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Space Suit Extravehicular Hazards Protection Development

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CONTENTS

TABLES

FIGURES

ABSTRACT

This paper presents an overview of the development of the integral thermal/micrometeoroid garment (ITMG) used for protection of a space-suited crewmember from hazards of various extravehicular (EV) environments. These hazard conditions can range from thermal extremes, meteoroid and debris particles, and radiation conditions in near-earth orbits and free space to sand and dust environments encountered on lunar or planetary surfaces. Representative ITMG materials cross-section layups are identified and described for various space suit configurations ranging from the Gemini program to planned protective requirements and considerations for anticipated Space Station EV operations.

INTRODUCTION

Space suits provide three basic functions for extravehicular (EV) astronauts. First, in combination with a portable life support system, the space suit maintains the physiological well-being of the astronaut. This includes supplying O_2 for breathing and ventilation, CO_2 removal, and metabolic heat removal. Secondly, the suit incorporates various mobility joint system features to enable the crewmember to perform useful tasks in the EV environment. Finally, the suit provides protection against the hazards of the particular EV environment. These hazards range from thermal extremes, meteoroid and debris particles, and radiation conditions in near-earth orbit and free space to sand and dust environments encountered on lunar or planetary surfaces. Additional hazards are encountered from sharp corners and edges of various structural elements of satellite or space vehicles as well as glove abrasion when performing physical EV tasks.

As the pressure retention layer of a space suit provides both the physiological protective barrier and structural foundation for the incorporation of various mobility systems, a separate outer coverlayer garment comprising various combinations of material layups constitutes the environmental protective barrier for the EV worker.

BACKGROUND

Throughout the Mercury program and until the initial feasibility of extravehicular activity (EVA) was established on the Gemini IV mission, space suits were essentially utilized as intravehicular backup emergency systems in case of loss of cabin pressure. The Gemini program provided the first experience for EVA in the United States manned space effort (fig. 1). The original program objectives included the following:

- Develop the capability for EVA in free space.
- Use EVA to increase the basic capability of the Gemini spacecraft.
- Develop operational techniques and evaluate advanced equipment in support of EVA for future programs.

In order to provide adequate thermal and micrometeoroid protection for the EV environment, the initial EVA protective coverlayer for the Gemini IV mission consisted of an outer protective layer of high temperature resistant (HT-1) nylon, a layer of ballistic felt for micrometeoroid protection, seven alternating layers of aluminized mylar and unwoven dacron spacer material as superinsulation, and two innermost layers of 6-ounce uncoated HT-1 for micrometeoroid shock and particle absorption (fig. 2). This coverlayer was integrated to and worn over the basic intravehicular Gemini G3C suit. Table 1 lists the general requirements for the G4C suit configuration (EV version of the basic G3C suit). The bulk of this coverlayer (later called the integrated thermal/micrometeoroid garment or ITMG) restricted astronaut mobility even with the suit in the unpressurized mode inside the vehicle cabin.

For the next EV mission (Gemini VIII), the coverlayer ITMG was redesigned to reduce bulk, increase mobility, and maintain or improve thermal and micrometeoroid protection. The micrometeoroid protective layers of the ITMG were modified to utilize two layers of neoprene-coated nylon in lieu of the ballistic felt and the two layers of uncoated HT-1 fabric. Overall suit mobility was noticeably improved without any loss of environmental protective capabilities by the introduction of the new ITMG layup. Figure 3 shows the relative comparison of the Gemini IV and Gemini VIII ITMG coverlayers. Subsequent Gemini EVA missions incorporated additional changes to the ITMG layup primarily in the lower torso area of the suit to provide increased thermal protection against the astronaut maneuvering unit (AMU) thrusters impinging on the suit surface. Temperatures as high as 1300° F were possible at the AMU thruster impingement areas. A stainless steel fabric was used as an outer fabric coverlayer along with eleven layers each of aluminized H-film (Kapton) and fiberglass cloth as thermal insulation for the legs (fig. 4).

To complete the G4C EV configuration, a gold-coated sun visor and special overgloves utilizing a silastic foam material were provided for thermal protection. The total man-hours of EVA experience gained in the Gemini program amounted to 12 hours and 25 minutes accomplished on 5 of the 10 manned Gemini missions.

LUNAR OPERATIONS

EVA technology from the Gemini program was incorporated wherever possible in the design of the Apollo extravehicular mobility unit (EMU). The ITMG for the Apollo EMU, however, required design considerations for the more severe lunar surface environment. EV hazards unique to the lunar surface included potential secondary debris particles ejected by primary meteoroid impacts on the lunar surface, abrasive characteristics due to the surface rocks, sand and dust environment, and worst-case thermal conditions due to the combination of lunar-day high-sun angles and the effect of lunar crater walls. Figure 5 shows a representative materials cross section incorporated in the ITMG for the Apollo EMU assemblies utilized during Apollo lunar surface missions. For protection against abrasion, an additional external layer of teflon fabric was attached to the knee, waist, elbow, and shoulder areas of the ITMG. Special lunar overboots (fig. 6), worn over the basic Apollo space suit pressure garment assembly boots, provided thermal and abrasion protection during lunar surface operations. Except for the silicone rubber sole area of the boot, the outer layer of the lunar boot was fabricated from stainless steel (Chromel-R) woven fabric with the tongue area of the boot made from teflon-coated Beta (fiber glass) cloth. A rib-structure sole configuration was used to increase thermal insulation qualities, to provide lateral rigidity, and to provide traction on the lunar surface. The inner layers of the lunar boots (from the Chromel-R fabric inward) consisted of two layers of aluminized polymid film (Kapton) followed by five layers of aluminized perforated mylar film

TABLE 1.- GENERAL REQUIREMENTS FOR GEMINI G4C EXTRAVEHICULAR SPACE SUIT ASSEMBLY

Weight	• 35 lb (G3C suit wt = 25 lbs)
Bulk	• Small enough to permit unassisted egress and ingress through Gemini hatch at zero-g
Pressure	
Operating	• 3.7 ± 0.2 psia for 5 hrs EVA in hard ambient vacuum
Structural	• 8.0 psig, 15 minutes
Mobility	• Sufficient for unassisted hatch egress and ingress at zero-g
Ventilation (EV)	
Inlet	• 14-18 acfm at 45 ± 3° F
Outlet	• 3.7 psia
Spacecraft external (EV)	
Temperature	• -150° to +250° F
Micrometeoroid environment (EV)	
Initial EV mission exposure	• 10 minutes (worst shower period)
Probability of no penetration (P_0) of suit bladder	• 0.999
Exposed suit surface area	• 25 ft^2

separated by four layers of nonwoven dacron and followed by an inner liner of teflon-coated Beta cloth. Two layers of Nomex felt in the sole area provided additional thermal insulation from the lunar surface.

The EV glove for the Apollo EMU consisted of a modified intravehicular pressure glove covered by an ITMG layup. The EV glove included an integral cuff, or gauntlet, that extended over the wrist disconnect on the space suit arm. The glove ITMG, a multilayer assembly, provided scuff, abrasion, and thermal protection for the pressure glove. The material cross-section layup of the Apollo EV glove is identified in figure 7. A woven stainless steel (Chromel-R) fabric was incorporated over the palm and fingers to provide abrasion protection. The thumb and fingertip shells were made of high strength silicone rubber (RTV 630) coated nylon tricot for improved tactility and strength. A clear silicone dispersion coating was applied to the palm and palm-side area of the fingers and thumb to provide increased gripping characteristics.

The lunar extravehicular visor assembly (LEVA) shown in figure 8 provided visual, thermal, and impact protection to the astronaut's helmet and head. The LEVA was composed of an outer protective shell that housed two visors and three eyeshades. The outer visor, or sun visor, was made of high temperature resistant polysulfone plastic and coated on the inside surface with a thin film layer of vacuum-deposited gold. The sun visor could be manually adjusted in position from "full up" to "full down" during EV operations. The second visor, or protective visor, fixed in the full down position, was made of ultraviolet-stabilized polycarbonate plastic. The outer visor filtered visible light and rejected a significant amount of ultraviolet and infrared rays. The protective visor filtered ultraviolet rays, rejected infrared rays, and in combination with the sun visor and pressure helmet formed an effective thermal barrier. The two visors in combination with the pressure helmet protected the astronaut from micrometeoroid damage and damage that could result from a fall on the lunar surface. The outer shell housing provided protection for the sun visor during periods of nonuse. Separate eyeshades (left, center, and right) could be adjusted individually by the astronaut to prevent surface glare from obscuring vision during EVA. The Apollo 11 mission (fig. 9) was the first mission on which the EMU was exposed to the lunar environment. On July 20, 1969, man first set foot on an extraterrestrial surface and collected scientific data while being sustained and protected from a hostile environment. Throughout the Apollo program, the EMU provided a haitable environment for more than 160 man-hours of manned lunar surface activities.

The Skylab program utilized a modified version of the Apollo EMU ITMG and successfully accomplished 82 man-hours of EVA over three missions (figs. 10 and 11).

SHUTTLE MISSIONS

As in the Apollo program where the foundation of basic EV environment protective knowledge came from the previous Gemini program efforts, the development of the Shuttle space suit ITMG stemmed from experience and knowledge gained during the Apollo and Skylab programs. Additionally, efforts were undertaken through advanced technology development activities for improvements to materials planned for use in the Shuttle ITMG layup. The most significant outgrowth of this activity was the development of a high-wear and abrasion-resistant fabric having high tear strength properties. The fabric, called Orthofabric, is a woven blend of three different materials. The outer surface of the fabric is Gore-Tex (teflon) backed by Nomex and containing a gridded interlay structure of Kevlar fibers. The Orthofabric is currently used as the outer protective layer of the Shuttle ITMG.

Due to the low earth orbit (LEO) operations of the Shuttle missions, which are unlike the harsh lunar surface thermal environment, changes to the numbers of layers of superinsulation were made that reduced overall ITMG bulk. This resulted in the ITMG being less restrictive to the astronaut's mobility while providing adequate thermal and micrometeoroid protection. The Shuttle ITMG incorporates five layers of aluminized mylar with a reinforcing layer of dacron gridded scrim backing each layer as opposed to the fifteen layers of superinsulation and spacer material used in the Apollo ITMG. The Shuttle space suit utilizes an extravehicular visor assembly (EVVA) similar in many regards to earlier Apollo LEVA and Skylab extravehicular visor assembly (SEVA) with the exception that the eyeshades have been deleted. Thermal protection for the Shuttle EV gloves is provided through an integral layup of superinsulation (fig. 12). The Shuttle program as of this date has successfully accomplished 136 man-hours of EVA (fig. 13).

ADVANCED THERMAL/MICROMETEOROID GARMENT (TMG) REQUIREMENTS

With the advent of the Space Station program and the anticipation of routine EVA's being conducted on a weekly basis over long periods of time, design requirements regarding protection against potentially new EVA hazards have become apparent. As shown in figure 14, along with the basic protective aspects of the typical Shuttle-type ITMG (such as thermal/abrasion and micrometeoroid protection), specialized provisions for chemical protection, enhanced radiation shielding, electrostatic charge control, increased impact protection due to orbital debris, possible material considerations for atomic oxygen degradation, and improved long-term wear characteristics are either necessary or desirable for advanced space suit ITMG's.

Proximity to satellite or spacecraft propellants and other chemicals during future EVA refueling operations requires the incorporation of a chemical contaminant control barrier on the exterior of the space suit. The propellant contaminants (if they persist as a liquid in space) would be capable of dissolving the mylar film in the TMG multiple layer superinsulation. Tests of the chemicals of concern, such as monomethylhydrazine ($N_2H_3CH_3$), hydrazine (N_2H_4), nitrogen tetroxide (N_2O_4), and ammonia (NH_3), indicate that a thin film (2 mil) of floral ethylene propylene (FEP) teflon, laminated to the inside surface of the exterior Orthofabric layer of the typical Shuttle ITMG, will provide the necessary barrier function. Similar protective measures can be utilized in the EV glove ITMG layups. Protection for the (Lexan) pressure helmet from chemical degradation can be provided by the addition of a thin polysulfone laminated layer over the polycarbonate surface.

In space, ionizing radiation hazards are produced by solar flare events, deep space galactic cosmic sources, and trapped solar electrons and protons from the Van Allen belts. Radiation in LEO depends upon the orbital altitude and inclination of the space vehicle (fig. 15). Of the three radiation sources mentioned, the trapped particles cause the most concern during planned routine Space Station EVA operations. For 28.5 degree orbits, typical of the Space Station flight path, radiation exposure from trapped protons is confined to the South Atlantic Anomaly (SAA) region of the inner Van Allen belt which is only encountered for approximately 15 minutes of each of five or six consecutive orbits per day. For polar orbit, exposure from trapped protons is confined to the SAA; however, most of the electron exposure comes from the outer belts which are encountered at high latitudes (50 to 80 degrees) on each orbit. At geosynchronous earth orbit (GEO) altitude, the nominal radiation exposure comes from trapped electrons and is continuous. Results of preliminary analysis concerning allowable radiation dose limits based on radiation attenuation characteristics of representative space suit material layups indicate that the nominal EVA environment in LEO, including polar orbit, does not present a significant radiation hazard (table 2).

Since the principal dose of harmful radiation from protons is experienced during transits in LEO through the SAA region, and since the duration of those periods of high proton flux represents a small and readily predictable portion of the Space Station orbit, the best strategy for protection against over-exposure appears to be avoidance of EVA's while the station is passing through this region. It is therefore recommended that EVA mission planners should avoid times that encounter the SAA in order to comply with the "as low as reasonably achievable" (ALARA) guidelines. This would allow approximately 16 consecutive hours out of a 24-hour period free of the SAA during which manned EVA's could be conducted safe from high proton flux.

In response to the philosophy of keeping radiation dosage ALARA, additional attenuation characteristics can be incorporated into the ITMG layup. Nuclear particle transport through any material is primarily governed by the electron density of the material. Energy losses due to ionization during particle transport are greater for low density materials, whereas secondary X-radiation (bremsstrahlung) protection is provided by high density materials; for example, teflon is approximately 35% more effective than aluminum in slowing down or stopping protons, whereas lead or tungsten is more effective in providing protection against X-ray production in electron transport. The material layup, therefore, most effective in terms of efficiently arresting both incident proton/electron flux and secondary X-radiation would be a composite material layup containing low atomic number material in the outer layers which are backed by a layer or layers of high atomic number materials.

The addition of a layer of tungsten-loaded silicone rubber as the innermost layer of the ITMG may provide an effective radiation attenuation media. Efforts are underway to fabricate and evaluate sample layers having thickness of 0.035 inches (0.089 cm) and containing about 75 percent tungsten by weight, as well as a layer 0.082 inches (0.21 cm) thick. The 0.089 cm layer provides an additional mass per unit area of 0.36 gm/cm^2; the 0.21 cm layer provides 0.86 gm/cm^2. It is planned that the thinner layer would be used in the ITMG layup covering the mobility joint elements of the Space Station space suit and the thicker layer material would be used in the nonflexing portions of the suit ITMG, covering such areas as the upper torso and brief elements. This approach would add approximately 28 pounds (13 kg) to the overall weight of the space suit.

A double benefit can be realized from this addition to the ITMG. Coupled with the potential for enhancing radiation shielding, the heavier layers incorporated into the multilayer composition of the ITMG will provide increased penetration resistance to micrometeoroid and debris particles. Several tests of these layups have been conducted with a hypervelocity gun facility at NASA-JSC. Based on these tests and preliminary analysis of the projected exposed EMU area, the proposed enhanced ITMG cross section should provide a probability of no lethal penetration from micrometeoroids or debris that meets the NASA Space Station goal of 0.9995. This is for one EMU having an EVA exposure time of 936 hours over a 1-year period (table 3).

In some orbits primarily associated with high inclination or polar orbit operations, static electrical charges from the auroras can build up on the surface of an EVA object such as the EMU. The concern

TABLE 2.- PRELIMINARY EVA SPACE SUIT RADIATION ANALYSIS

[Analysis - Equivalent AL Thicknesses, AP8 and AE8 Solar Minimum (1GRF 65/640), NRL GCR Model, Modes Man]

Total Trapped and GCR Dose (Millirem/Day) and Percent of Limits*

Shuttle space suit (SSA)	400 km x 28.5°	% limit	500 km x 28.5°	% limit	250 km x 90°	% limit
Eye (sun visor up)	92.1	0.05	353.8	0.18	24.4	0.01
Eye (sun visor down)	88.1	0.04	334.4	0.17	17.9	0.01
Skin (torso)	101.8	0.03	403.6	0.13	75.7	0.03
Skin (arms & legs)	141.5	0.05	579.0	0.19	362.0	0.12
Depth	48.1		165.1	0.33	11.4	0.02
NASA-JSC 8.0 psi Zero-prebreathe suit	Total 400 km x 28.5°	% limit	Total 500 km x 28.5°	% limit	Total 500 km x 28.5°	% limit
Eye (sun visor up)	84.1	0.04	317.1	0.16	15.2	0.01
Eye (sun visor down)	82.1	0.04	305.1	0.15	14.1	0.01
Skin (torso)	98.7	0.03	387.5	0.13	58.2	0.02
Skin (arms & legs)	88.2	0.03	339.2	0.11	24.0	0.01
Depth	48.1	0.10	164.1	0.33	11.4	0.02
NASA-ARC AX-5 hard suit	Total 400 km x 28.5°	% limit	Total 500 km x 28.5°	% limit	Total 250 km x 90°	% limit
(Without rad. prot.)						
Eye (sun visor up)	84.1	0.04	317.1	0.16	15.2	0.01
Eye (sun visor down)	82.1	0.04	305.1	0.15	14.1	0.01
Skin (torso)	94.4	0.03	371.0	0.12	49.1	0.02
Skin (arms & legs)	102.1	0.03	405.1	0.14	80.2	0.03
Depth	47.4	0.09	163.1	0.33	11.4	0.02
(With rad. prot.)						
Eye (sun visor up)	84.1	0.04	317.1	0.16	15.2	0.01
Eye (sun visor down)	82.1	0.04	305.1	0.15	14.1	0.01
Skin (torso)	76.1	0.03	282.1	0.09	13.5	0.005
Skin (arms & legs)	77.1	0.03	284.1	0.09	13.6	0.005
Depth	43.1	0.09	149.1	0.30	11.2	0.02

GCR (galactic cosmic ray) doses included are 4 millirem/day at 400 km x 28.5°
4 millirem/day at 500 km x 28.5°
10 millirem/day at 250 km x 90°
20 millirem/day at GEO

*Annual dose limits (86 NCRP tentative):

Depth	50 rem
Eye	200 rem
Skin	300 rem

TABLE 3.- PRELIMINARY MICROMETEOROID TEST RESULTS

Suit element	Effective[a] area (m^2)	Particle[b] energy (x 10^7 ergs)	Individual P_0[c]
Arms/legs (flex)	1.09	94.2 (test)	0.9997788
Torso, briefs EVVA shell (nonflex)	0.72	98 (calc.)	0.9998597
Helmet/visors[d]	0.084	31 (test & calc.)	0.9999452
		Combined P_0 =	0.9995838

Conditions:

- 500 km altitude; 28.5 degree inclination orbit
- 936 hours EVA per year (18 hours EVA per week per crewmember)
- One EMU

Notes:

(a) Assumes 60 percent of exposed EMU area, due to shielding effect of Space Station structural elements, workstation, satellites, etc.

(b) Energy of particle required for penetration (94.2 x 10^7 ergs energy is near upper capability of NASA-JSC gun)

(c) Probability (P_0) of no lethal hit, i.e., no leak exceeding O_2 makeup parameters (assumes nonlethal hole size of 0.25 cm; purge flow can maintain suit pressure approximately 30 minutes with hole size of 0.39 cm)

(d) Visor and helmet thicknesses three times Shuttle helmet thickness (Shuttle helmet plus protective visor and solar visor combined thickness = 0.5 cm) is that these charges might find their way into electronic circuits of the EMU causing subsequent arc discharges and disrupting normal operation or possibly disabling them. To provide a conductive surface and path for static charges to "bleed off" the EMU, conductive fibers can be woven into the outermost layer of the ITMG. This should result in a more uniform charge over the ITMG exterior and also provide a safe path for charged particles if the EMU contacts a body of unlike charges (e.g., vehicle or satellite).

CONCLUDING REMARKS

Approximately 400 man-hours of EVA experience have been accumulated over the past 20 years in space environments ranging fron near-earth orbit to lunar surface excursions. In all cases, the primary space suit environmental protective barrier, the ITMG, has been specifically designed for the unique environmental conditions encountered. Further material and design changes to the ITMG layup will be required for the various environmental conditions anticipated during forthcoming Space Station EVA operations.

As future space mission plans are developed that encompass longer stay times and diversified types of EVA operations, including lunar base activities and Mars surface exploration, new environmental hazards and material requirements will be established for the subsequent development of the next generation of ITMG assemblies.

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Figure 1.- Astronaut Ed White (Gemini IV).

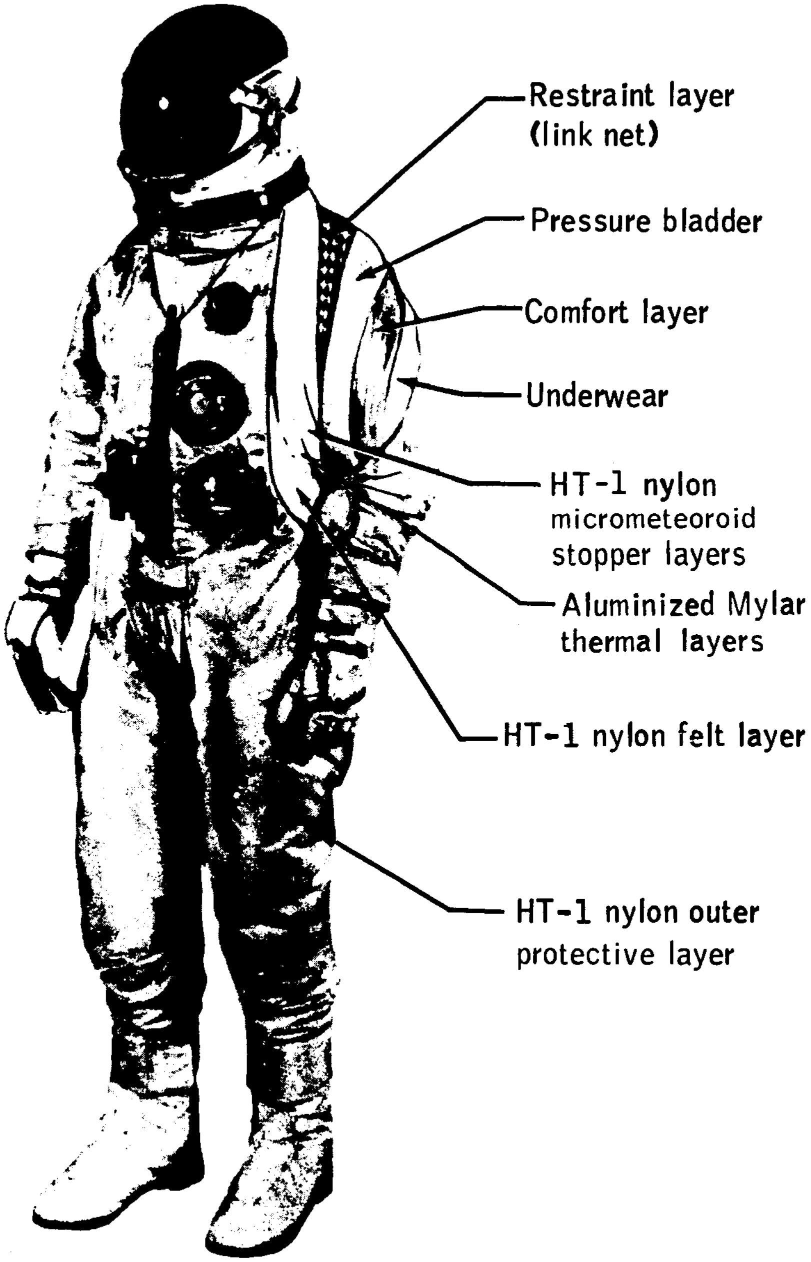

Figure 2.- Gemini G4C extravehicular space suit.

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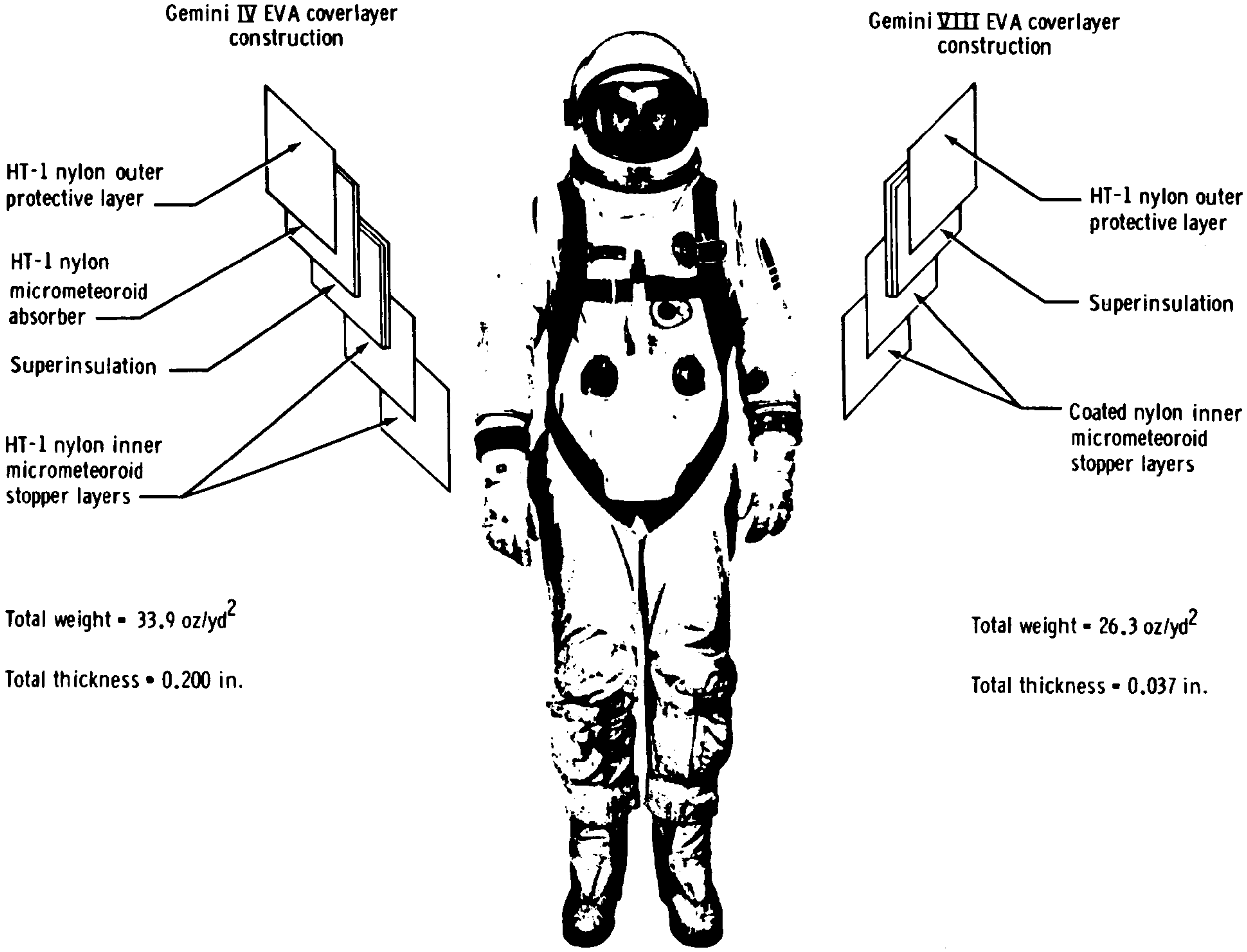

Figure 3.- Comparison of Gemini IV and Gemini VIII extravehicular coverlayers.

Figure 4.- Gemini "iron pants" ITMG.

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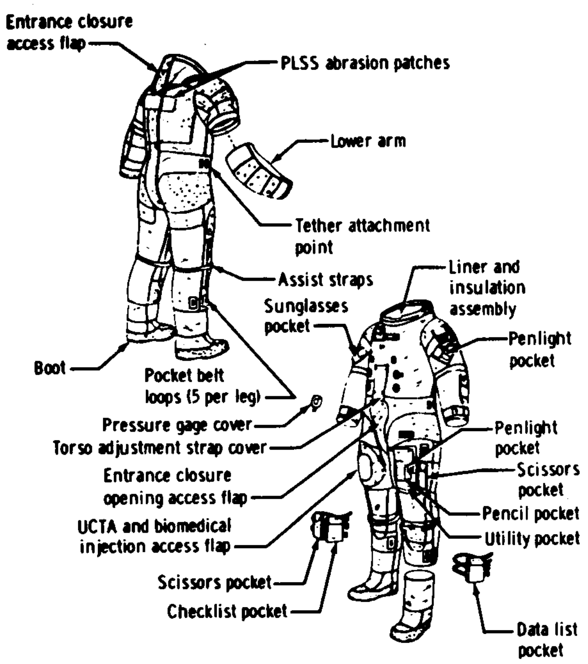

Material	Function 1	Function 2	Function 3
Rubber-coated nylon (ripstop)	Inner liner		Thermal, micrometeoroid protection cross section
Aluminized Mylar* (5 layers)	Thermal radiation protection	Thermal cross section	
Nonwoven Dacron* (4 layers)	Thermal spacer layer		
Aluminized Kapton film/Beta marquisette laminate (2 layers)	Thermal radiation protection		
Teflon-coated filament Beta cloth	Nonflammable and abrasion protection layer		
Teflon cloth	Nonflammable abrasion patches		

*Alternating layers of insulation and spacer.

(a) Lunar integrated thermal/ micrometeoroid garment.

(b) Material cross section for ITMG (Apollo 11 to 14 missions).

Figure 5.- Apollo ITMG cross section.

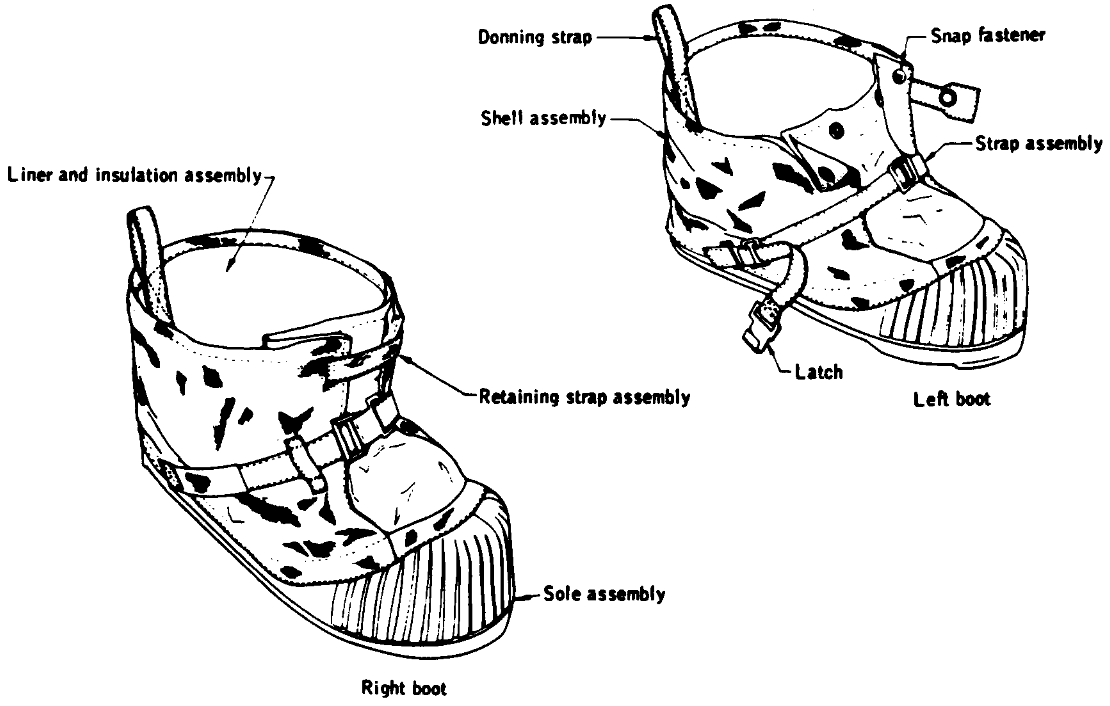

Figure 6.- Lunar overboots.

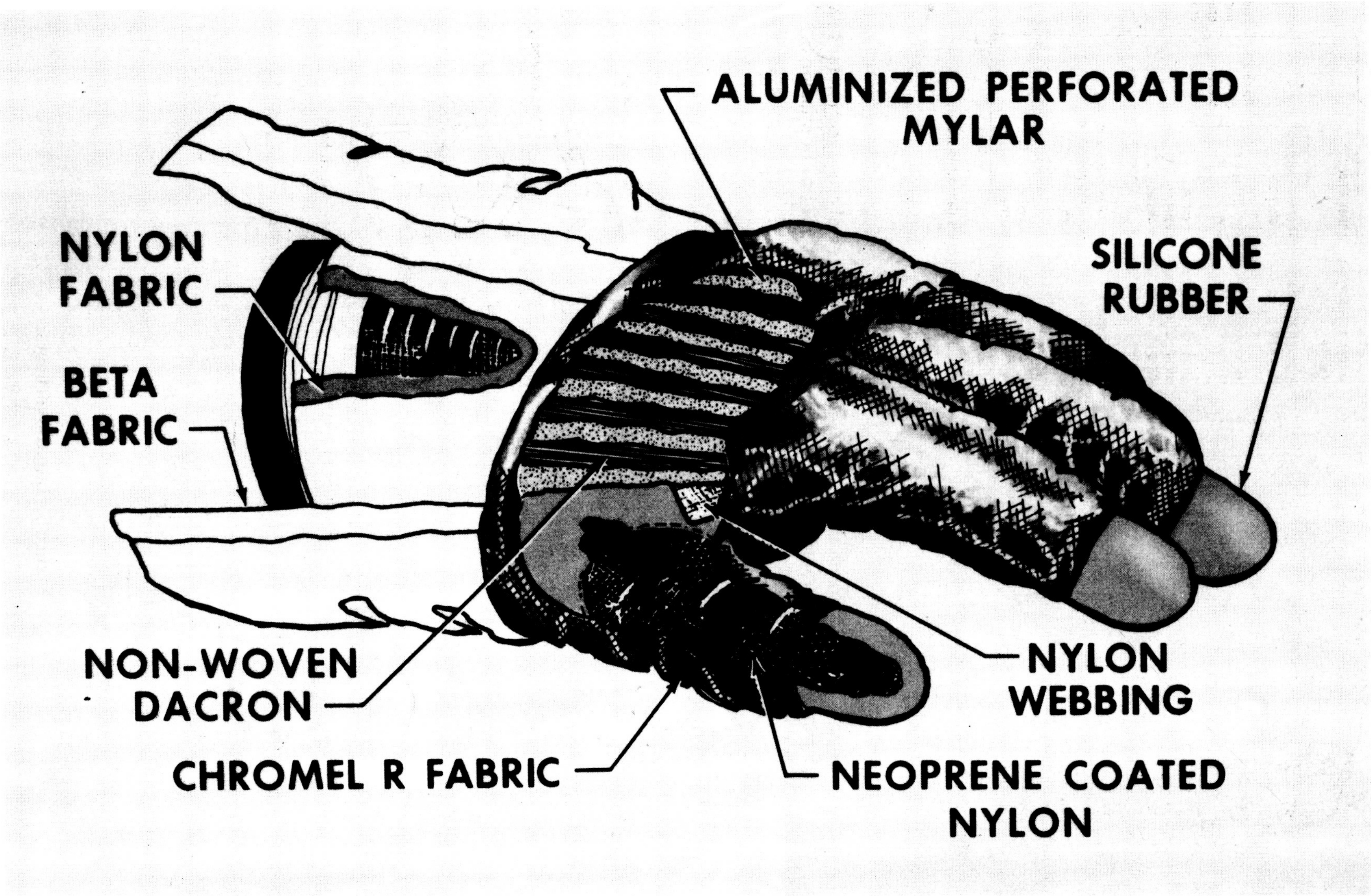

Figure 7.- Apollo extravehicular glove.

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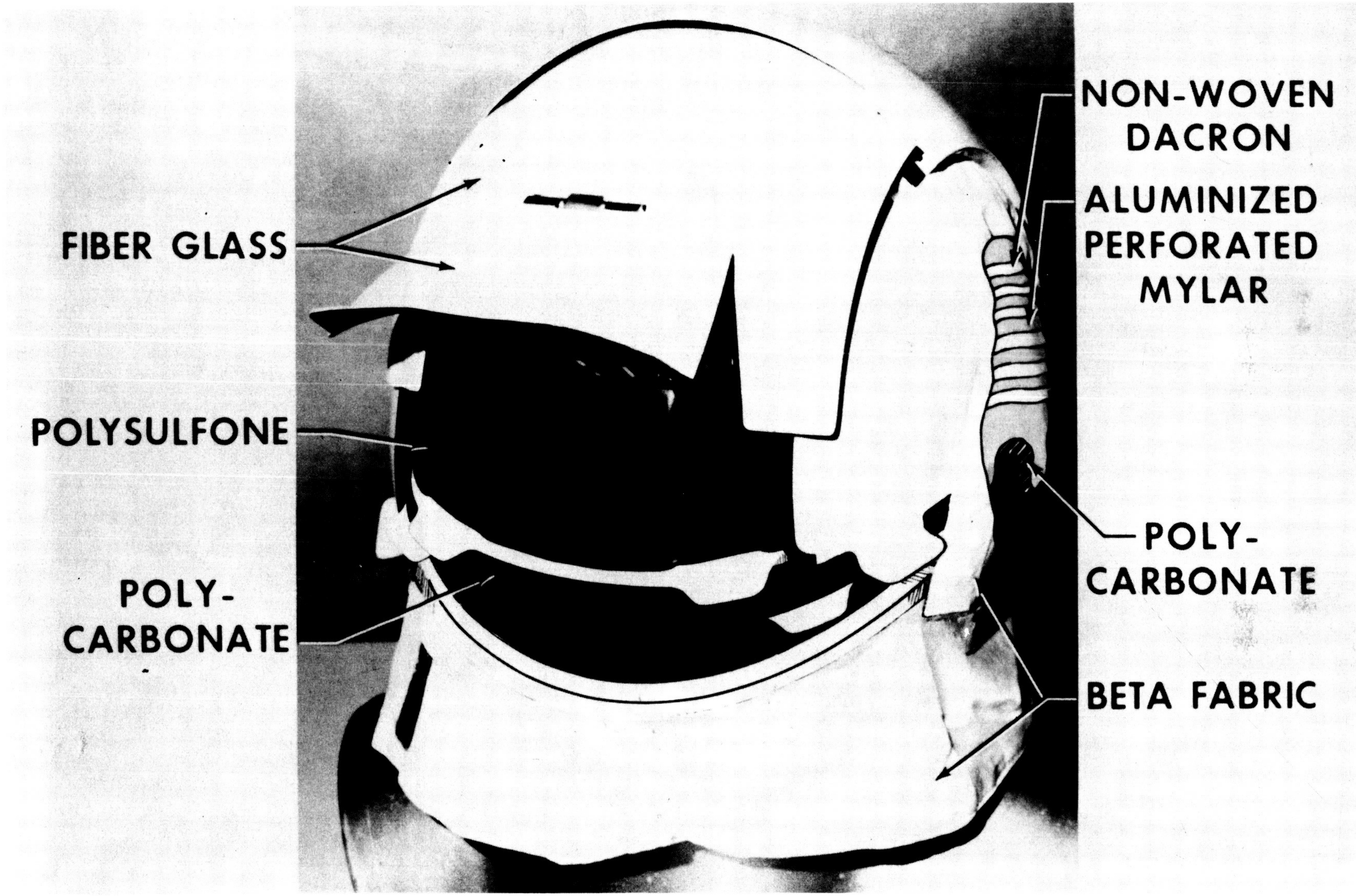

Figure 8.- Lunar extravehicular visor assembly.

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Figure 9.- Astronaut Aldrin (Apollo 11).

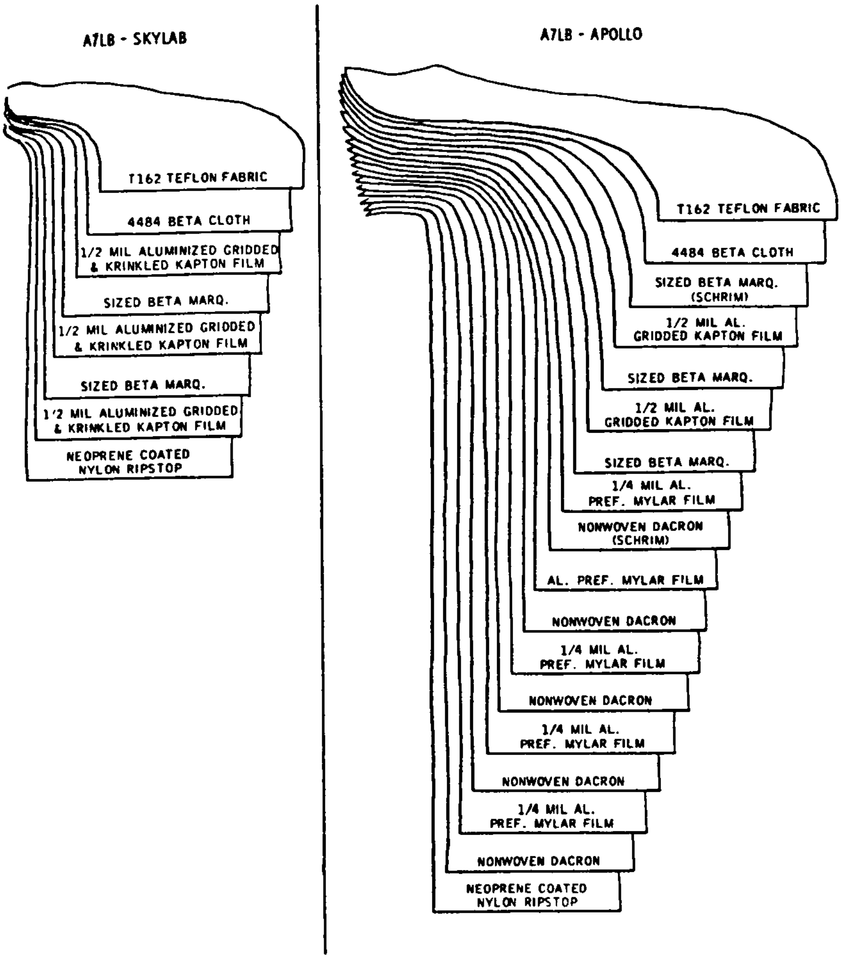

Figure 10.- Skylab vs. Apollo ITMG cross sections.

Figure 11.- Skylab EVA.

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Figure 12.- Shuttle EV glove.

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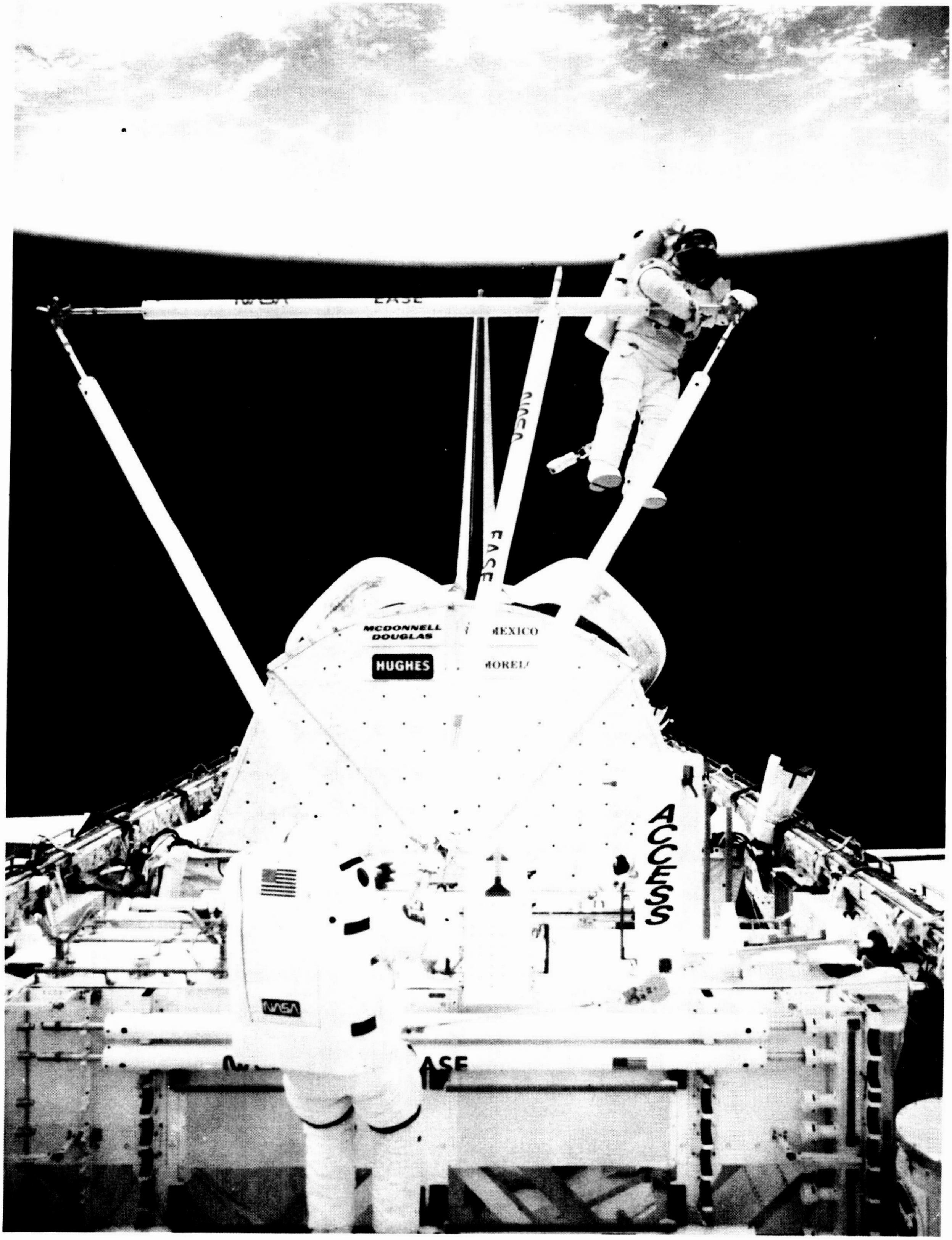


Figure 13.- Shuttle EVA (ease/access).

THERMAL/ABRASION
- THERMAL RADIATION
- THERMAL CONDUCTIVITY
- SHARP CORNERS

MICRO-METEOROID

(a) Basic protective features.

CHEMICAL PROTECTION
- PROPELLANT HANDLING

RADIATION PROTECTION
- PROTONS & ELECTRONS

ELECTRO-STATIC CHARGE PROTECTION

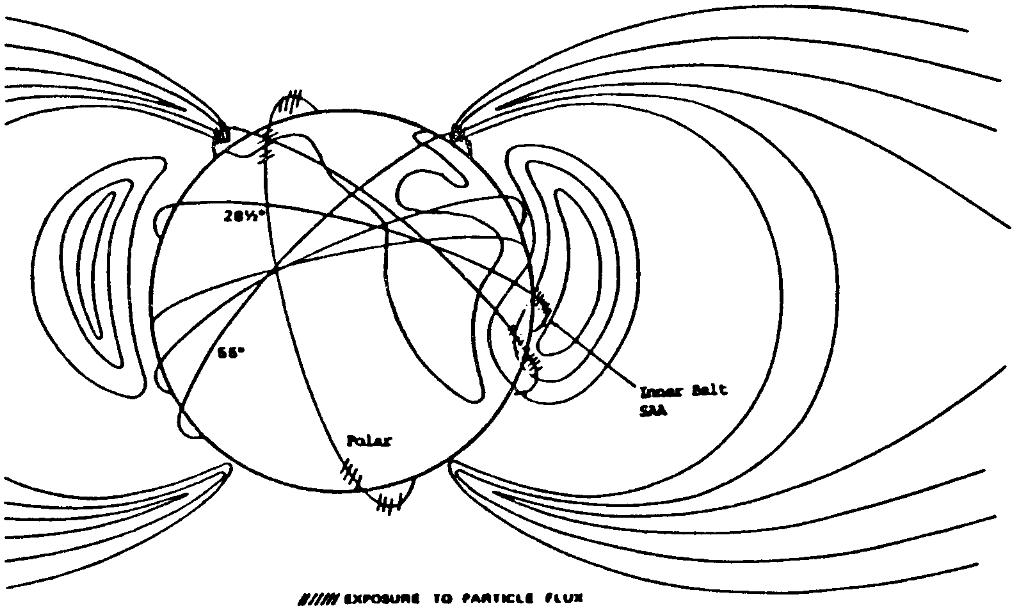
EXTENDED SERVICE LIFE

DEBRIS IMPACT PROTECTION

ATOMIC OXYGEN (?)

(b) Specialized protective/ construction features.

Figure 14.- Advanced ITMG specialized requirements (Space Station).



RADIATION IN LEO DEPENDS ON ORBIT TRACK

Figure 15.- Orbital paths (radiation).

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16. Abstract

This paper presents an overview of the development of the integral thermal/micrometeoroid garment (ITMG) used for protection of a space-suited crewmember from hazards of various extravehicular (EV) environments. These hazard conditons can range from thermal extremes, meteoroid and debris particles, and radiation conditions in near-earth orbits and free space to sand and dust environments encountered on lunar or planetary surfaces. Representative ITMG materials cross-section layups are identified and described for various space suit configurations ranging from the Gemini program to planned protective requirements and considerations for anticipated Space Station EV operations.

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