architecture: Low Earth Orbit Vs. Moon Vs. Mars [1] left off in the development of a space suit architecture that is modular in design and could be reconfigured prior to launch or during any given mission depending on the tasks or destination. This paper will walk through the continued development of a space suit system architecture and required technologies, and describe how they should evolve to meet the future exploration extravehicular activity (EVA) needs of the US human space flight program. [1,2,3]

In looking forward to future US space exploration to a future space suit architecture with maximum reuse of technology and functionality, a series of thought exercises and analyses have provided a strong indication that the Constellation Program space suit architecture is well postured to provide a viable solution for future exploration missions [4]. The destination environmental analysis presented in this paper demonstrates that the modular architecture approach provides the lowest mass and mission cost for the protection of the crew given any human mission outside of low-Earth orbit. Additionally, some of the high-level trades presented here provide a look and validation of the environmental and non-environmental design drivers that will become increasingly important the farther away from Earth humans venture.

This paper demonstrates a logical clustering of destination design environments that allows a very focused approach to technology prioritization, development, and design that will maximize the return on investment independent of any particular program and provide architecture and design solutions for space suit systems in time or ahead of need

dates for any particular crewed flight program in the future. The new approach to space suit design and interface definition discussion will show how the architecture is very adaptable to programmatic and funding changes with minimal redesign effort such that the modular architecture can be quickly and efficiently honed into a specific mission point solution if required.

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1. INTRODUCTION

Destinations for Human Exploration

In looking forward to the future of human space exploration, it is important to first consider the possible destinations that humans can realistically travel to, survive in, and possibly live in for extended periods of time with reasonable resources and budget. For example, it can be assumed with some level of confidence that there will be no crewed missions to Mercury due to the required infrastructure, logistics train and rocket design that would be needed to climb into and out of the inner gravity well of the sun. However, it is reasonable to consider visitation of the Earth-sun libration points. In following this line of thought, and using current knowledge of the physical environments of destinations in the solar system from which one can return in a decade or less, one can very quickly identify the destination design drivers required for exploration-class space suits.

Historically, technology development for human space exploration primarily did not happen until the mission was defined and funded or was done at the component level in efforts to improve existing systems. Low Technology Readiness Level technology development for pursuing advanced concepts have been also very limited. While the

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[2] This paper was peer reviewed for technical content by: Lindsay Aitchison (Pressure Garment Engineer), B. Michael Lawson (CxP Suit Element Life Support Subsystem Manager), Joseph J. Kosmo (Space Suit Advanced Development Lead Engineer), William Spenny (ISS EMU Engineering Subsystem Manager), Robert Trevino (Space Suit Life Support Technology Development), Sandra Wagner (EVA Systems Lunar & Mars dust mitigation) - NASA/JSC Crew & Thermal Systems Division, Space Suit and Crew Survival System Branch.

[3] IEEEAC paper #1330, Version 2, submitted December **XX**, 2010.

[4] One of the remaining challenges of the CxP suit architecture was incorporation of the launch, entry and abort functionality into the system without significantly compromising the survival or EVA functional performance. While this aspect of the architecture is still under debate, the modularity and commonality of the architecture for EVA missions is still valid and recommend.

logic in this is understood, given that humans only started venturing beyond the relatively benign environment of Earth in the last 50 years and had little idea of what might be encountered at each destination, today our approach should be questioned, given that humans have either physically stepped on, landed robotic probes, placed orbital vehicles around, or had close fly-bys of every single significant body in the solar system – with the exception of Pluto. Now with the volumes of data growing at a near-geometric rate, our knowledge of the environments in which humans can venture is well understood to the point where common design drivers and required design elements can be identified with high confidence. Given this knowledge of the environments and lessons learned from human space flight operations to date, an assessment of the progress that has been made in human exploration space suit technology with respect to the "design space" is proposed in this paper.

In the following pages, a review will be performed of the exploration space suit architecture developed in NASA's Constellation Program (CxP) and how it can be used for future human missions. Additionally, a methodical approach to common and probable destination environments will be addressed and how this should affect the prioritization of space suit technology development in the future.

2. OVERVIEW OF THE CxP SPACE SUIT ARCHITECTURE

The space suit architecture developed by NASA's Constellation Space Suit Element (CSSE) at its very core had many, if not all, of the key design-driving elements that will be required for human exploration in the solar system. The CSSE team[5] addressed this challenge by fully embracing "clean-sheet" or "textbook" systems engineering methodology by first defining the operational concepts, which focused on the development of an architecture with all defined design reference missions (DRMs), and keeping an eye on life cycle program costs. A comprehensive review of the functional designs, strengths, and limitations of previous US space suits, in addition to what is known of Russian space suits, took place to deduce historical lessons learned based not only on what did not work but, more importantly, on what worked right. The current strategy to accomplish the rather daunting task of meeting all space suit design requirements in the extreme environments previously detailed with a single system hinges on an arrangement that not only uses common hardware across multiple mission phases (to reduce developmental and logistics costs), but also features an open architecture that can be reconfigured and can leverage off components used during other mission phases where possible. [1]

The following were the key design figures of merit that were used in evaluating all of the following different

[5] This team is comprised of NASA civil servants and support contractor workforce with the responsibility of defining CxP space suit architecture and associated functional requirements and to later become the NASA oversight and subsystem managers.

architectures, some of which later became architecture design drivers: operational performance; work efficiency; launch, entry, and abort overhead; suit attributed mass and volume; field maintenance; commonality (design and hardware); extensibility; technical risk/feasibility; life cycle costs; and development schedule risk. The following were the suit performance criteria that defined the high-level functional requirements for the suit architecture: intravehicular mobility; microgravity mobility; microgravity environmental protection (thermal, radiation, micrometeoroid protection); comfort (un-/pressurized); ease of donning and doffing; crew's ability to escape the vehicles while wearing the suit; suit sizing methodology; ability of the suit to have sizing adjustments; high operational reliability; high evolvability and adaptability; extraterrestrial surface mobility; and extraterrestrial surface environmental protection

After 5 years and multiple design iterations, the CSSE suit architecture consisted of the following modular, or swap-able (from one configuration to another), hardware elements: helmet bubble and communications cap, gloves optimized for pressurized usage, boots optimized for 1g vehicle escape, lower arms and legs with mobility joints and umbilical connectors; and restraint mechanisms that are common in design. The fire protection outer cover layer and EVA thermal multilayer insulation (MLI)/thermal micrometeoroid protection garment (TMG) were unusual enough to very discrete mission phases that it was felt they would not be included functionally in the modular hardware so as to reduce the overhead of carrying around hardware for infrequent use or as bad-day risk mitigation. The outer layer of the TMG is not only fire resistant, but it provides low emissivity for reflecting solar radiation – thus the white coloration – and also provides cut, puncture, and abrasion resistance. The outer layer of the MLI/TMG may require a different coloration on Mars to meet the emissivity requirements for that environment.

Additionally, the portable life support system is used only on the lunar surface as life support functions are provided by the vehicle when the crew is inside or while performing microgravity EVAs. And, the core torso segment, which is optimized for 8-hour surface EVAs, is swapped out with the all-soft segment used for launch and landing. Prior to the CxP space suit design effort, a very similar design philosophy was recommended by Joseph Kosmo, NASA, in 1990. [2]

How This Works Well for the Different Destinations for Human Exploration.

The fundamental plan was for the CxP to evolve from microgravity to lunar exploration with sortie and long-duration habitation, and to progress eventually to Mars exploration. [3]

The common themes on how the CSSE suit architecture would be used for the CxP resonate with the possible design

reference missions being discussed today for future human exploration. At the most fundamental level, every human launch will need to provide protection for the crew against a bad day on the launch pad as well as a launch abort scenario and protection while reentering the atmosphere on mission completion. Each mission will either require a planned microgravity EVA or protection of the capability to perform contingency EVAs in the event the vehicle leaks or other hardware malfunctions require mitigation – particularly during missions with long transit durations. And, as with the Constellation suit, it is highly desirable for these future missions to be able to reconfigure a suit to meet the different needs of the crew and not to have to carry multiple suits per crew member to save mass and volume.

Additionally, multi-program life cycle costs and return on investment in technology development can be realized in this approach by designing to the architecture interfaces and only performing multiple designs for the hardware specifically required for the unique environments.

3. METHODOLOGY OF DESTINATION ENVIRONMENT DESIGN GROUPINGS

Determination of the Design Drivers

The formulation in a new way of prioritizing technology development efforts for space suits began with the President's new vision for NASA in February 2010. It seemed that the proposed emphasis of NASA's resources would be less focused on continuing with the CxP and building flight hardware but more in going back to the drawing board and developing the technology that would be required to make long-duration space exploration more successful when we as a nation were ready to step out into space for good. Along these lines, the question was asked, "If we don't have a particular mission to a particular destination, how can we define *what* technology is needed and then prioritize our resources?"

For this study, a different approach and performed an inventory of possible destinations in the solar system that humans could reasonably explore given the likely technology developments in the next 30 years regarding launch vehicle, engine, closed-loop life support systems, and subsequent durations of missions and space suit technology. When the destination list was complete, the subsequent environments and characteristics were assessed and grouped for commonality.

Destination Design Environments

The environments of the destination locations will be briefly discussed in the sections to follow; however, they will not be discussed in great detail as the individual environments have been well documented in the source materials referenced. It is worth mentioning that for this exercise, and to a large extent in space suit design, the exact numbers for environmental design drivers are not critical discriminators in the first-order design of the system. For example, whether

the local vacuum of space is 1×10^{-5} torr or 1×10^{-13} torr, for a suit pressurized to 4 lbs/in^2, is of marginal consequence. The same can be said for designing a suit to tolerate a touch temperature of -125 or -148ºC (-193 or -234.4°F) in which the design challenge is largely the same and may only impact final material selection or second-order suit heater impacts to the power budget. The specific environmental values that are used for this study are summarized in Table 1, and the major suit design driver for suit development will be summarized in each section.

Low-Earth Orbit (LEO) Operations (ISS, LEO satellites)

The LEO microgravity environment, which is the most familiar in human exploration, is where the largest amount of experience in performing human EVA operations has taken place in the last 50 years. The environment is thus well understood. The local gravitational acceleration, while in the gravity well of Earth, is in a state of orbital free fall and, therefore, will be quantified on the order of micro-g's. Additionally, the atmospheric drag at the altitude most Shuttle missions and ISS operations take place will be considered negligible with regard to space suit design. And, the radiation environment, which is greater than the environment high-altitude pilots are exposed to due to lack of an atmosphere, still resides within the Earth's Van Allen belts. The exception is for a region above the Earth known as the South Atlantic Anomaly[6] where EVAs performed while the passing through this region are limited to 3-5 for any particular crew member before they are rescheduled; however, the actual limitation is defined by the personal accumulated radiation dosage which is tracked for the mission and for life of the crew member. The solar wind is still a non-trivial influence in this environment and, with most of the EVAs performed to date – and likely in the future – being around human-made structures, the affects of the interaction between the solar wind and large metallic structures (or solar panel elements), plasma generation, and conductance has been an increasing safety concern in the community.

Therefore, the design drivers for this environment will be: pressurized suit mobility in microgravity, life support consumables in a vacuum, thermal exposure and management in a vacuum around human-made structures, and plasma charging fields.

Geosynchronous Earth Orbit (GEO) Operations (within and outside the Van Allen Belts)

Probable future human activity in this region will consist of retrieving, repairing, refueling, or deploying geosynchronous satellites (35,786 km [22,236 mi] above the Earth's surface) or multiday experimental missions. This

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[6] The South Atlantic Anomaly is a result of the Earth's magnetic field is not completely symmetric and aligned with the Earth's surface and thus allows a portion of the solar (particle) flux to extend down through LEO and affects communication with satellites, the Hubble space telescope, high-altitude aircraft and the Space Shuttle.

Table 1. Destination Environment Design Values Used to Develop Design Driver Groupings for Space Suits

Destination EVA/ Parameter	LEO/GEO [5][6][7][8]	Lagrange Points [9]	In-transit Mission	NEO/NEAs	Earth's Moon [10][20][21]	Moons of Mars, Jupiter, and Saturn with No Atmosphere [11]	Mars Surface [12][13]
Mission Duration	1-2 weeks	3-6 months Transit + Mission Dwell time	6 months to 3.5 years	6 months to 3 years	Sortie: 1-2 weeks 6 months to 1 year	Martian moons: 3 to 5 years Jovian/Saturnian moons: 5 to 10 years	6 months to 1.5 years
Gravity Field (m/s²)	μg	μg	μg	Effectively μg	1.63	Phobos – Effectively μg Demos – Effectively μg Europa – 1.314 Ganymede – 1.43	3.71
Radiation Gama Plasma	LEO (shielded) Van Allen (trapped)	Solar and Cosmic†	Solar and Cosmic	Solar and Cosmic	Solar and Cosmic	Solar, Cosmic & Trapped	Atmospheric Shielded
Thermal Environment (°C) Touch Temperatures	-78 to 125				Shadows at poles to center of crater at equator at lunar noon (-244 to 120)	Europa – Min. -223 Mean -171 Max. -148	Min. -87 Mean -63 Max. 20
Dust Environment	None	None	None	High Abrasion	High Abrasion	High Abrasion‡	Low Abrasion
Atmospheric Pressure	High Vacuum <1 Pa	High Vacuum <1 Pa	High Vacuum <1 Pa	High Vacuum <1 Pa	High Vacuum <1 Pa	High Vacuum <1 Pa	0.61 (4.57) kPa

† Includes the primary radiation from the source and secondary radiation as a result of the interaction of the source radiation and local materials of the space craft and/or space suit.

‡ Moons that have ice processes in place (Europa, Enceladus) may provide sufficient mechanism to provide dust that would fall into the Low Abrasion category.

environment is very similar to that of the LEO missions but with the significant difference of being within or outside the Earth's Van Allen belts for some or most of the time[7]. Consequently, the effects of the solar wind, and to a lesser extent cosmic radiation, are elevated due to direct exposure from the sun or the concentration of geomagnetically trapped radiation in Earth's magnetic fields. The inner Van Allen belt extends from an altitude of 1000 to 10,000 km (62.1 to 6,213.7 mi) above the Earth's surface, and the large outer radiation belt extends from an altitude of about 19,113 to 44,597 km (11,876.3 to 27,711.3 mi) above the Earth's surface. [22]

The duration of such missions would not be expected to exceed a 1- to 2-week duration; therefore, the time element of the design would not be considered a driver. The environmental design drivers for this region would be:

pressurized suit mobility in microgravity, life support consumables in a vacuum, thermal exposure and management in a vacuum around human-made structures, plasma charging fields, and solar/cosmic/concentrated radiation effects.

Lagrangian Points: Sun-Earth-Moon

Interest in human missions to the Lagrangian[8], or libration, points in the sun-Earth and Earth-moon systems has increased in recent years. In a two-body gravitational system in circular orbit about one another (as is the case with the sun-Earth and Earth-moon systems), there are five regions in which the gravitational balance between the two bodies are in equilibrium and lend themselves well for placement of satellites, observatories, or rendezvous depots for space missions with minimal fuel consumables for positional station-keeping.

[7] While the geostationary orbit is above the inner Van Allen belt, it can reside in or outside of the outer belt due to the compression of the outer belt on the side of the Earth facing the sun and the pressure of the solar wind. Therefore, at times the satellite might be on the outer edges or outside the belt, depending on the relative position with respect to the sun and current solar activity levels.

[8] The concept was first conceived by Joseph L. Euler around 1750 when he predicted the collinear points commonly known as L1, L2, and L3. Later, Luis Lagrange, in his work with two-body orbital mechanics, further predicted the existence of points L4 and L5; these points were all later named after Lagrange in his honor.

The duration of such missions is likely to exceed 3 months – with the potential for more than 1 year depending on the libration point; therefore, the time element of the design would be considered a driver. The environmental design drivers for this region are encompassed by the GEO environment.

In-transit Contingency Microgravity EVAs

This classification, while more missions specific, does define a design environment. This environmental scenario is a catchall for the instances during a mission in which crew members are required to go outside the vehicle to either investigate, repair, or replace hardware associated with their vehicle. NASA's experience during the last 50 years of operations is that Murphy[9] is never far away and having the capability to perform unscheduled, or contingency, EVA is a critical capability for all missions. This environment is largely encompassed by the GEO environment in terms of vacuum, radiation, and plasma charging. However, the thermal environment will probably differ due to varying distances from the sun. Additionally, due to the fact that the probable mission duration (time away from Earth) will be anywhere from 3 months to 10 years, it is imperative that this time away be factored into the suit design, fabrication, and reliability engineering.

Low-mass Near-Earth Object (NEO)/Near-Earth Asteroid (NEA) (half mass of the moon) EVAs

The suit design environment of low-mass NEO/NEA EVAs is an interesting combination of the microgravity environment of LEO EVAs and that of the thermal and dust environment of the lunar EVAs (discussed later). This destination is associated with missions to NEO/NEA that are half the mass of the moon or smaller and would have a local gravitational acceleration between microgravity and 0.817 m/s^2, thus rendering normal human ambulation not possible. The extremely low gravitational acceleration will require the use of an attachment mechanism (to the object being studied) and mobility aids to transverse the object. And, in some ways the lack of meaningful gravity will affect the EVAs and how the crew performs tasks due to the fact that any dust generated/stirred up will likely hover in a cloud around the work site for indeterminable amounts of time and could potentially impact work site visibility, dust coverage of the suit, and dust mitigation strategies. The characteristics of the dust (physical and chemical) are expected to fall within the range analyzed both from the moon and from recent studies of comets[10].

Jovian/Saturnian Moons

This destination environment is one of the more difficult to define given the widely varying conditions that can be encountered in and around Jupiter and Saturn. In this paper, only the moons of both planets were considered that were a viable destination because they were relatively stable (Io being an example of a moon that would not make the first cut for first Jovian mission) and would hold a great deal of either geological or biological interested for us. With those parameters, the field is narrowed significantly to Jupiter's Europa but is kept generalized to all of the rocky bodies with no atmosphere. Europa – and most Jovian moons of interest – lie within the dense bands of trapped radiation and at some estimates are 2 to 3 times what would be experienced within Earth's Van Allen Belts.

It also should be noted that missions to Saturn would have be of incredible interest or necessity for us to take the additional mission transit time to reach the planet and most likely destinations of interest, such as the moon Enceladus, would orbit outside the debris field of its rings. Additionally, Saturn does not have the same extreme region of trapped radiation that is present around Jupiter. Titan offers reduced gravity acceleration and an atmospheric pressure of 147 kPa, satellite data suggest lakes of liquid methane and with significant methane in the atmosphere with very little oxygen and indications of atmospheric lightening. The implications would be that a human presence would provide a source of oxygen and facilitate a very dangerous environment for the crew members. Thus, Titan has been removed from the analysis performed for this study.

Design drivers for this environment will be nearly identical to those of the Earth's moon due to the abrasive dust, cryogenic temperatures, and trapped radiation conditions (most extreme of EVA destinations), but will be dramatically impacted by mission duration and robustness of design due to relatively unknown surface conditions and required tasks.

Martian Moons: Phobos/Deimos Missions

The environment of the martian moons is expected to combine lunar dust characteristics with thermal extremes at vacuum that are no greater than those seen on Earth's moon, with the low gravitational acceleration challenges seen with the NEO/NEA EVA environment. As with the in-transit EVA environment, mission duration is expected to play a major component of the design driver challenges.

Earth's Moon

The recent lunar environment definition for suit design for the CxP encompassed the entire lunar extremes as defined by the CxP goal of global access to the lunar surface with a single suit system. [1], [3] The dust environment is a known variable given the experience gained and information gathered as part of the surface EVAs and the dust and rock samples and space suit hardware returned from the Apollo Program.

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[9] Societal reference for when something or a situation can go wrong, it will.
[10] Samples of comet Wild 2 returned by NASA's Stardust and data returned from the EPOXI (Extrasolar Planet Observation and Deep Impact Extended Investigation) spacecraft.

As part of the "go anywhere, anytime" philosophy of the CxP, suit engineers now had to consider the design impacts of suit(s) designs that would allow crew members to function in the permanently shadowed crater interiors at the lunar poles with cryogenic touch temperatures and also to operate in the solar furnace-like environments of craters at the equator during lunar noon.

The gravity, while one-sixth that of Earth's gravity, did provide mobility challenges to the Apollo crews since the pressurized suit design hindered natural human ambulation. Advances in space suit mobility elements since that time have significantly minimized this environmental impact to the design of a space suit. Therefore design drivers for this environment, in addition to the mission durations of 2 weeks to 1 year and associated reliability design challenges, will be as follows: pressurized suit mobility in reduced-gravity; life support consumables in a vacuum; thermal exposure and management in a vacuum at extreme temperatures; high-abrasion, very fine, and statically charged dust; and potential plasma charging fields.

Martian Surface Missions

The martian surface environment, in many aspects, is the most benign of all those to be considered for human EVAs. The presence of the martian atmosphere, albeit much less prominent than Earth's, does provide the mechanisms for wind erosion in addition to minimizing thermal extremes, solar wind protection, and some cosmic radiation shielding. Recent discoveries from NASA martian rovers and orbiters indicate an ever-increasing evidence base for the past existence of liquid flowing on the surface. Between the flowing of liquid on the surface and the atmospheric erosion mechanisms, the martian dust physical characteristics will be considered low abrasion albeit more abrasive to what might be found on Earth. However, while knowledge of the chemical makeup of the martian dust is limited, with the spectral information from the orbiting satellites and the spot analyses from the rovers, the generalized list of chemical makeup is growing.

The current NASA design reference missions [14], [15], [16] indicate a probable mission duration of upwards of 3.3 years. This poses quite a design challenge for space suit engineers to design a suit that is highly operable, does not require frequent maintenance, is very durable for significant usage at Mars, and is highly reliable – not requiring repair or replacement – during the mission.

Therefore, the design drivers for this environment, in addition to the mission durations of as many as 3.3 years and associated reliability design challenges, will be: pressurized suit mobility in reduced gravity; life support consumables in a rarified atmosphere; thermal exposure and management in a rarified atmosphere at cold to moderate temperatures; and low-abrasion, very fine, and potentially chemically reactive dust.

4. MAPPING DESTINATION ENVIRONMENTS TO MUTUALLY INCLUSIVE DESIGN DRIVERS

Destination Mapping Phased Approach

The first phase of this study, after defining the list of potential human exploration destinations, was to define a list of space suit design drivers per destination. The second phase took the destination-based design drivers for space suit hardware and focused on the physical characteristics of the local environments, grouping them into common design drivers. These subsequent groupings were: microgravity, reduced gravity, thermal extremes at vacuum, solar, and cosmic radiation; high-abrasion dust; low-abrasion dust; and thermal management in the presence of an atmosphere. And lastly, the third phase of defining the design drivers focused on unique aspects of missions that would affect the design of space suits; this resulted in: mission length and distance from Earth (hardware reliability, maintainability, and complexity) and long durations of exposure to radiation.

Phase I: Defining EVA Design Drivers

Microgravity Destinations—Mobility in microgravity becomes an issue as Newton's third law of motion comes into play: Bodies remain in a state of rest or uniform motion (constant velocity) unless they are acted upon by an external unbalanced force. How this transfers to suit design is in the ability to move and translation from one location to another with minimal resistance from the suit itself, and in smooth motions that will not excite unwanted suit dynamic motion or cause undesired impact forces to interactions with the local environment that would set the crew member in unwanted directions. This is referred to as "fighting the suit", or work (pressured X delta volume of the suit) in the suit design world. While it is largely independent of the gravity field, it is one of the leading causes of astronaut fatigue during micro-gravity EVAs.

Reduced-gravity Destinations—The reduced-gravity destination environment group is comprised of potential EVA environments in which the local gravity field is defined as $1.6 \text{ m/s}^2 <$ local acceleration $> 6.5 \text{ m/s}^2$. Of the possible destinations where humans can survive and potentially live long term with a return to Earth within 5 years, the following present themselves as viable destination candidates: Earth's moon and Mars. In a reduced-gravity environment, as defined previously, the two major design drivers are the mobility and mass of the space suit. Similarly, as discussed with the microgravity environment, pressurized mobility of the suit and minimizing suit-induced fatigue on the astronaut are highly desirable given the relatively short EVA time available and the voluminous lists of desired tasks during EVAs – if crew members are exhausted early in the EVA, not all objectives will be met. As has been seen in the past, crew fatigues is more of a combination of suit pressurization and tasks required of the crew, the gravity environment will obviously frame what tasks are required of the crew.

Secondly, the mass of the suit is very important in a few different ways. The gravity environment in which the suit will be used and the length of time the crew member has been out of the Earth's 1g environment should be considered when defining the mass of the space suit. For example, if the crew has only been away from Earth for 1 week and will be operating a 150-lbm suit on the moon, this is a manageable situation (other than the inertial resistance of the suit) as this suit would appear to weigh on the moon the equivalent of 25 lbs (11.3 kg). However, if the crew member has been on the moon for 1 year and his/her muscular strength has adapted to the moon (eg, no muscle resistance training to mitigate muscle atrophy), the suit would appear to weigh 150 lbs (68 kg) on the moon and would adversely affect the fatigue levels of the crew. Granted this is a scenario that is unlikely under normal mission operations, but it is used here to exaggerate the point. There is growing thought that the EVAs themselves, when done regularly, could prevent atrophy due to the loading of the skeletal system from the suit; however, the ISS paradigm would imply the necessity of exercise protocol throughout a mission to prevent the known long-term affects of weightlessness.

There is also growing thought in the space suit community that a different look should be taken at how the mass of the suit is viewed and managed. The thought is that in reduced gravity environments, such as Earth's moon and that of the smaller moons, natural human ambulation as performed on Earth is not really practical or easy given the presence of reduced gravity. This was seen in the Apollo EVA video footage in which the crew would frequently fall over or would lope across the surface. Loping was easier to do than traditional earth ambulation and was not as physically taxing. So, when thinking about a new suit design, if the mass of a suit is such it makes an astronaut more massive, using this to provide the extra "weight" may enable a more natural ambulation. However, as some recent simulated reduced gravity testing performed at JSC has indicated that event the suit-less human ambulation changes in the reduced gravity environment and that new approaches to suit mobility in these environments should be investigated further.

As with all things relating to space exploration, there is a trade-off between the amount of mass that can be launched from Earth and that required to perform the task optimally in the destination environments. Mass is always king on launch day, so careful mass margin management, and how it will impact the mission objects at the final destination, should be considered.

Radiation—The non-thermal radiation environment for human exploration missions within and outside of Earth's Van Allen belts will increase the risk to human survival in two general situations: high-energy solar events and long-duration exposure to cosmic and solar radiation. Given the propulsion technology of today and the cost of space travel, any destination in our solar system will either require substantial time for the mission or the time spent at the mission destination will be prolonged so as to maximize the return on the financial investment.

Design Impacts due to Usage Duration—For the same reasons as discussed in the radiation section, most human exploration missions outside of Earth's orbit will necessitate long periods of time away from the safety and resources of Earth. Therefore, it becomes critical that space suit design be robust enough to endure expected usage or be maintainable by a crew with minimal recurring maintenance and required replacement parts during the mission.

This discussion on space suit reliability to a large extent is an uncharted area of study given that, historically, space suit hardware is non-commercial, custom hardware that is manufactured and operated in non-statistically significant quantities to use standard statistical reliability calculation methods. For exploration missions, space suits will be a mission-critical item that must fail safe, but the trades must be done to optimize the acceptable risk posture, mass impacts due to robustness and redundancy (extra mass on suits or spare parts and required tools launched on the vehicle), and cost associated with developing design and testing methods to be able to characterize and predict the mean time between failure and modes of failure.

High-abrasion Dust—High-abrasion dust is characterized generically as *in-situ* regolith material the size of granules of sand or smaller in which no natural erosion processes are present; ie, water or atmospheric mechanisms that have eroded or smoothed the edges of the particles once formed. While the extraterrestrial dust world has further segregated philosophically – arguments based on particle size and whether particles are considered "dust" or "regolith" – for the purpose of this discussion it is not necessary to further stratify the definition.

Low-abrasion Dust—Low-abrasion dust is characterized generically as *in-situ* regolith material the size of granules of sand or smaller in which natural erosion processes are present; ie, water or atmospheric mechanisms that have eroded or smoothed the edges of the particles once formed.

Extreme Thermal Management at Vacuum:

Lunar Pole in Permanent Shadows of Craters – Cold Extreme—There has been evidence in recent years of lunar ice at or below the surface of permanently shadowed areas within the craters at the lunar poles. These areas have been part of the CxP design reference missions. Since water is a primary constituent required for human survival, very expensive to launch from Earth to support missions, and the product generated through electrolysis that can be used for rocket fuel, any destination that has a form of water available for utilization will be highly desirable.

However, for ice to exist it must be protected from the solar wind and sublimation process that would require it to be

Table 2. Space Suit System Mass Values for NASA Historical and Currently Operational EVA-capable EMUs

Parameter/Weight on Earth: kg (lbs)	Apollo EMU [17]	Space Shuttle EMU [17]	ISS EMU [18]	CxP Suit Element (goal requirements) [19]
Space Suit/Pressure Garment	35.4 (78)		65.2 (143.7)	ISS: (92) Lunar: (92)
Portable Life Support backpack	60.8 (134)		89.2 (196.7)	Lunar: (108)
Total	96.2 (212)	170 (375)	154.4 (340.4)	(200)
Operational Pressure kN/m² (psia)	25.9 (3.75)	Nominal: 29.7 (4.3)	Nominal: 29.7 (4.3) DCS Treatment: 55.2 (8 above ambient)	29.7 (4.3) DCS Treatment: 55.2 (8 above ambient)

outside the line of sight of the sun, be buried beneath a protective layer of dust, or be at cryogenic temperatures. This will place the astronauts working in an environment of cryogenic touch temperatures and, in turn, will drive the need for development of advanced materials that are highly flexible at these temperatures or of advanced glove or manipulator technology to increase crew productivity. Advancements will also have to be made to be able to provide the thermal management of the crew for long durations at these temperatures.

Lunar Equator, Center of Crater at Noon – Hot Extreme— Earth's moon also offers the other end of the thermal management extreme for possible human exploration in the center of a crater, at the equator at lunar noon. The Apollo Program mitigated the impacts of both the cold polar and the hot equatorial thermal extremes by visiting the mid-latitude areas at lunar twilight[11]. While this approach was perfectly acceptable for humankind's first venture from home, the approach will significantly handicap future extensive exploration and permanent habitation away from Earth.

While it is possible that L1 of the sun-Earth Legrangian/ libration points has higher solar flux from the sun, the solar albedo[12] resulting from a combination of normal reflection from the lunar surface (the angle of refection and reabsorption   by astronauts is higher) coupled with the solar flux[13] normal to the surface (case for maximum surface coverage) and the "solar cooker" effect of the walls of the crater creates a thermal environment that will be the

most radiative thermally challenging for any destination humans may attempt to visit in the foreseeable future.

Moderate Thermal Extremes—The two environments that fall into this category are LEO (near a structure with significant thermal mass) and the martian surface. This is an interesting grouping as these two environments represent the milder thermal management design challenges for space suits. They are both unique in that they are less extreme as far as how the design must be changed to address the environment.

The radiative thermal environment in LEO takes advantage of local albedo from the structure the astronaut is working around and that is being reflected from the Earth. Given the approximate 90-minute orbit duration[14] (45 minutes in the sun and 45 in the Earth's shadow), the conductive temperatures are moderated and can be further smoothed depending on the thermal inertia of the structure.

The martian thermal environment can range from the moderately cold LEO temperatures to, at the hottest, what would be a typical winter day in Scandinavia (-112 to -8ºC [-170 to 17.6°F]). The presence of an atmosphere, albeit one that is 1/168th that of Earth, does provide some convective and conductive heat transference that renders the current thermal insulation approach in vacuum inviable.

Phase II: First-order Environmental Impacts to Design

The two most common groupings of destination environments were *microgravity* (LEO, GEO, sun-Earth-moon Lagrangian points, in-transit mission contingency EVAs, low-mass NEO/NEA, moons of Mars, moons of Jupiter and Saturn) and *reduced-gravity environments* (local gravitational fields of one-third Earth or less: Mars and Earth's moon). The decision to group the environments in terms of the gravity field hinged on the mobility of the human performing the mission tasks and the technology required per the experience of NASA that the technology, tools and mobility methods are dramatically different for a microgravity environment, a reduced gravity environment

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[11] This is not part of the discussion of this study, but it should be noted that the twilight conditions of the Apollo mission EVAs, in addition to providing thermal mitigation, also provided an optimum balance of lighting conditions. In the absence of an atmosphere to diffract light, the contrast between the directly illuminated surface and that of the shadows is difficult for the human eye to readily adapt. The result is a lack of depth perception and an inability to see into shadows until within the shadow. This would remain an issue for design and operations of future missions.

[12] The albedo of an object is a measure of how strongly it reflects light from light sources such as the sun. It is therefore a more specific form of the term reflectivity. Albedo is defined as the ratio of total-reflected to incident electromagnetic radiation.

[13] Solar flux, or radiative flux, is the amount of energy moving in the form of photons at a certain distance from the source per angle of incidence per second.

[14] This orbital period is representative of the typical operational orbit for the space shuttle.

and that of Earth's surface gravity. Experiences from Apollo EVAs and the suit mobility designs of the day resulted in the astronauts loping across the lunar surface for long traverse as they found this to be an easier and more expedient means of traversing than fighting the internal pressurized forces of the suit via a more earth-like ambulation. Likewise the current knowledge of the near earth asteroids – and quite frankly our hope – that there are none currently that will approach the size of the moon or larger necessitating earth-like ambulation; despite what Hollywood would have you believe.

The need for human life support (which in this case will be defined as requiring inspired oxygen and hydration) within the biological requirements for normal bodily function is necessary for all human excursions outside the bounds of the Earth's surface. Therefore this is common to all destination environments and not called out specifically as a design driver – with the exception of when there is an atmosphere or not, as this will influence the technologies and strategies for providing these life support functions. It should be noted that life support systems are one of the more complicated and expensive systems required in space flight and should therefore not be trivialized or forgotten when prioritizing development.

It should also be noted that the impacts due to the internal operational pressure of the suit can significantly impact suit design and system mass. In Table 2, the impact to system mass of the ISS EMU due to an operational pressure of 8-psi, as opposed to the typical 4.3-psi, is significant. While a designed operational pressure of 8-psi is not required for EVAs, it does profoundly decrease the amount of pre-breath time on pure oxygen to denitrogenate the blood to prevent decompression sickness. As a 4.3-psi suit impacts the operational timeline of a mission but does not limit either mission technology or design, the 4.3-psi suit is considered operationally desirable for this study; it is not singled out as an environmental design driver.

And lastly the suit operating pressure inside the vehicle has to be coordinated with the cabin atmosphere and pressure, oxygen concentrations, which affect flammability considerations, EVA pre-breathe protocols, and vehicle operational constraints.

Phase III: Second-order Environmental Impacts to Design

Once the destination environments were grouped, a mapping to the environmental suit design drivers was performed as can be seen in Figure 1. In environment groups in which all of the included environments contribute to a suit design driver, the line for the group begins at the group boundary and proceeds to the design driver. For design drivers in which all of the environments within a group do not map to the design driver, lines specific to that environment map to the driver. For example, all of the microgravity environments map to the microgravity and to the extreme-thermal-at-vacuum drivers and, thus, the black
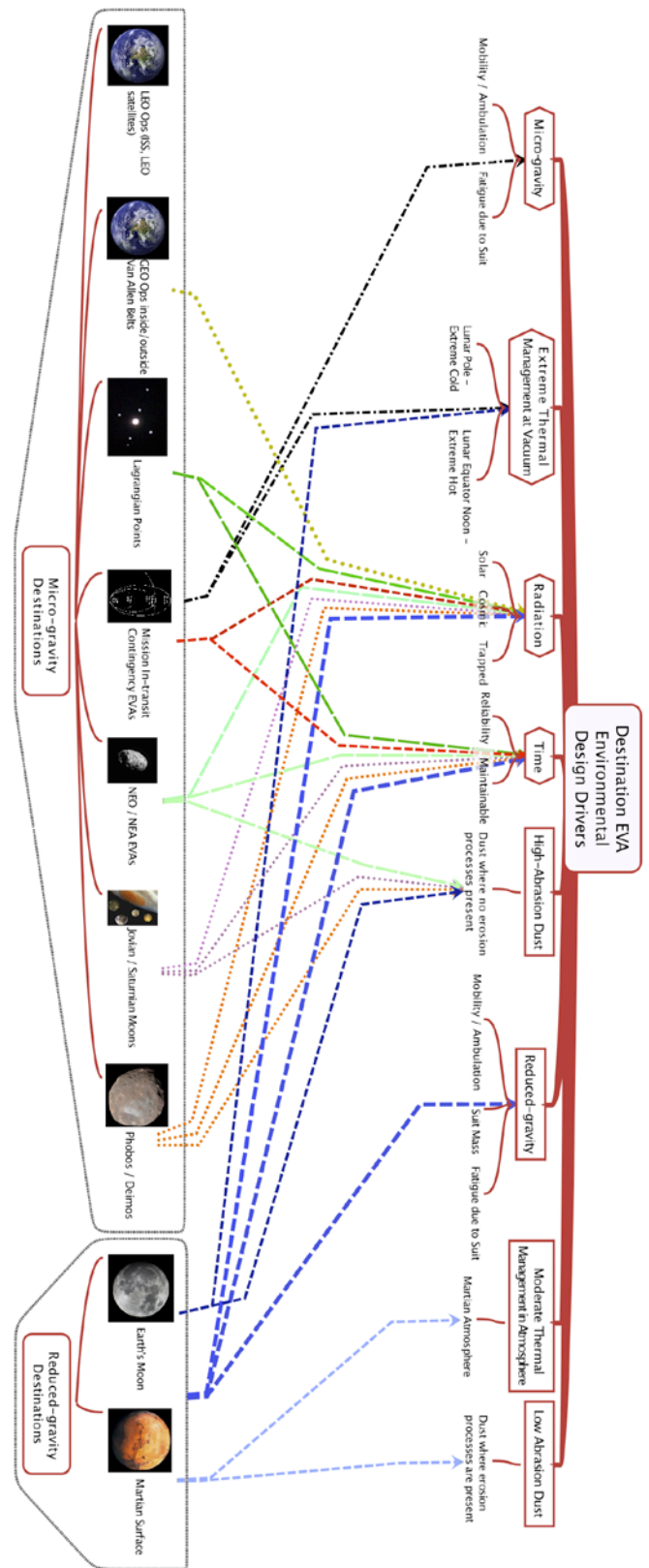

Figure 1 – Mapping of the probable human EVA destination environments to the primary space suit design drivers.
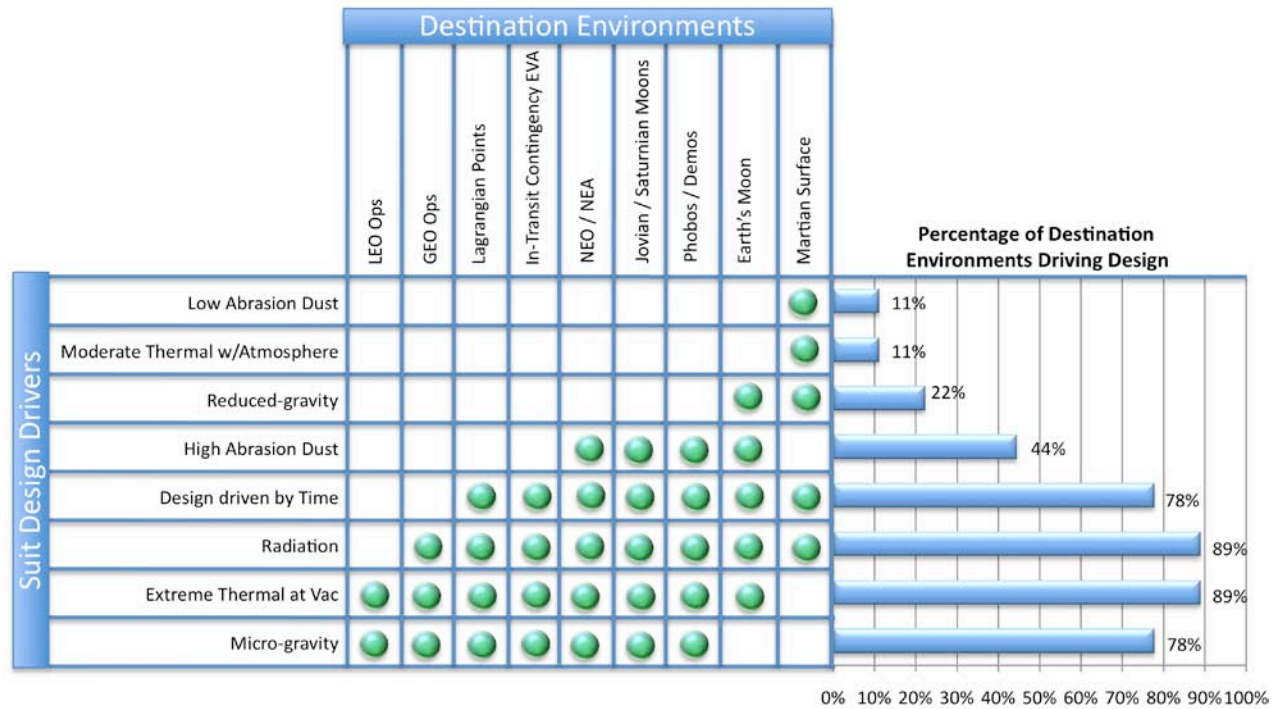
Figure 2 – Mapping of the EVA destination environments to the design drivers so as to identify commonality percentages; this will aid in identifying the most common design drivers for all the possible human EVA destinations

dotted line maps from the microgravity destinations group border. However, all of the microgravity destinations map to the radiation design driver except for the LEO environment; therefore, all of the microgravity environments – except for LEO – map via lines to the radiation design driver.

As seen in Figure 1, and perhaps more clearly in Figure 2, extreme thermal management in vacuum and radiation protection from a high-level assessment are design drivers for 89% of all possible destinations on which humans are likely to perform EVAs. Coming in a close second at 78% of all destination environments are the design drivers due to mission duration (time) and microgravity. Following these we see at surprisingly low percentages: high-abrasion dust at 44% reduced gravity at 22%, and moderate thermal and low-abrasion dust tied last at 11%.

Extreme Thermal at Vacuum—Not surprisingly, all destination environments listed, with the exception of Mars, have to contend with thermal management in the vacuum of space. And, in reviewing the data, it is seen that of the destinations available for human EVA, the thermal extremes seen on Earth's moon encompass all other environments.

Radiation—Historically, due to mass constraints for launch capability and cost, protection against solar and cosmic radiation has been "best-effort" strategy in which outer garments provide protection against alpha particle radiation but limited effectiveness against anything else. To date, NASA has mitigated exposure for LEO operations by monitoring solar activity and limiting EVA time during high-activity or solar events. A similar approach was used, for the Apollo missions, but the information regarding solar activity was limited due to ground-based telescopes and radiation monitors on the lunar lander.

It should be noted that there is no delineation in Figure 2 in the percentages as to what form of radiation each of the environments includes; instead the percentages are rolled up. Environmental groupings in Figure 1 show that radiation protection is a significant environmental design driver that is common to all destinations outside of LEO and can have a profound impact on human life due to the long mission durations and for long-term exposure. Given the leaps of understanding on the mechanics of radiation and decay, and their effects on humans, it is feasible and critical that a concerted effort be applied to suit development for human exploration.

Design Impacts due to Time—With the exception of LEO and GEO, all potential destinations for human EVA will require long mission durations at quite a distance from the resources and supplies of Earth. Therefore, it should be recognized that a methodical approach must be taken for developing highly reliable space suit system. By focusing the on the individual design element with regard to the most extreme operational environment and the maximum mission duration, the goal would be to drive the mean time to failure well beyond any mission hardware needs. Such a systematic approach will over time drive out the failure modes, increase the design reliability and build a statistical

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operational experience base such that failures are well understood and at times predictable.

Microgravity Design Drivers—Similar to the discussion of thermal management at extreme temperatures in a vacuum, the number of destinations with very low to negligible gravitational acceleration by far outweigh the destinations in which a reduced, yet significant, gravity field is present that is relatively hospitable to humans.

High-abrasion Dust—High-abrasion dust, as a design driver, comes into play in less than half of the environments discussed in this paper given the number of destinations that pertain to deep-space EVAs or Mars, where the dust has been eroded over time. It should also be noted that our experience with the dust on Earth's moon is indicative of what is expected for destinations with high-abrasion dust.

Reduced Gravity, Thermal Management in an Atmosphere, and Low-abrasion Dust—The last three are grouped because the percentages, while not initially expected, make sense when considering all other destinations. All three have to do with Mars and Earth's moon, which are the only significant bodies within current human exploration. Moreover, Mars is the only other body with an atmosphere that facilitates two of these three design drivers. Further implications of these findings will be discussed later.

5. IMPLICATIONS TO TECHNOLOGY DEVELOPMENT STRATEGIES

Given the past success rate of projects to be funded through completion within NASA, it is advised to obtain funding via non-flight program monies, develop the technologies that will give the highest probable return on investment with the greatest likelihood of being needed, and coordinate the effort at the agency level to reduce the likelihood of redundant effort or miss-vectoring.

This study addresses the likelihood of design drivers as a function of the possible destinations that human EVA will potentially encounter given the likelihood of technological advancements within the next few decades. With this in mind, results could differ from those one would expect given past efforts in suit design and technology developed to any significant level. In the past, these efforts were defined by a particular mission with a particular destination in mind – usually the first time visiting that destination. In that framework, that paradigm of design and technology development prioritization made sense. However, in a future in which resources to be applied to space suit design and technology development will be scarce and prioritization will be expected, the need for exploration as well as the destinations to be explored will vary with policy makers in power; therefore, a prioritization based on the likelihood of occurrence should be seriously considered.

This is not to say that Mars as a destination is not warranted. If it is clear that Mars is a high-priority destination due to national security, discovery of unobtainium, or survival of the species, the prioritization presented here will be overcome by events. But, in light of such direction, we see here that half of the significant design drivers for space suits encompass 78% to 89% of all destinations for human EVA. What we do see is that only one-quarter of the suit design drivers are specific to Mars.

So, from a perspective of return on investment to reach the maximum yield of dollars invested in space suit design and technology development, a new focus should be brought into the forefront for discussion. A modular suit architecture as discussed in [1] and [2], would allow for a generic set of suit hardware components or elements that would address the majority of destination environments while minimizing the impact to performance. Additionally, it would provide hardware and design interfaces such that suit components that needed to be changed due to specific and/or unique environmental constraints would be changed. Furthermore, by minimizing the costs due to suit redesign, cost savings in terms of launch mass, and only launching the suit components necessary for destinations of that mission, savings in terms of schedule can be realized since the technology can be developed prior to the mission that is being defined; ie, the sooner you launch, the cheaper it is given you have saved the money in the out-years due to inflated dollars.

It is not the intent of this paper to assess the current state-of-the-art of space suit design with respect to any of the design drivers discussed here. It is the intent to bring to the stage, in a systematic and well managed effort, the notion of addressing the design drivers that will be most frequently encountered in human EVAs in the foreseeable future.

6. CONCLUSION

This study systematically addresses all potential destinations in the solar system for human EVAs within the next 30 years based on current technological capability and, using linear extrapolation, that which can be achieved based on experiences during the last 50 years of human space flight. The destination determination was based on environmental extremes that are within human technology (no warp drives and force fields available) to address and within probable resources (based on funding trends over last 50 years) that will likely be allocated for human exploration.

What we see is that the destination list, which is based on these selection criteria, is greatly narrowed and the possible destinations for our human (in-person) exploration reduces into a well-defined subset of space suit design drivers that are not likely to change significantly in the near future and can be used now to solve most – if not all – of the major design challenges facing space suit engineers and exploration programs today.

The findings and rankings presented in this paper provide a mission-independent, EVA system development approach

based on destination environmental space suit design driver likelihood. This approach will help ensure the highest likelihood, and highest return on investment while there is no programmatic destination of record and will also ensure the opportunity to provide the largest return on taxpayer dollars that will meet multiple future mission destinations. This allows a greater chance of providing better technical solutions to future missions when they are needed, as opposed to waiting for a mission to be identified and then starting to solve the technical suit design problems once the programmatic and budgetary clocks have begun to tick.

It is also highly recommended that this development approach be considered and managed as a "Flight Program," meaning that development technical requirements, budgets, and developmental milestones are well defined and managed to agreed-upon completion dates. This will help ensure that these efforts will reach the desired engineering solution in a reasonable amount of time and not evolve into never-ending science projects.

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In leading the CxP Suit Element engineering team, Terry had the responsibilities of JSC's Engineering Project Manager, the CxP EVA Systems Suit Element Deputy Lead, and Element Lead during his tenure on the project. He facilitated the development of system functional requirements for space suit development and a "clean-sheet" design approach that has been widely recognized within and outside NASA.

BIOGRAPHY

Terry R. Hill *is a member of the NASA Lyndon B. Johnson Space Center (JSC) International Space Station/Shuttle Extravehicular Mobility Unit (EMU) Team where he is responsible for providing engineering insight into the 2010 life extension hardware modifications, determining what the system hardware impacts are to extending the ISS EMU support out until 2028, and investigating how the EMU can be used as a demonstration platform for technology development.*

Terry has a B.S. in Aerospace Engineering and an M.S. in Guidance, Navigation, and Control Theory with a minor in Orbital Mechanics from the University of Texas at Austin. He began his career at NASA while working on his graduate thesis project in developing banks of simplified Kalman filters integrated into an artificial neural network to obtain an optimal state solution for precision landing on Mars.

While at NASA, Terry has worked on projects and programs spanning from ISS navigation software verification to Shuttle navigation design test objectives and back-room mission support, X-38 Crew Return Vehicle navigation algorithm development, Space Launch Initiative technology development, Orbital Space Plane Project office ISS-prime integration, Space Shuttle "Return to Flight" STS-107 tile repair capability development, and to CxP Space Suit Element leadership.

Terry and the Suit Element have been interviewed by the Associated Press and covered by media outlets including CNN.com, Forbes.com, and National Geographic video "Living on the Moon" air date 2009. Terry has also been identified as one of NASA's Constellation Stars, and was identified as NASA Tech Brief's "Who's Who at NASA" for November 2010.

Exploration Space Suit Architecture and Destination Environmental-Based Technology Development

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Abstract—This paper continues forward where EVA Space Suit Architecture: Low Earth Orbit Vs. Moon Vs. Mars [1] left off in the development of a space suit architecture that is modular in design and could be reconfigured prior to launch or during any given mission depending on the tasks or destination. This paper will address the space suit system architecture and technologies required based upon human exploration extravehicular activity (EVA) destinations, and describe how they should evolve to meet the future exploration EVA needs of the US human space flight program.[1, 2, 3]

In looking forward to future US space exploration to a space suit architecture with maximum reuse of technology and functionality across a range of mission profiles and destinations, a series of exercises and analyses have provided a strong indication that the Constellation Program (CxP) space suit architecture is postured to provide a viable solution for future exploration missions[4]. The destination environmental analysis presented in this paper demonstrates that the modular architecture approach could provide the lowest mass and mission cost for the protection of the crew given any human mission outside of low-Earth orbit (LEO). Additionally, some of the high-level trades presented here provide a review of the environmental and non-environmental design drivers that will become increasingly important the farther away from Earth humans venture.

This paper demonstrates a logical clustering of destination design environments that allows a focused approach to technology prioritization, development, and design that will maximize the return on investment, independent of any particular program, and provide architecture and design solutions for space suit systems in time or ahead of need dates for any particular crewed flight program in the future. The approach to space suit design and interface definition discussion will show how the architecture is very adaptable to programmatic and funding changes with minimal re-design effort such that the modular architecture can be quickly and efficiently honed into a specific mission point solution if required. Additionally, the modular system will allow for specific technology incorporation and upgrade as required with minimal redesign of the system.

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1. INTRODUCTION

Destinations for Human Exploration

In looking forward to the future of human space exploration, it is important to first consider the possible destinations that humans can realistically travel to, survive in, and possibly live in for extended periods of time with reasonable resources and budget. For example, it can be assumed with some level of confidence that there will be no crewed missions to Mercury due to the required infrastructure, logistics train and rocket design that would be needed to climb into and out of the inner gravity well of the sun. However, it is reasonable to consider visitation of the Earth-sun libration points. In following this line of thought, and using current knowledge of the physical environments of destinations in the solar system from which one can return in a decade or less, one can very quickly identify the destination design drivers required for exploration-class space suits.

Historically, technology development for human space exploration primarily did not happen until the mission was

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[2] IEEEAC paper #1330, Version 3, submitted December 22, 2010.

[3] This paper was peer reviewed for technical content by: Lindsay Aitchison (Pressure Garment Engineer), Kimberley Baird (Dep. Branch Manager), Cinda Chullen (EVA Technology Development), B. Michael Lawson (CxP Suit Element Life Support Subsystem Manager), Joseph J. Kosmo (Space Suit Advanced Development Lead Engineer), Amy Ross (Pressure Garment Development Lead), William Spenny (ISS EMU Engineering Subsystem Manager), Robert Trevino (Space Suit Life Support Technology Development) and Sandra Wagner (EVA Systems Lunar & Mars dust mitigation) - NASA/JSC Crew & Thermal Systems Division, Space Suit and Crew Survival System Branch.

[4] One of the remaining challenges of the CxP suit architecture was incorporation of the launch, entry and abort functionality into the system without significantly compromising the survival or EVA functional performance. While this aspect of the architecture is still under debate, the modularity and commonality of the architecture for EVA missions is still valid and worth consideration.

defined and funded or was done at the component level in efforts to improve existing systems. Low technology readiness level technology development for pursuing advanced concepts has been also very limited. While the logic in this is understood, given that humans only started venturing beyond the relatively benign environment of Earth in the last 50 years and had little idea of what might be encountered at each destination, today the approach should be questioned, given that humans have either physically stepped on, landed robotic probes, placed orbital vehicles around, or had close fly-bys of every single significant body in the solar system – with the exception of Pluto. Now with the volumes of data growing at a near-geometric rate, the knowledge of the environments in which humans can venture is understood to the point where common design drivers and required design elements can be identified with reasonable confidence. Given this knowledge of the environments and lessons learned from human space flight operations to date, an internal assessment (performed within the Space Suit and Crew Survival Systems Branch at the Johnson Space Center) of the progress that has been made in human exploration space suit technology with respect to the "design space" is proposed in this paper.

In the following pages, a review will be performed of the exploration space suit architecture developed in NASA's Constellation Program (CxP) and how it can be used for future human missions. Additionally, a methodical approach to common and probable destination environments will be addressed and how this should affect the prioritization of space suit technology development in the future.

2. OVERVIEW OF THE CxP SPACE SUIT ARCHITECTURE

The space suit architecture developed by NASA's Constellation Space Suit Element (CSSE) only addressed crew survival, low earth orbital operations and lunar surface EVAs, but at the very core had many, if not all, of the key design-driving elements that will be required for human exploration in the solar system. The CSSE team[5] addressed this challenge by fully embracing "clean-sheet" or "textbook" systems engineering methodology by first defining the operational concepts, which focused on the development of an architecture with all CxP design reference missions (DRMs), and keeping an eye on life-cycle program costs. A comprehensive review of the functional designs, strengths, and limitations of previous US space suits, in addition to what is known of Russian space suits, took place to deduce historical lessons learned based not only on what did not work but, more importantly, on what worked right. The current strategy to accomplish the rather daunting task of meeting all space suit design requirements in the extreme environments previously detailed with a single system hinges on an arrangement that not only uses

common hardware across multiple mission phases (to reduce developmental and logistics costs). And also features an open architecture that can be reconfigured and can leverage off components used during other mission phases where possible. [1]

The following were the key design figures of merit that were used in evaluating all of the following different architectures, some of which later became architecture design drivers: operational performance; work efficiency; launch, entry, and abort overhead; suit attributed mass and volume; field maintenance; commonality (design and hardware); extensibility; technical risk/feasibility; life cycle costs; and development schedule risk. The following were the suit performance criteria that defined the high-level functional requirements for the suit architecture: intra-vehicular mobility; microgravity mobility; microgravity environmental protection (thermal, radiation, micro-meteoroid protection); comfort (un-/pressurized); ease of donning and doffing; crew ability to escape the vehicles while wearing the suit; suit sizing methodology; ability of the suit to have sizing adjustments; high operational reliability; high evolvability and adaptability; extraterrestrial surface mobility; and extraterrestrial surface environmental protection

After five years and multiple design iterations, the CSSE suit architecture consisted of the following modular, or swap-able (from one configuration to another), hardware elements: helmet bubble and communications cap, gloves optimized for pressurized usage, boots optimized for 1g vehicle escape, lower arms and legs with mobility joints and umbilical connectors; and restraint mechanisms that are common in design. The fire protection outer cover layer and EVA thermal multilayer insulation (MLI)/thermal micro-meteoroid protection garment (TMG) were unique enough to very discrete mission phases that it was felt they would not be included functionally in the modular hardware so as to reduce the overhead of carrying around hardware for infrequent use or as bad-day risk mitigation. The outer layer of the TMG is not only fire resistant, but it provides low emissivity for reflecting solar radiation – thus the white coloration – and also provides cut, puncture, and abrasion resistance. The outer layer of the MLI/TMG may require a different coloration on Mars to meet the emissivity requirements for that environment.

With the maturity of human exploration into space is still in its infancy and with limited resources to apply to development, a flexible system that will minimize the cost by decreasing the development cost per mission is desirable. However, with a system that operates in varying environments there is the risk that performance in specific environments will be compromised. As experience in specific environments grows or human habitation is more permanent, then specialized suits and hardware will be warranted.

Additionally, the portable life support system will be used only on the lunar surface as life support functions are

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[5] This team was comprised of NASA civil servants and support contractor workforce with the responsibility of defining CxP space suit architecture and associated functional requirements and to later become the NASA oversight and subsystem managers.

provided by the vehicle when the crew is inside or while performing microgravity EVAs. And, the core torso segment, which is optimized for eight hour surface EVAs, is swapped out with the all-soft segment used for launch and landing. Prior to the CxP space suit design effort, a very similar design philosophy was recommended by Joseph Kosmo, NASA, in 1990. [2]

How This Works Well for the Different Destinations for Human Exploration.

The fundamental plan was for the CxP to evolve from microgravity to lunar exploration with sortie and long-duration habitation, and to progress eventually to Mars exploration. [3]

The common themes on how the CSSE suit architecture would be used for the CxP resonate with the possible design

reference missions being discussed today for future human exploration. At the most fundamental level, every human launch will need to provide protection for the crew against a bad day on the launch pad as well as a launch abort scenario and protection while reentering the atmosphere on mission completion. Each mission will either require a planned microgravity EVA or the capability to perform contingency EVAs in the event the vehicle leaks or other hardware malfunctions require mitigation – particularly during missions with long transit durations. And, as with the Constellation suit, it is highly desirable for these future missions to be able to reconfigure a suit to meet the different needs of the crew (to save mass and volume) and not carry multiple suits per crew member.

Additionally, multi-program life cycle costs and return on investment in technology development can be realized in

Table 1. Destination Environment Design Values Used to Develop Design Driver Groupings for Space Suits.

Destination EVA/ Parameter	LEO/GEO [4][5][6][7]	Lagrange Points [8]	In-transit (Deep Space) Mission	NEO/NEAs	Earth's Moon [9][10][11]	Moons of Mars, Jupiter, and Saturn with No Atmosphere [12][13]	Mars Surface [14][15]
Mission Duration	1-2 weeks	3-6 months Transit + Mission Dwell time	6 months to 3.5 years	6 months to 3 years	Sortie: 1-2 weeks Outpost: 6 months to 1 year	Martian moons: 3 to 5 years Jovian/Saturnian moons: 5 to 10 years	6 months to 1.5 years + transit time
Gravity Field (m/s²)	μg	μg	μg	Effectively μg	1.63	Phobos – Effectively μg Demos – Effectively μg Europa – 1.314 Ganymede – 1.43	3.71
Radiation (Solar Wind, Cosmic, Trapped)	LEO (shielded) Van Allen (trapped)	Solar and Cosmic†	Solar and Cosmic	Solar and Cosmic	Solar and Cosmic	Solar, Cosmic & Trapped	Atmospheric Shielded
Thermal Environment Touch Temperatures (°C)	-78 to 125				Shadows at poles to center of crater at equator at lunar noon (-244 to 120)	Europa – Min. -223 Mean -171 Max. -148 Ganymede – Min. -279 Max. -189	Min. -87 Mean -63 Max. 20
Dust Environment	None	None	None	High Abrasion	High Abrasion	High Abrasion‡	Low Abrasion
Atmospheric Pressure	High Vacuum <1 Pa	High Vacuum <1 Pa	High Vacuum <1 Pa	High Vacuum <1 Pa	High Vacuum <1 Pa	High Vacuum <1 Pa	0.61 (4.57) kPa

† Includes the primary radiation from the source and secondary radiation as a result of the interaction of the source radiation and local materials of the space craft and/or space suit.

‡ Moons that have ice processes in place (Europa, Enceladus) may provide sufficient mechanism to provide dust that would fall into the Low Abrasion category.

this approach by designing to the architecture interfaces and only performing multiple designs for the hardware specifically required for the unique environments.

3. METHODOLOGY OF DESTINATION ENVIRONMENT DESIGN GROUPINGS

Determination of the Design Drivers

The formulation in a new way of prioritizing technology development efforts for space suits began with the President's new vision for NASA in February 2010. It seemed that the proposed emphasis of NASA's resources would be less focused on continuing with the CxP and building flight hardware but more in going back to the drawing board and developing the technology that would be required to make long-duration space exploration more successful when we as a nation were ready to step out into space for good.

For this study, a different approach was taken with an inventory of possible destinations in the solar system that humans could reasonably explore given the likely technology developments in the next 30 years regarding launch vehicle, engine, closed-loop life support systems, and subsequent durations of missions and space suit technology. When the destination list was complete, the subsequent environments and characteristics were assessed and grouped for commonality.

Destination Design Environments

The environments of the destination locations will be briefly discussed in the sections to follow; however, they will not be discussed in great detail as the individual environments have been documented in the source materials referenced. It is worth mentioning that for this exercise, and to a large extent in space suit design, the exact numbers for environmental design drivers are not critical discriminators in the first-order design of the system. For example, whether the local vacuum of space is 1×10^{-5} torr or 1×10^{-13} torr, for a suit pressurized to 4 lbs/in^2, is of marginal consequence. The same can be said for designing a suit to tolerate a touch temperature of -125 or -148°C (-193 or -234.4°F) in which the design challenge is largely the same and may only impact final material selection or second-order suit heater impacts to the power budget. The specific environmental values that are used for this study are summarized in Table 1, and the major suit design drivers for suit development will be summarized in each section.

Low-Earth Orbit (LEO) Operations (ISS, LEO satellites)

The LEO microgravity environment, which is the most familiar in human exploration, is where the largest amount of experience in performing human EVA operations has taken place in the last 50 years. The environment is thus well understood. The local gravitational acceleration, while in the gravity well of Earth, places an object in a state of orbital free fall and, therefore, will be quantified on the

order of micro-g's. Additionally, the atmospheric drag at the altitude most Shuttle missions and ISS operations take place will be considered negligible with regard to space suit design. The radiation environment, which is greater than the environment high-altitude pilots are exposed to due to lack of an atmosphere, still resides within the Earth's Van Allen belts. The exception is for a region above the Earth known as the South Atlantic Anomaly[6] where potential EVAs performed while the passing through this region are limited to 3-5 passes for any particular crew member before they are rescheduled; however, the actual limitation is defined by the personal accumulated radiation dosage which is tracked for the mission and for life of the crew member. The current flight rules [16] for EVA radiation exposure state specifically:

A. For predicted exposure less than the action level (non-restrictive)

  1. Consider delaying the EVA up to two days or delaying or accelerating egress 1-2 revs if this will reduce the exposure while accomplishing mission objectives consistent with normal crew ground rules and constraints.
  2. An EVA in progress will continue. Consider not adding unscheduled items to existing timeline if this results in additional EVA crew exposure.

B. Predicted crew exposure greater than the action level at the end of the EVA (restricted)

  1. Delay EVA up to 14 days if still possible to accomplish mission objectives, or delay or accelerate egress 1-2 revs.
  2. An EVA in progress will continue. Consider expediting tasks not required for primary mission objectives.

C. Predicted crew exposure greater than the high dose rate limit (high dose rate limits)

  1. A planned EVA shall be rescheduled as required to reduce the exposure to below the high dose rate limit.
  2. An EVA in progress shall be expedited by deleting tasks not required for primary mission objectives.

D. Predicted crew exposure greater than the joint exposure limits

  1. A planned EVA shall be rescheduled as required to reduce the crewmember's mission exposure to below the joint exposure limit.

[6] The South Atlantic Anomaly is a result of the Earth's magnetic field and is not completely symmetric and aligned with the Earth's surface and thus allows a portion of the solar (particle) flux to extend down through LEO and affects communication with satellites, the Hubble space telescope, high-altitude aircraft and the Space Shuttle.

2. An EVA in progress shall be terminated.

The solar wind is still a non-trivial influence in this environment and, with most of the EVAs performed to date – and likely in the future – being around human-made structures, the effects of the interaction between the solar wind and large metallic structures (or solar panel elements), plasma generation, and conductance has been an increasing safety concern in the community.

Therefore, the design drivers for this environment will be: pressurized suit mobility in microgravity, life support consumables in a vacuum, thermal exposure and management in a vacuum around human-made structures, and plasma charging fields.

Geosynchronous Earth Orbit (GEO) Operations (within and outside the Van Allen Belts)

Probable future human activity in this region will consist of retrieving, repairing, refueling, or deploying geosynchronous satellites (35,786 km [22,236 mi] above the Earth's surface) or multi-day experimental missions. This environment is very similar to that of the LEO missions but with the significant difference of being within or outside the Earth's Van Allen belts for some or most of the time[7]. Consequently, the effects of the solar wind, and to a lesser extent cosmic radiation, are elevated due to direct exposure from the sun or the concentration of geomagnetically trapped radiation (electron and proton) in Earth's magnetic fields. The inner Van Allen belt extends from an altitude of 1000 to 10,000 km (621.4 to 6,213.7 mi) above the Earth's surface (the South Atlantic Anomaly is a result of the inner proton belts dipping down as low as 220 km), and the large outer radiation belt extends from an altitude of about 19,113 to 44,597 km (11,876.3 to 27,711.3 mi) above the Earth's surface. [17][18]

The duration of such missions would not be expected to exceed a 1- to 2-week duration; therefore, the time element of the design would not be considered a driver. The environmental design drivers for this region would be: pressurized suit mobility in microgravity, life support consumables in a vacuum, thermal exposure and management in a vacuum around human-made structures, plasma charging fields, and solar/cosmic/concentrated radiation effects.

Lagrangian Points: Sun-Earth-Moon

Interest in human missions to the Lagrangian[8], or libration, points in the sun-Earth and Earth-moon systems has

increased in recent years. In a two-body gravitational system in circular orbit about one another (as is the case with the sun-Earth and Earth-moon systems), there are five regions in which the gravitational balance between the two bodies are in equilibrium and lend themselves well for placement of satellites, observatories, or rendezvous depots for space missions with minimal fuel consumables for positional station-keeping.

The duration of such missions is likely to exceed 3 months – with the potential for more than one year depending on the libration point; therefore, the time element of the design would be considered a driver. The environmental design drivers for this region are encompassed by the GEO environment.

In-transit Contingency (Deep Space) Microgravity EVAs

This classification, while more mission specific, does define a design environment. This environmental scenario is a catchall for the instances during a mission in which crew members are required to go outside the vehicle to either investigate, repair, or replace hardware associated with their vehicle. NASA's experience during the last 50 years of operations is that Murphy[9] is never far away and having the capability to perform unscheduled, or contingency, EVA is a critical capability for all missions. This environment is largely encompassed by the GEO environment in terms of vacuum, radiation, and plasma charging. However, the thermal environment will probably differ due to varying distances from the sun. Additionally, due to the fact that the probable mission duration (time away from Earth) will be anywhere from three months to ten years, it is imperative that this time away be factored into the suit design, fabrication, and reliability engineering.

Low-mass Near-Earth Object (NEO)/Near-Earth Asteroid (NEA) (half mass of the moon) EVAs

The suit design environment of low-mass NEO/NEA EVAs is an interesting combination of the microgravity environment of LEO EVAs and that of the thermal and dust environment of the lunar EVAs (discussed later). This destination is associated with missions to NEO/NEA that are half the mass of the moon or smaller and would have a local gravitational acceleration between microgravity and 0.817 m/s^2, thus rendering normal human ambulation not possible. The extremely low gravitational acceleration will require the use of attachment mechanisms (to the object being studied) and mobility aids to transverse the object. In some ways the lack of meaningful gravity will affect the EVAs and how the crew performs tasks due to the fact that any dust generated/stirred up will likely hover in a cloud around the work site for indeterminable amounts of time and could potentially impact work site visibility, dust coverage of the suit, and dust mitigation strategies. If dust is present on these bodies, the characteristics of the dust (physical and

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[7] While the geostationary orbit is above the inner Van Allen belt, it can reside in or outside of the outer belt due to the compression of the outer belt on the side of the Earth facing the sun and the pressure of the solar wind. Therefore, at times the satellite might be on the outer edges or outside the belt, depending on the relative position with respect to the sun and current solar activity levels.

[8] The concept was first conceived by Joseph L. Euler around 1750 when he predicted the collinear points commonly known as L1, L2, and L3. Later, Luis Lagrange, in his work with two-body orbital mechanics, further predicted the existence of points L4 and L5; these points were all later

named after Lagrange in his honor.

[9] Societal reference for when something or a situation can go wrong, it will.

chemical) are expected to fall within the range analyzed both from the moon and from recent studies of comets[10].

Jovian/Saturnian Moons

This destination environment is one of the more difficult to define given the widely varying conditions that can be encountered in and around Jupiter and Saturn. In this paper, only the moons of both planets were considered as a viable destination because they are relatively stable (Io being an example of a moon that would not make the first cut for first Jovian mission) and would hold a great deal of either geological or biological interest. With those parameters, the field is narrowed significantly to Jupiter's Europa but is kept generalized to all of the rocky bodies with no atmosphere. Europa – and most Jovian moons of interest – lie within the dense bands of trapped radiation and at some estimates are two to three times what would be experienced within Earth's Van Allen Belts.

It also should be noted that missions to Saturn would have to be of incredible interest or necessity for the investment of the additional mission transit time to reach the planet and destinations of interest, such as the moon Enceladus. Saturn does have a region of trapped radiation that is present but it is not as extreme as what is found around Jupiter. Titan offers reduced gravity acceleration and an atmospheric pressure of 147 kPa, but satellite data suggest lakes of liquid methane and with significant methane in the atmosphere with very little oxygen and indications of atmospheric lightning. The implications are that a human presence would provide a source of oxygen and facilitate a very dangerous environment for the crew members. Thus, Titan has been removed from the analysis performed for this study.

Design drivers for this environment will be nearly identical to those of the Earth's moon with regard to the abrasive dust, cryogenic temperatures. Trapped radiation conditions (most extreme of EVA destinations), in addition to mission duration and robustness of design due to relatively unknown surface conditions and required tasks will dramatically impact the required design and technologies.

Martian Moons: Phobos/Deimos Missions

The environment of the martian moons is expected to combine lunar dust characteristics with thermal extremes at vacuum that are no greater than those seen on Earth's moon, with the low gravitational acceleration challenges seen with the NEO/NEA EVA environment. As with the in-transit EVA environment, mission duration is expected to play a major component of the design driver challenges.

Earth's Moon

The recent lunar environment definition for suit design for the CxP encompassed the entire range of lunar extremes as

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[10] Samples of comet Wild 2 returned by NASA's Stardust and data returned from the EPOXI (Extrasolar Planet Observation and Deep Impact Extended Investigation) spacecraft.

defined by the CxP goal of global access to the lunar surface with a single suit system. [1], [3] The dust environment is a known variable given the experience gained and information gathered as part of the surface EVAs and the dust and rock samples and space suit hardware returned from the Apollo Program.

As part of the "go anywhere, anytime" philosophy of the CxP, suit engineers now had to consider the design impacts of suit(s) designs that would allow crew members to function in the permanently shadowed crater interiors at the lunar poles with cryogenic touch temperatures as well as the solar furnace-like environments of craters at the equator during lunar noon.

The gravity, while one-sixth that of Earth's gravity, did provide mobility challenges to the Apollo crews since the pressurized suit design hindered natural human ambulation. Advances in space suit mobility elements since that time have significantly minimized the impact of low gravitational acceleration combined with suit pressurization to the design of a space suit. Therefore design drivers for this environment, in addition to the mission durations of two weeks to one year and associated reliability design challenges, will be as follows: pressurized suit mobility in reduced-gravity; life support consumables in a vacuum; thermal exposure and management in a vacuum at extreme temperatures; high-abrasion, very fine, and statically charged dust; and potential plasma charging fields.

Martian Surface Missions

The martian surface environment, in many aspects, is the most benign of all those to be considered for human EVAs. The presence of the martian atmosphere, albeit much less prominent than Earth's, does provide the mechanisms for wind erosion in addition to minimizing thermal extremes, solar wind protection, and some cosmic radiation shielding. Recent discoveries from NASA martian rovers and orbiters indicate an ever-increasing evidence base for the past existence of liquid flowing on the surface. Between the flowing of liquid on the surface and the atmospheric erosion mechanisms, the martian dust physical characteristics will be considered low abrasion albeit more abrasive than what might be found on Earth. However, while knowledge of the chemical makeup of the martian dust is limited, with the spectral information from the orbiting satellites and the spot analyses from the rovers, the generalized list of chemical makeup is growing.

The current NASA design reference missions [19], [20], [21] indicate a probable mission duration of upwards of 3.3 years. This poses quite a challenge for space suit engineers to design a suit that is highly operable, does not require frequent maintenance, is very durable for significant usage at Mars, and is highly reliable – not requiring repair or replacement – during the mission. Additionally some surface data from the Spirit Mars Exploration Rover indicates that the surface temperatures can vary from -23 to

-90 degrees Celsius diurnally from late summer to fall respectively. [22] Therefore some consideration may be required for long mission stays that may span seasons at some of the martian latitudes.

Therefore, the design drivers for this environment, in addition to the mission durations of as many as 3.3 years and associated reliability design challenges, will be: pressurized suit mobility in reduced gravity; life support consumables in a rarified atmosphere; thermal exposure and management in a rarified atmosphere at cold to moderate temperatures; and low-abrasion, very fine, and potentially chemically reactive dust.

4. MAPPING DESTINATION ENVIRONMENTS TO MUTUALLY INCLUSIVE DESIGN DRIVERS

Destination Mapping Phased Approach

The study was approached in three phases to provide a systematic review of what is needed in space suit design as a function of the potential destinations for human EVA. The first phase of this study, after defining the list of potential human exploration destinations, was to define a list of space suit design drivers per destination. The second phase took the destination-based design drivers for space suit hardware and focused on the physical characteristics of the local environments, grouping them into common design drivers. These subsequent groupings were: microgravity, reduced gravity, thermal extremes at vacuum, solar, and cosmic radiation; high-abrasion dust; low-abrasion dust; and thermal management in the presence of an atmosphere. And lastly, the third phase of defining the design drivers focused on unique aspects of missions that would affect the design of space suits; this resulted in: mission length and distance from Earth (hardware reliability, maintainability, and complexity) and long durations of exposure to radiation.

Phase I: Defining EVA Design Drivers

Microgravity Destinations—Mobility in microgravity becomes an issue as Newton's third law of motion comes into play: Bodies remain in a state of rest or uniform motion (constant velocity) unless they are acted upon by an external unbalanced force. How this transfers to suit design is in the ability to move and translate from one location to another with minimal resistance from the suit itself, and in smooth motions that will not excite unwanted suit dynamic motion or cause undesired impact forces to interactions with the local environment that would set the crew member in unwanted directions. What is desired is a suit that provides the required pressure and has mobility joints that provide low torque and no programming[11]. While it is largely independent of the gravity field, it is one of the leading causes of astronaut fatigue during micro-gravity EVAs.

[11] Some space suit mobility joints are made of sets of circular bearings that are offset at different angles to obtain the desired range of motion for that joint. However, this often results in a mobility joints that require proper alignment of the bearings to obtain certain reach zones.

Reduced-gravity Destinations—The reduced-gravity destination environment group is comprised of potential EVA environments in which the local gravity field is defined as $1.6 \text{ m/s}^2 <$ local acceleration $> 6.5 \text{ m/s}^2$. Of the possible destinations where humans can survive and potentially live long term with a return to Earth within five years, the following present themselves as viable destination candidates: Earth's moon and Mars. In a reduced-gravity environment, as defined previously, the two major design drivers are the mobility and mass of the space suit. Similarly, as discussed with the microgravity environment, pressurized mobility of the suit and minimizing suit-induced fatigue on the astronaut are highly desirable given the relatively short EVA time available and the voluminous lists of desired tasks during EVAs – if crew members are exhausted early in the EVA, not all objectives will be met. As has been seen in the past, crew fatigue is primarily a combination of suit pressurization and tasks required of the crew of which the gravity environment will obviously frame what tasks are required of the crew.

Secondly, the mass of the suit is very important in a few different ways. The gravity environment in which the suit will be used and the length of time the crew member has been out of the Earth's 1g environment should be considered when defining the mass of the space suit. For example, if the crew has only been away from Earth for one week and will be operating a 68 kg (150 lbm) suit on the moon, this is a manageable situation (other than the inertial resistance of the suit) as this suit would appear to weigh on the moon the equivalent of 11.3 kg (25 lbs). However, if the crew member has been on the moon for one year and his/her muscular strength has adapted to the moon (e.g., no muscle resistance training to mitigate muscle atrophy), the suit would appear to weigh 68 kg (150 lbs) on the moon and would adversely affect the fatigue levels of the crew. Granted this is a scenario that is unlikely under normal mission operations, but it is used here to exaggerate the point. There is growing thought that the EVAs themselves, when done regularly, could prevent atrophy due to the loading of the skeletal system from the suit; however, the ISS paradigm would imply the necessity of exercise protocol throughout a mission to prevent the known long-term effects of weightlessness.

There is also growing thought in the space suit community that a different look should be taken at how the mass of the suit is viewed and managed. The thought is that in reduced gravity environments, such as Earth's moon and that of the smaller moons, natural human ambulation as performed on Earth is not really practical or easy given the presence of reduced gravity. This was seen in the Apollo EVA video footage in which the crew would frequently fall over or would lope across the surface. Loping was easier to do than traditional earth ambulation and was not as physically taxing. However, as some recent simulated reduced gravity testing performed at JSC has indicated that even the suit-less human ambulation changes in the reduced gravity

environment and that new approaches to suit mobility in these environments should be investigated further.

As with all things relating to space exploration, there is a trade-off between the amount of mass that can be launched from Earth and that required to perform the task optimally in the destination environments. Mass is always king on launch day, so careful mass margin management and impacts on mission objectives at the final destination, should be considered.

Radiation—The non-thermal radiation environment for human exploration missions within and outside of Earth's Van Allen belts will increase the risk to human survival in two general situations: high-energy solar events and long-duration exposure to cosmic and solar radiation. Given the propulsion technology of today and the cost of space travel, any destination in our solar system will either require substantial time for the mission or the time spent at the mission destination will be ideally maximized so as to get the return on the financial investment. However, in the early exploration missions the destination stay duration may be minimized initially to limit the risk with longer durations for subsequent missions.

Design Impacts due to Usage Duration—For the same reasons that will be discussed later, most human exploration missions outside of Earth's orbit will necessitate long periods of time away from the safety and resources of Earth. Therefore, it becomes critical that space suit design be robust enough to endure expected usage or be maintainable by a crew with minimal recurring maintenance and required replacement parts during the mission.

This discussion on space suit reliability to a large extent is an uncharted area of study. Historically, space suit hardware is non-commercial, custom hardware that is manufactured and operated in non-statistically significant quantities for standard statistical reliability calculation methods. For exploration missions, space suits will be mission-critical items that must fail safe, but the trades must be done to optimize the acceptable risk posture, mass impacts due to robustness and redundancy (extra mass on suits or spare parts and required tools launched on the vehicle), and cost associated with developing design and testing methods to be able to characterize and predict the mean time between failure and modes of failure.

High-abrasion Dust—High-abrasion dust is characterized generically as *in-situ* regolith material the size of granules of sand or smaller in which no natural erosion processes are present; i.e., water or atmospheric mechanisms that have eroded or smoothed the edges of the particles once formed. While the extraterrestrial dust world has further segregated philosophically – arguments based on particle size and whether particles are considered "dust" or "regolith" – for the purpose of this discussion it is not necessary to further stratify the definition.

Low-abrasion Dust—Low-abrasion dust is characterized generically as *in-situ* regolith material the size of granules of sand or smaller in which natural erosion processes are present; i.e., water or atmospheric mechanisms that have eroded or smoothed the edges of the particles once formed.

Extreme Thermal Management at Vacuum:

Lunar Pole in Permanent Shadows of Craters – Cold Extreme—There has been evidence in recent years of lunar ice at or below the surface of permanently shadowed areas within the craters at the lunar poles. These areas have been part of the CxP design reference missions. Since water is a primary constituent required for human survival, very expensive to launch from Earth to support missions, and the products generated through electrolysis can be used for rocket fuel, any destination that has a form of water available for utilization will be highly desirable.

However, for ice to exist it must be protected from the solar wind and sublimation process that would require it to be outside the line of sight of the sun, be buried beneath a protective layer of dust, or be at cryogenic temperatures. This will place the astronauts working in an environment of cryogenic touch temperatures and, in turn, will drive the need for development of advanced materials that are highly flexible at these temperatures or of advanced glove or manipulator technology to increase crew productivity. Advancements will also have to be made in order to provide the thermal management of the crew for long durations at these temperatures.

Lunar Equator, Center of Crater at Noon – Hot Extreme— Earth's moon also offers the other end of the thermal management extreme for possible human exploration in the center of a crater, at the equator at lunar noon. The Apollo Program mitigated the impacts of both the cold polar and the hot equatorial thermal extremes by visiting the mid-latitude areas at lunar twilight[12]. While this approach was perfectly acceptable for humankind's first venture from home, the approach will significantly handicap future extensive exploration and permanent habitation away from Earth.

While it is possible that L1 of the sun-Earth Lagrangian/ libration points has higher solar flux from the sun, the solar albedo[13] resulting from a combination of normal reflection from the lunar surface (the angle of reflection and re-

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[12] This is not part of the discussion of this study, but it should be noted that the twilight conditions of the Apollo mission EVAs, in addition to providing thermal mitigation, also provided an optimum balance of lighting conditions. In the absence of an atmosphere to diffract light, the contrast between the directly illuminated surface and that of the shadows is difficult for the human eye to readily adapt. The result is a lack of depth perception and an inability to see into shadows until within the shadow. This would remain an issue for design and operations of future missions.

[13] The albedo of an object is a measure of how strongly it reflects light from light sources such as the sun. It is therefore a more specific form of the term reflectivity. Albedo is defined as the ratio of total-reflected to incident electromagnetic radiation.

Table 2. Space Suit System Mass Values for NASA Historical and Currently Operational EVA-capable EMUs.

Parameter/Weight on Earth: kg (lbs)	Apollo EMU [23]	Space Shuttle EMU [23] [24]	ISS EMU [25]	CxP Suit Element (goal requirements) [26]
Space Suit/Pressure Garment	35.4 (78)	43 (94)	65.2 (143.7)	ISS: 42 (92) Lunar: 42 (92)
Portable Life Support backpack	60.8 (134)	65.8 (145)	89.2 (196.7)	Lunar: 48.9 (108)
Total	96.2 (212)	108 (239)	154.4 (340.4)	90.7 (200)
Operational Pressure kN/m^2 (psia)	25.9 (3.75)	Nominal: 29.7 (4.3)	Nominal: 29.7 (4.3) DCS Treatment: 55.2 (8 above ambient)	29.7 (4.3) DCS Treatment: 55.2 (8 above ambient)

absorption by astronauts is higher) coupled with the solar flux[14] normal to the surface (case for maximum surface coverage) and the "solar cooker" effect of the walls of the crater creates an environment that will be the most radiative thermally challenging of any destination humans may attempt to visit in the foreseeable future.

Moderate Thermal Extremes—The two environments that fall into this category are LEO (near a structure with significant thermal mass) and the martian surface. This is an interesting grouping as these two environments represent the milder thermal management design challenges for space suits. They are both unique in that they are less extreme as far as how the design must be changed to address the environment.

The radiative thermal environment in LEO takes advantage of local albedo from the structure the astronaut is working around and that is being reflected from the Earth. Given the approximate 90-minute orbit duration[15] (45 minutes in the sun and 45 in the Earth's shadow), the conductive temperatures are moderated and can be further smoothed depending on the thermal inertia of the structure.

The martian thermal environment can range from the moderately cold LEO temperatures to, at the hottest depending upon the latitude, what would be a typical winter day in Scandinavia (-112 to -8ºC [-170 to 17.6°F]). The presence of an atmosphere, albeit one that is 1/168th that of Earth, does provide some convective and conductive heat transference that renders the current thermal insulation approach in vacuum inviable.

Phase II: First-order Environmental Impacts to Design

The two most common groupings of destination environments were *microgravity* (LEO, GEO, sun-Earth-moon Lagrangian points, in-transit mission contingency EVAs, low-mass NEO/NEA, moons of Mars, moons of Jupiter and Saturn) and *reduced-gravity environments* (local gravi-

tational fields of one-third Earth or less: Mars and Earth's moon). The decision to group the environments in terms of the gravity field hinged on the mobility of the human performing the mission tasks and the technology required per the experience of NASA that the technology, tools and mobility methods are dramatically different for a microgravity environment, a reduced gravity environment and that of Earth's surface gravity. Experiences from Apollo EVAs and the suit mobility designs of the day resulted in the astronauts loping across the lunar surface for long traverse as they found this to be an easier and more expedient means of traversing than fighting the internal pressurized forces of the suit via a more earth-like ambulation. Likewise the current knowledge of the near earth asteroids suggests – and quite frankly our hope – that there are none that approach the size of the moon or larger necessitating earth-like ambulation; despite what Hollywood would have you believe.

The need for human life support (which in this case will be defined as requiring, pressure management, thermal control, inspired oxygen and hydration) within the biological requirements for normal bodily function is necessary for all human excursions outside the bounds of the Earth's surface. Therefore this is common to all destination environments and not called out specifically as a design driver – with the exception of when there is an atmosphere or not, as this will influence the technologies and strategies for providing these life support functions. It should be noted that life support systems are one of the more complicated and expensive systems required in space flight and should therefore not be trivialized or forgotten when prioritizing development.

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[14] Solar flux, or radiative flux, is the amount of energy moving in the form of photons at a certain distance from the source per angle of incidence per second.

[15] This orbital period is representative of the typical operational orbit for the space shuttle.

It should also be noted that the impacts due to the internal operational pressure of the suit can significantly affect suit design and system mass. In Table 2, the impact to system mass of the ISS EMU due to an operational pressure of 8-psi, as opposed to the typical 4.3-psi, is significant. While a designed operational pressure of 8-psi is not required for EVAs, it does profoundly decrease the amount of pre-breathe time on pure oxygen to denitrogenate the blood to prevent decompression sickness. [27] As a 4.3-psi suit impacts the timeline of a mission due to required pre-breathe and uses known technology for design, the 4.3-psi suit is considered operationally desirable for this study; it is not singled out as an environmental design driver.

And lastly the suit operating pressure inside the vehicle has to be coordinated with the cabin atmosphere and pressure, oxygen concentrations, which affect flammability consider-ations, EVA pre-breathe protocols, and vehicle operational constraints.

Phase III: Second-order Environmental Impacts to Design

Once the destination environments were grouped, a map-ping to the environmental suit design drivers was performed as can be seen in Figure 1. In environment groups in which all of the included environments contribute to a suit design driver, the line for the group begins at the group boundary and proceeds to the design driver. For design drivers in which all of the environments within a group do not map to the design driver, lines specific to that environment map to the driver. For example, all of the microgravity environ-ments map to the microgravity and to the extreme-thermal-at-vacuum drivers and, thus, the black dotted line maps from the microgravity destinations group border. However, all of the microgravity destinations map to the radiation design driver except for the LEO environment; therefore, all of the microgravity environments – except for LEO – map via lines to the radiation design driver.

As seen in Figure 1, and perhaps more clearly in Figure 2, extreme thermal management in vacuum and radiation protection from a high-level assessment are design drivers for 89% of all possible destinations on which humans are likely to perform EVAs. Coming in a close second at 78% of all destination environments are the design drivers due to mission duration (time) and microgravity. Following these we see at surprisingly low percentages: high-abrasion dust at 44%, reduced gravity at 22%, and moderate thermal and low-abrasion dust tied last at 11%.

Extreme Thermal at Vacuum—Not surprisingly, all destination environments listed, with the exception of Mars, have to contend with thermal management in the vacuum of space. And, in reviewing the data, it is seen that of the destinations available for human EVA, the thermal extremes seen on Earth's moon encompass all other environments.

Radiation—Historically, due to mass constraints for launch capability and cost, protection against solar and cosmic
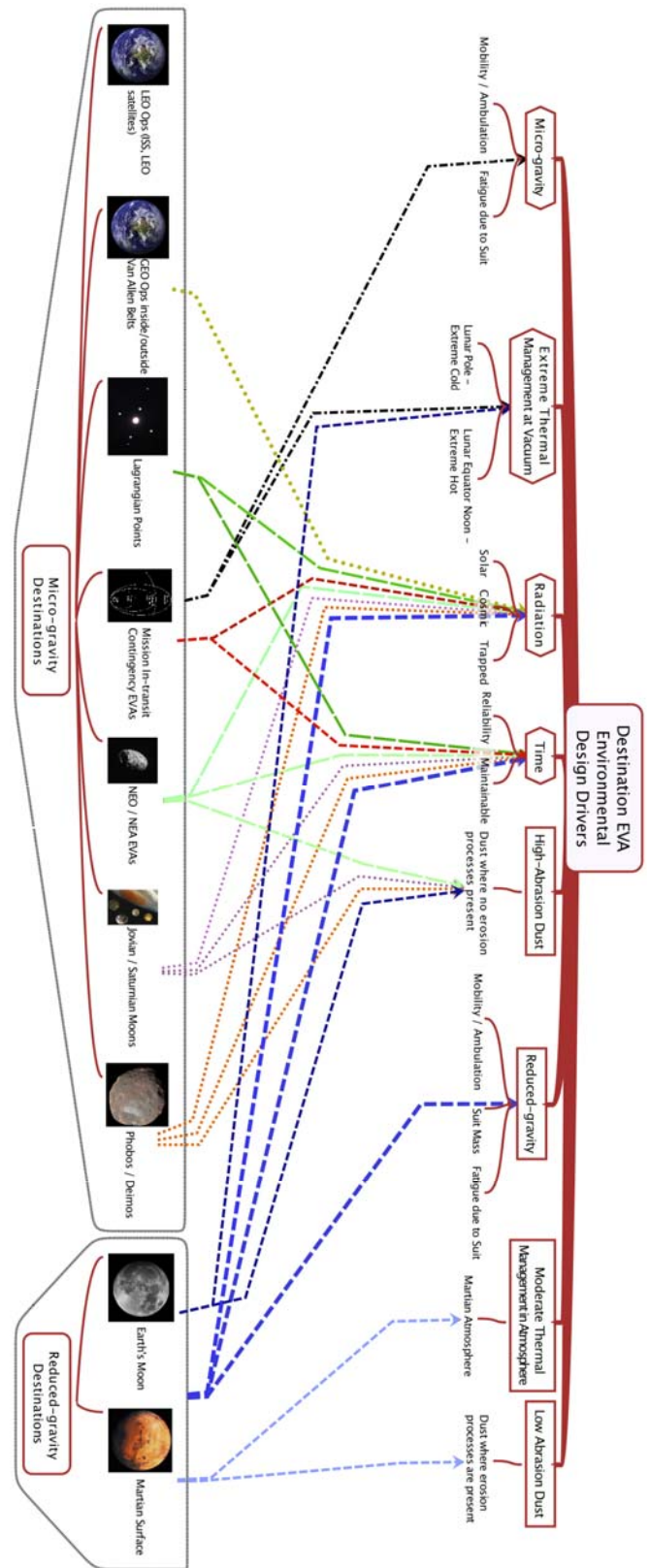

Figure 1 – Mapping of the probable human EVA destination environments to the primary space suit design drivers.
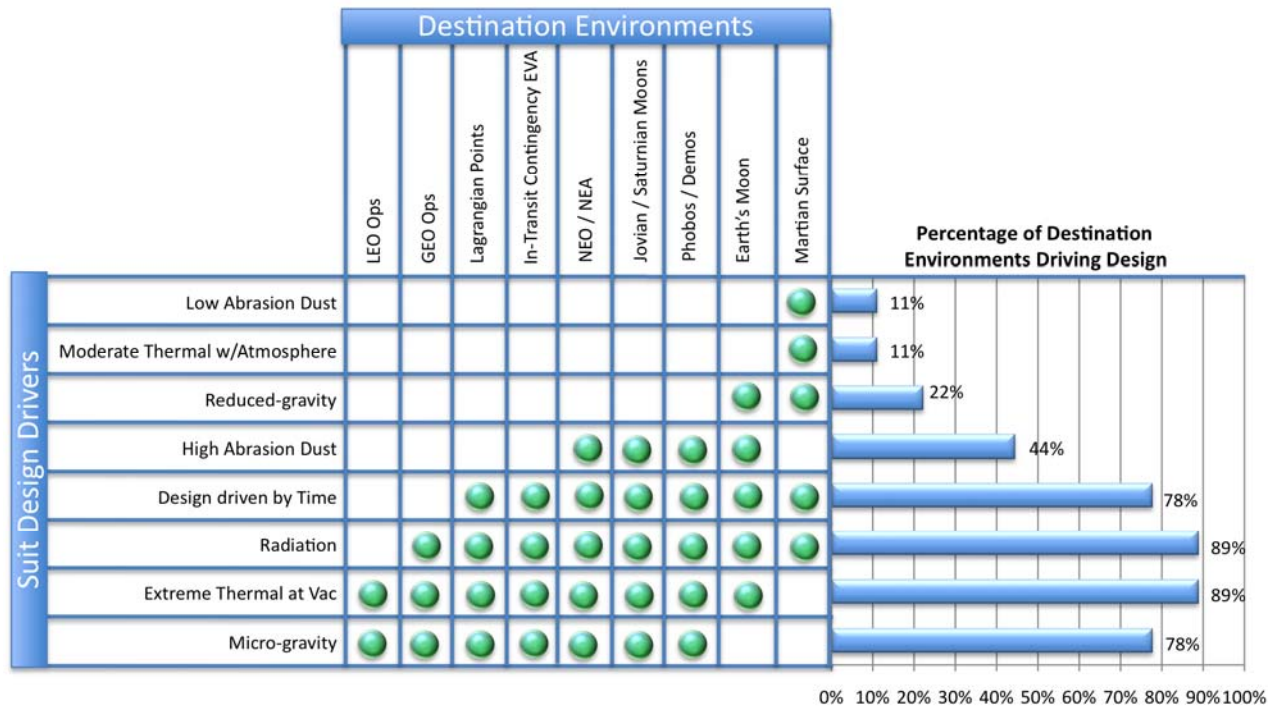
Figure 2 – Mapping of the EVA destination environments to the design drivers so as to identify commonality percentages; this will aid in identifying the most common design drivers for all the possible human EVA destinations.

radiation has been "best-effort" strategy in which outer garments provide protection against alpha particle radiation but limited effectiveness against anything else. To date, NASA has mitigated exposure for LEO operations by monitoring solar activity and limiting EVA time and providing vehicle shielding during high-activity or solar events to limit exposure to the crew. A similar approach was used for the Apollo missions, but the information regarding solar activity was limited due to ground-based telescopes and radiation monitors on the lunar lander.

It should be noted that there is no delineation in Figure 2 in the percentages as to what form of radiation each of the environments includes; instead the percentages are rolled up. Environmental groupings in Figure 1 show that radiation protection is a significant environmental design driver that is common to all destinations outside of LEO and can have a profound impact on human life due to the long mission durations and for long-term exposure. Given the leaps of understanding on the mechanics of radiation and decay, and their effects on humans, it is critical that a concerted effort be applied to suit development for human exploration in this area.

Design Impacts due to Time—With the exception of LEO and GEO, using the assumption that manned vehicles will be limited to current chemical combustion technology, all potential destinations for human EVA will require long mission durations at quite a distance from the resources and supplies of Earth. Therefore, it should be recognized that a methodical approach must be taken for developing a highly

reliable space suit system. By focusing on the individual design element with regard to the most extreme operational environment and the maximum mission duration, the goal would be to drive the mean time to failure well beyond any mission hardware needs. Such a systematic approach will over time drive out the failure modes, increase the design reliability and build a statistical operational experience base such that failures are well understood and at times predictable.

Microgravity Design Drivers—Similar to the discussion of thermal management at extreme temperatures in a vacuum, the number of destinations with very low to negligible gravitational acceleration by far outweigh the destinations in which a reduced, yet significant, gravity field is present that is relatively hospitable to humans.

High-abrasion Dust—High-abrasion dust, as a design driver, comes into play in less than half of the environments discussed in this paper given the number of destinations that pertain to deep-space EVAs or Mars, where the dust has been eroded over time. It should also be noted that our experience with the dust on Earth's moon is indicative of what is expected for destinations with high-abrasion dust.

Reduced Gravity, Thermal Management in an Atmosphere, and Low-abrasion Dust—The last three are grouped because the percentages, while not initially expected, make sense when considering all other destinations. All three have to do with Mars and Earth's moon, which are the only significant bodies within current human exploration.

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Moreover, Mars is the only other body with an atmosphere that facilitates two of these three design drivers. Further implications of these findings will be discussed later.

5. IMPLICATIONS TO TECHNOLOGY DEVELOPMENT STRATEGIES

Given the past success rate of projects to be funded through completion within NASA, it is advised to obtain funding via non-flight program monies, develop the technologies that will give the highest probable return on investment with the greatest likelihood of being needed, and coordinate the effort at the agency level to reduce the likelihood of redundant effort or miss-vectoring.

This study addresses the likelihood of design drivers as a function of the possible destinations that human EVA will potentially encounter given the likelihood of technological advancements within the next few decades as have been seen in the past 30 years. With this in mind, results could differ from those one would expect given past efforts in suit design and technology developed to any significant level. In the past, these efforts were defined by a particular mission with a particular destination in mind – usually the first time visiting that destination. In that framework, that paradigm of design and technology development prioritization made sense. However, in a future in which resources to be applied to space suit design and technology development will be scarce and prioritization will be expected, the need for exploration as well as the destinations to be explored will vary with policy makers in power; therefore, a prioritization based on the likelihood of occurrence should be seriously considered.

If it is clear that Mars is a high-priority destination due to national security, discovery of unobtainium, or survival of the species, the prioritization presented here will be overcome by events. But, lacking such direction, we see here that half of the significant design drivers for space suits encompass 78% to 89% of all destinations for human EVA. What we do see is that only one-quarter of the suit design drivers are specific to Mars.

So, from a perspective of return on investment to reach the maximum yield of dollars invested in space suit design and technology development, a new focus should be brought into the forefront for discussion. A modular suit architecture as discussed in [1] and [2], has the potential for a generic set of suit hardware components or elements that would address the majority of destination environments while minimizing the impact to performance. It would provide hardware and design interfaces such that suit components that needed to be changed due to specific and/or unique environmental constraints would be changed. Additionally, the modular nature of the architecture would allow integration of new technologies as needed without a massive redesign effort. Furthermore, by minimizing the costs due to suit redesign, cost savings in terms of launch mass, and only launching the suit components necessary for destinations of that mission,

savings in terms of schedule can be realized since the technology can be developed prior to the mission that is being defined; i.e., the sooner you launch, the cheaper it is given you have saved the money in the out-years due to inflated dollars.

It is not the intent of this paper to assess the current state-of-the-art of space suit design with respect to any of the design drivers discussed here. It is the intent to bring to the stage the notion that by addressing the design drivers, in a systematic and well-managed effort, that will be most frequently encountered in human EVAs in the foreseeable future will yield the largest return on investment outside of a specific mission and destination.

6. CONCLUSION

This study addresses how a generic, modular space suit architecture would be beneficial when combined with the study of all potential destinations in the solar system for human EVAs within the next 30 years (based on current technological capability and, using linear extrapolation, that which can be achieved based on experiences during the last 50 years of human space flight – no warp drives and force fields available) combined with a systematic prioritization of technology development as defined by likelihood of need for human EVAs. These two when combined provide a space suit architecture that is easily modified depending on the mission destination and can be upgraded when new technology is available with minimal cost and redesign. One example to illustrate the modular architecture and ablity to upgrade as required is the TMG. The TMG can be minimized for use in LEO, and when a mission is required to go to the moon, it can be replaced with a version that is specialized for the lunar environment. The TMG can later be replaced with versions that are optimized for the other thermal and micrometeoroid environments defined in this paper. As long as the suit and TMG interfaces are well defined, it will minimize the cost of upgrading the suit capability by not requiring a major redesign effort.

The destination list, which is based on these selection criteria, is greatly narrowed and the possible destinations for our human (in-person) exploration reduces into a well-defined subset of space suit design drivers that are not likely to change significantly in the near future and can be used now to solve most – if not all – of the major design challenges facing space suit engineers and exploration programs today.

The findings and rankings presented in this paper provide a mission-independent, EVA system development approach based on destination environmental space suit design driver likelihood. This approach will help ensure the highest likelihood, and highest return on investment while there is no programmatic destination of record and will also ensure the opportunity to provide the largest return on taxpayer dollars that will meet multiple future mission destinations. This allows a greater chance of providing better technical

solutions to future missions when they are needed, as opposed to waiting for a mission to be identified and then starting to solve the technical suit design problems once the programmatic and budgetary clocks have begun to tick.

It is highly recommended that this development approach be considered and managed as a "Flight Program," meaning that development technical requirements, budgets, and developmental milestones are well defined and managed to agreed-upon completion dates. This will help ensure that these efforts will reach the desired engineering solution in a reasonable amount of time and aid in maturing the technology incrementally as the funding is available. And lastly, it should be noted that while the environment is the primary design driver in space suit design, the largest secondary driver is the activity of which will be performed in the suit and should not be forgotten when formulating the space suit architecture and considering how to incorporate the needed technologies for the destination environment.

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BIOGRAPHY

Terry R. Hill is a member of the NASA Lyndon B. Johnson Space Center (JSC) International Space Station/Shuttle Extravehicular Mobility Unit (EMU) Team where he is responsible for providing engineering insight into the 2010 life extension hardware modifications, determining what the system hardware impacts are to extending the ISS EMU support out until 2028, and investigating how the EMU can be used as a demonstration platform for technology development.

Terry has a B.S. in Aerospace Engineering and an M.S. in Guidance, Navigation, and Control Theory with a minor in Orbital Mechanics from the University of Texas at Austin. He began his career at NASA while working on his graduate thesis project in developing banks of simplified Kalman filters integrated into an artificial neural network to obtain an optimal state solution for precision landing on Mars.

While at NASA, Terry has worked on projects and programs spanning from ISS navigation software verification to Shuttle navigation design test objectives and back-room mission support, X-38 Crew Return Vehicle navigation algorithm development, Space Launch Initiative technology development, Orbital Space Plane Project office ISS-prime integration, Space Shuttle "Return to Flight" STS-107 tile repair capability development, and to CxP Space Suit Element leadership.

Terry and the Suit Element have been interviewed by the Associated Press and covered by media outlets including CNN.com, Forbes.com, and National Geographic video "Living on the Moon" air date 2009. Terry has also been identified as one of NASA's Constellation Stars, and was identified as NASA Tech Brief's "Who's Who at NASA" for November 2010.

In leading the CxP Suit Element engineering team, Terry had the responsibilities of JSC's Engineering Project Manager, the CxP EVA Systems Suit Element Deputy Lead, and Element Lead during his tenure on the project. He facilitated the development of system functional requirements for space suit development and a "clean-sheet" design approach that has been widely recognized within and outside NASA.