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ANALYZING THE LONGEVITY AND EFFECTS OF SPACE EXPOSURE ON SATELLITE COMPONENTS

What are the effects on propulsion systems

ABSTRACT

Satellites are exposed to a unique harsh space environment and often require a 15–20-year longevity to justify their mission life cost. Satellites being "unique one-of-a-kind" systems cannot be replaced, at least until the next launch window which may delay a critical space mission for many years. Thus, all satellite materials and components must be designed, analyzed, built, screened, and tested one hundred percent to perform with no failure for at least the required mission life period. This is even truer for satellites in low Earth orbit (LEO) that are subjected to harsher environmental conditions due to atmospheric drag, and temperature variations, and are exposed to potentially higher levels of radiation particle flux (during the South Atlantic Anomaly passages). The longevity of satellite components in space is, therefore, a crucial requirement to guarantee the success of the satellite mission. Small satellite parts and materials, often taken for granted in terms of operation, performance, and large quantity, can profoundly affect the overall satellite functionality and reliability if any one of them fails.

David Green / Mark Kettles
Satellite Augmentation, Space debris, and effects of materials used in space study

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1. The Importance of Returning Spacecraft Components from Space After Decades of Space Exposure

1.1. Introduction

Spacecraft orbiting the Earth has exposed important space mission hardware for decades, while other space mission hardware has been exposed to space through the Space Transportation Systems (STS) that have flown for 36 years. Examples of important spacecraft orbiting the Earth are the International Space Station (ISS), GPS navigation satellite constellations, numerous Earth and space telescopes including the Hubble Space Telescope, and dedicated weather and reconnaissance satellites. All these spacecraft have special materials, devices, and components that can be returned and analyzed after different lengths of space exposure. However, a decision has been made not to return the ISS solar blankets and solar cells from different years of space exposure. The decision to not return the ISS solar blankets and solar cells of different years of space exposure was largely driven by Roadmap Technology Gaps and Defining Documents that capture Ground-Based and Space-Based Testing of Spacecraft Systems.

An earlier strong pursuit of returning important space-exposed components from space to the Michoud Assembly Facility, and then beginning three different pre-development programs and concept studies, lead to the third pre-development program named the Reusable Limited Capability Spacecraft (ReLICS). The ReLICS program arrived at the Michoud Assembly Facility via major opening roles of the Return Vehicle/Orbiter Team, Spacecraft Return Enclosure, Spacecraft Support Elements, and prototype support equipment. The NASA/Space Shuttle/MDA ReLICS space capsule concept was designed to return spacecraft components for post-flight analyses after being exposed to the space environment. These same concepts can also apply to commercial space habitats where commercial space actors are performing commercial space activities. The Spacecraft Return Enclosure was the next major step for the safe and successful returning of important space-exposed hardware from orbiting the Earth.

Hardware flown for decades on spacecraft faces many opportunities and challenges, especially in the case of hardware for Mars, its moons, and the Martian orbit, where the distance from Earth, the limited number of communications opportunities, and the environment of space and Mars limit the frequency with which the hardware can be operated and present new failure modes to be overcome. These are on top of the very stringent environmental challenges faced by spacecraft hardware in every space mission that must contend with vacuum, pressure, such temperature extremes that can range in a single day over 300 °C from the heat of the Sun to the cold of the magnetically shielded dark side of a Mars moon, space radiation that includes solar particle storms of immense intensity and short duration (the August 1972 storm had an intensity more than 7,000 times the "100-year" storm and would be 6 times the dose from the worst solar storm predicted for any given year shortly during long transit missions, lasting up to a year), and space laws, along with other difficult challenges like the need for mass and volume efficiency.

1.2. Historical Significance of Components Flown in Space

Every space mission incorporates the combined product of a variety of components and subsystems. Most of these assemblies will have been deployed in the demanding environment of space. Any failure of such equipment can compromise the mission objectives, subsequently impacting the potential scientific or operational returns. The development of proven space hardware significantly increases the likelihood of mission success.

The components used in space are generally cutting-edge, high-performance items that are required to operate. Therefore, an electromagnetic relay or an integrated circuit that has survived the stresses of launch and has been operated in space can be considered extremely reliable. If a unit has been space flown as part of previous missions, one can embody them with an almost infinite doubling of credibility. Moreover, well-documented environmental and performance data recorded during space flight can significantly benefit the design and validation of subsequent space equipment, possibly allowing for space qualification by similarity. For radiation-hardened devices or those that cannot be validated by similarity, the use of space-proven parts may even be the only viable route for demonstrating reliability on a component level.

1.3. Introduction Longevity of Satellite Components in Space

Satellites are exposed to a unique harsh space environment and often require a 15–20-year longevity to justify their mission life cost. Satellites being "unique one-of-a-kind" systems cannot be replaced, at least until the next launch window which may delay a critical space mission for many years. Thus, all satellite materials and components must be designed, analyzed, built, screened, and tested one hundred percent to perform with no failure for at least the required mission life period. This is even truer for satellites in low Earth orbit (LEO) that are subjected to harsher environmental conditions due to atmospheric drag, and temperature variations, and are exposed to potentially higher levels of radiation particle flux (during the South Atlantic Anomaly passages). The longevity in space of satellite components is, therefore, a crucial requirement to guarantee the satellite mission success. Small satellite parts and materials, often taken for granted in terms of operation, performance, and large quantity, can profoundly affect the overall satellite functionality and reliability if any one of them fails.

The "zero-effect" concept of space component aging and degrading is unrealistic. All components in space are exposed to harsh conditions that induce electrical degradation. Some are temperature-dependent, and some are not. Among the more exotic long-term processes are the ballistic transport which perturbs the electronic devices functionalities, and the electron-heavy ion precipitation which enhances solar and cosmic radiation degradation of electronic devices. A critically important parameter for all long-term degradation mechanisms in space (as well as in other forms of radiation effects) is the cumulative energy deposited in the sensitive volume over some time. It must be remembered that space component aging and degradation is not environmentally driven, but radiation serendipitous. As in any form of charged particle transport-induced failure, a component gets older whether in the absence or presence of radiation environment data. Indeed, even ground laboratory test models, as well as in-situ experiment flies on the satellite body or inside its "quasi-in-flight" full size model, get older. Time-independent degradation factors must be added to the radiation time-dependent degradation processes. The latter are linked to both time and depth. Therefore, satellite component aging and degradation analyses must be anchored in time. It is simply unacceptable to take only "snapshot" results from the ground laboratory (complemented with flight data) studies to design "longevity in space" satellite components. The lifetime cumulative effect is one of the energy bounds. The quantitative understanding of the specific degradation mechanisms associated with space materials and components is generally hard to come by and not well known.

2. Environmental Challenges in Space

2.1. Material Environmental Challenges in Space Radiation Exposure

Environmental exposure to space radiation is a major concern for long-term space missions, such as journeys to Mars. It represents a unique health risk in space and arises from the continuous source of low-flux, high-linear energy transfer (LET) radiation passing through the spacecraft. Presently, one of the most significant contributions to accumulated dose equivalent onboard the spacecraft comes from space radiation. Unlike the Earth's environment, outside the spacecraft, shielding materials reach significant dose levels as they become bombarded by cosmic particles, built up by secondary neutrons and other secondary radiation. Additionally, while space radiation causes failures in electronic devices that generate energetic, heavy ions, neutron radiation can significantly impact photovoltaic power generation systems. Many factors are likely to limit mission duration with human crews, with anticipated mission duration in the range of three years, in particular, due to radiation exposure.

Inside the space vehicle, the requirement is to minimize exposure, ideally to below an acceptable health threshold, but also to reach cost/benefit targets. A classic case of mass versus mass saving targets is the use of radiation shielding versus high mass power and life support systems. A very promising approach to limit the impact of space radiation will be offered by the new generation of intelligent multifunctional radiation shielding systems. These systems, denying only the needed radiation intensity and are transparent for the necessary values, can support long-term manned space mission plans. They will be beneficial for operational protection concepts, significantly reducing complexity, power consumption, and crew workload. This will make crew journeys into space much safer. However, to achieve advanced enhancements, effective synergy between radiation and other shielding systems would be necessary, providing substantial improvements over monofunctional structures and merging the combat roles of radiation sources.

2.2. Background of Space Radiation Exposure

Man has been exposed to space radiation since the start of space travel. As the duration of the exposure can increase with long-duration space flight, interplanetary space missions, or a prolonged stay on the lunar surface, with rising interest in space tourism and space habitation, occupational health standards have become more important. There is a need to address the range of potential adverse health effects from these exposures. Health models to quantify the effects of space radiation have been developed through ground-based measurements, modeling, and spaceflight linearity dose-response models. At an organ dose level, thresholds are associated with five adverse health events. For occupational health, the highest incidence of cancer could be determined but for leukemia and other cancers.

Should some of these be diagnosed at a younger age and potential reproductive life have been lost, discussions are ongoing concerning age/gender-based organ weighting factors and adaptive protection strategies. The medical data that will inform risk levels and potential dose limits for various organ-specific adverse health effects in populations are currently being collected and compared to predictions from linear dose/response models. Given the limited number of potential exposure events, these rates should not be expected to drastically change the shape of dose-response curves currently in use. However, given the single exposure event for escapes or protective solar particle event exposures, it is important to have exposure limits that protect short and long-term human health. Recognizing this, discussions are ongoing concerning the upper bound on the allowed probability of exposure in terms of cancer risk assessments concerning space missions and medical ethics.

3. Introduction to Space Radiation

3.1. Overview of Space Radiation

Space radiation refers to the mutagenic and cancer-causing properties of the radiation from space. The residual effect is the low amount of human injury when exposed to a large amount of radiation over a short period. This includes cosmic rays, and solar and galactic cosmic radiation, which can penetrate living tissue and seriously affect the health of humans in outer space. Astronauts are exposed to significantly greater doses of radiation than on Earth. The reason for the increased exposure is that our breathable atmosphere protects us from the majority of cosmic rays. During space missions, astronauts often spend long periods living in outer space. With the return of the Space Shuttle, and plans being worked out for returning to the Moon and traveling to Mars, measures have to be developed to properly protect the astronauts if they are to be exposed to long durations of high radiation levels.

Galactic cosmic radiation is the term used to denote the flux of cosmic rays that approach the Earth from all directions in space. These cosmic rays are the nuclei of atoms and subatomic particles that have been accelerated to high speeds by distant supernova explosions or events in other galaxies. The resulting collision between these rays and naturally occurring atoms within a planet's magnetosphere can cause nuclei of these higher energy particles to reach the planet's surface. Alpha particles and heavy nuclei are stopped by only the first matter they encounter, but the biological damage they cause is fairly well understood. The consensus seems to be that if relatively low exposure levels are used for international space station missions, the risks can be reasonably managed.

3.2. Sources of Space Radiation

Space radiation refers to high-energy particles from the sun, distant stars and galaxies, as well as unstable isotopes of heavy elements. Collectively, the high-energy particles are referred to as cosmic rays. Without the continual protection provided by the Earth's atmosphere and magnetosphere, critically important biological macromolecules (nucleic acids, proteins, lipids) necessary to maintain cellular function in the human body, or any other life form, are at risk of being ionized, fragmented, or electromagnetically excited, hence disrupting the biochemistry and biological processes critical to the viability of the cell. The higher risk of developing various kinds of cancer is a direct consequence of the mutagenic effects of ionizing radiation. Indeed, cancer was associated with ionizing radiation early in the history of radiology and radiation therapy.

Most frequently, the source of primary solar particles, or cosmic rays, is the Seyfert (an AGN) or quasar nucleus of an active galaxy. Active galaxies are associated with gravitational collapse, the result of massive dying stars with collapsed cores, hitherto known as neutron stars, pulsars, or black holes. Alternatively, the higher-energy radiation can originate in associations of stars with large numbers of dead stars. What makes these sources especially interesting is the possibility, if not the likelihood, that some fraction of the galactic associated particles are metastable neutral particles, massive neutrinos. These sub-dominant heavy neutrinos are not significantly hindered by any known kind of matter, and so propagate much like light speed neutrinos. With mass, the neutrinos travel more slowly than the light speed limit, and cosmic ray fluxes tend to be correlated with short timescale cosmic flares that may be obscured when radio-Fermi radiation is absorbed in intense tidal forces near the galactic core.

3.3. Types of Space Radiation

In an average day, humans are exposed to a variety of ionizing radiation from a variety of sources, most of which are manmade. However, above the protective layers of the Earth's atmosphere and magnetosphere lies the harsh unfiltered flow of space radiation. Galactic Cosmic Rays (GCR), solar cosmic radiation, trapped radiation belts, and earth-limb radiation are the four major types of radiation that make up this unique and harsh space radiation environment of interstellar and interplanetary space. Each of these sources produces unique types of ionizing energy and can pose a variety of dangers to humans and human space systems. To gain an understanding of human risk to the Space Radiation Environment, one must know the different types of radiation and how each type is produced.

All types of space radiation pose some threat to human health - from the negligible doses of solar particle events heralding the arrival of Coronal Mass Ejections (CME) from the sun to their great, continuous Galactic Cosmic Ray (GCR) flux from the galaxy. Prolonged exposure to these types of ionizing radiation can cause a variety of health effects, including cataracts and cancer, and can pose severe to fatal danger to unshielded humans in deep space. In designing deep space missions, such as Voyager, Galileo, Ulysses, and missions to Mars, one must deal with the radiation environment in determining shielding requirements, potentially dangerous times when events such as large Solar Particle Events (SPE) can occur, and the appropriate lifetime limitations of spacecraft electronics and materials specific to the environment. Since one can easily shield against GCR (and in fact, one can reduce the GCR dose of large solar storms by adding hydrogen to the shielding), it is as important to separate the different types of radiation and understand their characteristics as it is to deal with the immediate dangers of the particle events themselves.

3.4. Definition and Sources

Space radiation can be divided into three major categories in terms of its origin and source: (1) the solar particle events (SPEs) and the associated background and prompt radiations; (2) the galactic cosmic rays (GCRs); and (3) the trapped radiation, which consists chiefly of protons, trapped electrons, and heavy ions. Because both the medical and biological problems to be discussed involve the qualitative interactions within the biological system, an increased dose of the encountered radiation could generate a radical change in the response of the system or an overwhelming quantity of these reactions, with an increased probability of interference intrinsically possible.

In a nuclear interaction, a nucleus encounters free nucleons, other nuclei, or electrons and then exchanges participants via the nuclear force. The available strongly interacting particles distort the incoming hadron and are transformed into outgoing nuclear products. Interactions can occur between the projectile ions and the nuclei or electrons of the biological molecules. Therefore, in consideration of the effects of nuclear interactions, it is important to consider the value of the atomic number of the target. Finally, the nucleon causes the nuclear excitation and can also be ejected. We can observe radiative capture reactions, knockout reactions, elastic and inelastic scattering, and the particle and gamma decay of virtual states. The concurrent process of energy deposition will lead to the ejection or radiative destruction of atomic electrons within atoms and the Compton scattering of the ejected electrons or bremsstrahlung photo. The abundance of inelastic processes occurs in a different order with electrons.

Ionizing radiation is an inextricable part of space, according to a high-energy space environment harshly filled with Galactic Cosmic Rays such as X-rays, gamma rays, and strongly ionizing fast neutrons that tend to induce complex bio-organic damage. Additionally, Solar Particle Events characterized by lower energy protons and heavy ions, and long-term effects that include a harshly charged plasma environment with electrostatic charging associated environmental factors need to be considered as extremely severe. Consequently, there is a pressing need to perform on-site real-time measurements using single or distributed instruments in a variety of mission scenarios, such as near-term manned exploration missions, to further refine the current predicted models to provide a valid approach of chronic exposure from previous giant space missions that include the International Space Station. Indeed, new deep space exploration missions will introduce various orbit and habitat characteristics that can greatly affect radiological risk.

Despite the military and scientific progress, the current technologies do not provide feasible tools for in vivo real-time diagnostics, with no recognized guidelines available for counter measurements or radioprotection strategies to enhance human tolerance and function during space radiation exposure episodes. These challenges are interesting, as they are combined with environmental factors found in harsh extraterrestrial habitats – microgravity and ionizing radiation – that both induce unique biological and pathophysiological influences. Specifically, microgravity-induced losses in bone density and body mass are anticipated to increase the risk factors for ionizing radiation-induced malignancies and other age-related pathologies in selected organ systems such as lung, skeletal, and colon systems, via possible interactions to thought in physiological and biological mechanisms.

3.5. Sources of Space Radiation

Space radiation consists of high-energy charged particles released at the Sun's surface during solar flares and by supernovas and associated events, such as cosmic rays. As cosmic rays travel through the galaxy, they are influenced by the various magnetic fields they encounter, which remove these heavy ions from the flow. For this reason, in the absence of the solar wind, these cosmic rays would be present from all angles. But in directions near the Sun, Earth's atmosphere and magnetic field minimize the cosmic ray fluence to below the requirement for advanced shielding.

Galactic cosmic rays are primarily protons (87%), alpha particles from helium ionization (11%), and heavy ions (2.5%) composed of the nuclei of intermediate mass atoms such as lithium, beryllium, boron, silicon, and others. These ions are swollen up to 1 MeV/nuc by the galactic magnetic fields that bend sufficiently of course.

In addition, there is a population of lower energy, highly variable charged particles also electrostatically stripped of their electrons in the solar radiation associated with the solar wind or coronal mass ejections. The passage of solar energetic particles can be life-threatening to cosmonauts traveling to or from Mars, either in orbit or on the planetary surface. This is due to the greatest reduction of the number of protons that the Earth's atmosphere filters away to zero at a point that requires advanced deep-space shielding.

Furthermore, were it not for the Earth's magnetic field and atmosphere, the number of secondary cosmic rays produced in an exponential contact loss is largely due to the tissue. Of equal importance, but a different level of risk, are trapped protons, a much less lethal form of solar radiation encountered in deep space, and radiation from the Van Allen Belts, particles trapped in the Earth's magnetic field.

4. Introduction to Microgravity Research

The study of materials in microgravity was born nearly at the same time as the first events of manned space exploration. The interest in understanding how zero gravity could change material properties, even from physical, technological, or physiological points of view, was then and still is very high, especially if one considers the recent and not very recent data about the creation and almost immediate increase of the number of effects of the space environment on materials. Primarily physical properties, like heat capacity, electrical resistivity, diffusion coefficients, flux pinning, and flux flow, then physical phenomena, have been studied mainly in different types of superconducting materials and in liquid mixtures and alloys like He3-He4, solid He3, or 4He, as well as other systems. For example, different molecular gas-solid and liquid-solid mixtures, self-diffusion of germanium, and tracer diffusion of zinc and boron in germanium.

In the following years, not to forget several relevant fluid dynamic experiments already developed in conditions of microgravity on board Skylab, the properties of liquid metals and of semiconductors, polymers, and composite materials usually used in the aerospace field, as well as structural and functional materials, have been considered and non-negligible funds have been invested to carry out many promising experiments on board American shuttles, Russian space station MIR, European Spacelab, and many other international projects up to the wonderful International Space Station (ISS). The goals and the performed activities of these investigations have been sometimes very different, and the experimental conditions usually requested to reach the desired scientific results have presented severe requirements, due to the different natures of the involved materials or to the necessity to perform on board a series of particular sequential processing operations for the preparation of the planned items useful for further more detailed ground-based characterization and final technological utilization.

4.1. Definition and Importance of Microgravity

The microgravity environment is a condition where the influence of gravity on the weight and structure of the material is limited or absent, and only small gravity- and buoyancy-induced convection bring extra forces, which can change the behavior of a system in a fundamental way. Consequently, it is possible to observe phenomena such as phase separation, diffusion, and molecule interaction at amplitudes and growth rates that cannot be achieved under normal gravitational conditions. This possibility of observing the influence of gravitation on matter is used to conduct various scientific investigations to enhance human understanding and develop new technologies and products with important benefits for earthbound inhabitants. Space research therefore provides stakeholders with important economic and technological tools that have the potential to return important benefits for society, thanks to associated technologically advanced products and novel scientific knowledge.

At present, European researchers do not have specialized experimental facilities to conduct their investigations, and consequently they are forced to quasi-commercial solutions in Russia (with the use of its mini laboratory located in the ISS) or fly as partners of NASA or other space agencies on their free fliers. This paper reviews the role of the current space infrastructures in promoting European and worldwide scientific research in the microgravity material science sector and enhancements offered by novel specialized spacecraft. The peculiarities and possible complementarities of these two infrastructures are also considered and discussed.

5. Introduction Long-term effects of Thermal Cycling on materials in space

Thermal cycling on space hardware, from launch through orbital life, has long-term effects that can modify or limit the performance of the materials from which it is made. These components are subjected to external temperature fluctuations due to movement through eclipse and exposure to sunlight, as well as internal power dissipation. The selection process for materials intended for use on space hardware considers constant temperature (isothermal) property degradation, such as tensile strength, and physical parameters like density, coefficient of thermal (expansion) contraction (CTE), and dimension tolerance. The long-term effects on some materials have been documented by a history of space flight missions, but essentially because of their use in hardware designed for constant temperature (heat pipes and some solar hardware).

The response of materials to thermal cycling can differ significantly from materials' behavior subject to slow terrestrial testing, in which the temperature (T) modulation is generally limited to a few cycles and sustained for a limited number of segments to avoid thermal shock. Additionally, thermal cycling via a finite number of cycles to simulate the launch and mission life has been summarized to avoid thermal shock. In general, the problems and potential improvements in our understanding of these materials' behavior with thermal cycling are not well defined. Commercial off-the-shelf (COTS) surface mount technology (SMT) components are another class of materials that are intended for use in mild or steady-state ambient conditions. They are being considered for use in military and aerospace applications within the payload of USAF space orbiters or on Naval surveillance satellites to repair malfunctioning or failed hardware in space.

5.1. Material Thermal Cycling

It is currently very difficult to simulate the thermal environment that a material or component will experience during a space mission in the laboratory on the ground. This is mainly because the radiation and convection environments in space are very different from those on the ground, and this often makes them the dominant factors in determining the temperature distribution in the material/component during a space mission. In almost all spacecraft, the thermal control arrangements are designed to maintain the critical or sensitive items on the spacecraft within their specified temperature range for most of the mission time. However, the actual thermal environment in many regions of the spacecraft, both externally and internally, changes dramatically during a typical space mission with lots of cyclic (usually daily) excursions. For low Earth orbit missions, during the zero-G radiation environment and the high-Q sun/night transitions, there is usually intense conductive-radiative radiation heat flux generated in the use of normal multi-layer insulation (MLI) and structural materials.

Because quite a few spacecraft materials experience potential daily thermal cycling of the actual spaceflight mission for many successive months of the mission, the impact of such highly asymmetric thermal environmental transients on the in-situ material performance is very important to the spacecraft design community. Such dynamic thermal excursions during the mission can give rise to mechanical fatigue, thermal fatigue, thermal stresses, and non-stresses that can lead to microstructural materials property evolution or degradation such as phase change, creep, radiation damage, gas release, intergranular penetration corrosion, blistering and thermal wrinkling and delamination in thin films and coatings on various materials. In general, thermal cycling and thermal cycling analysis have not been given as much attention in the space research community as the mechanical fatigue literature in aerospace.

5.2. Definition and Importance

Materials are subjected to environmental cycling during their use or service. Materials cycling could include moisture, thermal, and mechanical cycling during usage. While materials often fail due to mechanical or fatigue loadings, it is believed that a significant number of material failures would not occur at all if they were made more resistant to environmental cycling. A fast means for material evaluation is to use real-life space environments for engineering evaluation and selection.

Most space applications contain periods of vacuum exchanges ranging from 60 to 90 min/day. In LEO permanent orbits, the spacecraft thermal cycle is timed, with maximum cold and heat flux being encountered during the night and daytime, approximately every 45 and 90 min, respectively. In deep space, no thermal flux variations occur, with the spacecraft thermal cycling approximately once a year. Several occurrences of this type of exposure exist, including the LDEF first mission, the EOS mission, the Space Station missions for periods of daylight, as well as any circumlunar or Martian missions. Several materials were shown to degrade after orbital cycles in LDEF, with some materials that have not been exposed to any of these thermal cycling conditions, except returned crewed missions.

5.3. The Thermal Environment in Space

Since the first step into space by cosmonaut I. Ya. Gagarin, a great number of scientific and technological results have been achieved that relate to the fields of energetics (solar energy utilization), information science (telecommunications and techniques), and scientific experiments, as well as the ongoing construction of a manned orbital space station and the general investigation of several problems associated with living organisms in the unique environment of space. The presence of this environment, which is without atmosphere, gives rise to particular problems, part of which depend on the specific power and material constraints of the spacecraft. The most critical of these problems is the thermal environment, both in terms of the control measures necessarily implemented to provide adequate conditions for the proper functioning and comfort of humans and materials, and in terms of the basic laws that govern the modes of heat transfer in the absence of a gaseous medium.

Although the first difficulty has long been recognized and treated, leading to interesting technological developments in the fields of multi-layer insulation techniques, heat loops, and thermal control systems, as well as to interesting biomedical and physiological experiments based on such quantum benefits as chronic respiratory diseases therapies and the production of some previously impossible pharmaceutical crystals (monocrystalline purification), a rational approach either in relation to the available resources or in relation to human needs has not yet been defined for 'global life support' analysis. This paper aims to present a state-of-the-art review of the various aspects of 'space thermal problematics', with particular emphasis on human requirements. The available experimental results on the thermo-physiological effects of space and the relevant man models for predictive analysis are summarized. Special attention is given to the goal of' Zero Energy Balance' and to the thermophysiological implications that space life-cycle shortening will have. Special reference is made here to the particularly critical situation that will be faced at the beginning of the manned Mars mission. Some final considerations are then drawn, revisiting the man-associated problems gotten along the paper, and here, from a critic viewpoint.

5.4. Overview of the Thermal Environment in Space

The thermal environment in space is a unique and interesting phenomenon which has a profound impact on the design of spacecraft and space systems. Space itself is a good vacuum and therefore has no intrinsic property to transport heat via conduction or convection. The sun is the principal source of thermal energy in space. Solar radiation, in conjunction with the earth, whose radiant flux is also proportional to the absolute temperature, contributes the environmental energy necessary to govern the temperature of a satellite or spacecraft in orbit. The principal factors that affect spacecraft thermal control include the magnitude and variation of solar, earth, albedo, and EMS radiative fluxes, the circularity and obliqueness of the earth, vacuum thermal insulating properties, conduction couplings with the internal structure, and radiative and conducting couplings with the earth's free molecular atmosphere.

The primary functional object of control is the temperature of the spacecraft's hardware, which is determined by the balance of the incident radiant heat and energy transferred by internal heating or waste heat, by conduction to the radiator surfaces. An important engineering goal, then, is to maintain spacecraft hardware within prescribed temperature limits without using excessive amounts of mass or power for a radiator. Consideration is given to environment parameters, which are necessary for accurate shading geometry models; internal parameters required for state-of-the-art, transient thermal analysis of a spacecraft; and the regulatory considerations or constraints of the space station program, which define the maximum temperatures of various hardware components in the station modules.

5.5. An Analytical Study of Thermal Control Systems in Space

The thermal control system on any satellite, spacecraft, or space station is one of the most important systems on board. This is to ensure that the spacecraft and its payloads (the mission equipment in the most general sense) survive and continue to operate satisfactorily through the environment and propulsion systems in all mission flight modes. The mission operations account for 80-90% of the spacecraft's life and include the orbital phase of the mission after all in-flight tests are completed during launch and the spacecraft is isolated from the launch vehicle. The mission is generally assigned time and physical objectives at each moment during all in-flight activities, and a power management approach that will meet these objectives, allow for degraded operating conditions when appropriate, and is amenable to automation by ground command with online spacecraft and system sensors is required. With a conservative development strategy, the existing design guides should allow for the achievement of compatible and integrated thermal and power management hardware and software.

To achieve this result, there are several thermal design considerations to be taken into account for satellites, spacecraft, and space stations such as the heated portion of the spacecraft, heat transfer into and through each structural element, and in the form of absorbed solar and reflected earth and planetary thermal energy, interaction of the TCS with the other spacecraft systems, service environment and gas loads, and displacement and acoustic environments and control system performance. The requirements for verification of both the design and application of the spacecraft TCS will be dependent primarily on the mission objective, the spacecraft's unique design, and the level of understanding required. However, it is assumed that a good understanding and analysis of the mission, system, and component interactions require a test that duplicates the thermal environment to the extent that required verification and demonstration of spacecraft behavior are thorough and completely conclusive. It is also assumed that the goals of each mission should be supported by an extensive ground test program to ensure the validity of the thermal models, the thermal test results, and the validity of the conclusions. Before the completion of the design, ground tests serve the further purpose of redundantly demonstrating the validity of the design while space flight and actual system verification activities are being completed. The most effective sequence of ground testing activities to ensure a flight-proven, verified, and validated design is using thermal vacuum, electronics thermal vacuum, thermal balance, and various specialized tests such as thermal cycling, time-lapse, heat transfer, and individual component tests. These tests present several constraints and requirements that depend on a proper "front-end" understanding of the spacecraft TCS that satisfies the mission goals and the spacecraft life and orbital mechanics characteristics of the mission profile. These requirements are addressed in this study.

5.5.1. Importance of Thermal Control in Space

This paper deals with an overall overview and different details of thermal control systems for long-duration space cabins. Since temperature plays a much more direct effect on the life of humans and of delicate electronic equipment in space, much attention is being given to space thermal control systems throughout the world. The two fundamentals of life in space are water and air in plenty with various sophisticated arrangements, and these have been done over the years to make human habitation in space possible.

The public and even the non-space scientists usually will be attracted more towards medical, biological, earth resources, materials, communications, navigation, or defense aspects of the scientific studies conducted in space independent of their launching country. Heating-radiation and cooling sunlight are two relatively simple fundamentals in the thermal science of space, which go to decide many complex activities of human life in space.

In this paper, we will first enumerate the fundamental principles of the heating and cooling mechanisms, followed next by summaries of space thermal systems in space to date. A few pictures and sketches accompany the necessary descriptions. Practical complex thermal systems and their mathematical representations are very much essential to the interactions, during our long continued stay and travel in space, as well as our complex systems of mutual defense and other peaceful interactions with different life forms in our own home, the Earth.

5.6. Passive Thermal Control in Space Introduction

Space systems sometimes require passive means of stabilizing the temperature of their components. This chapter is focused on means of controlling the thermal environment of space systems passively. We cover the basic heat transfer modes in the space environment and give a brief introduction to surface coatings. The radiator configuration is introduced, followed by the basic equations that describe the operation of a space radiator. Next, we introduce the concept of radiator efficiency and address the issue of the optimal radiator configuration that maximizes the available cooling power. Finally, we address advanced design concepts and their effect on radiation properties.

For systems parked in orbit, there is always a tradeoff between thermal performance, the degree of flexibility of getting rid of thermal energy in a controlled manner, and the complexity of the radiator systems attached to the hardware. The choice of the complexity of the solution depends much on how much flexibility in the radiator systems the mission wants and the specific tolerance of the hardware to its maximum temperature. Several missions have electronics parked into the spacecraft, which has an active attitude control system that always points in a constant direction with the heat pipe attached to the electronics. By so doing, the electronics can be passively cooled throughout an orbit acted for instance by a combination of low- and high-absorptance coatings applied to the heat pipe. Such arrangements can be cumbersome and difficult to be realized for extremely long-duration missions. Successive space astronomy missions have selected passive radiator configuration as their baseline solution.

5.7. Passive Thermal Control in Space

Space is a naturally hostile environment for manmade hardware, and spacecraft must be designed to survive under the extreme conditions of space. Key issues for any space mission are the environmental factors that may significantly impact the performance of the spacecraft, the operational functions, and ultimately, the mission's success.

The main environmental factors that will affect the spacecraft's performance are direct solar radiation, albedo, Earth and planetary infrared radiation, orbital variations for different Earth orbits, differential heating, sky temperature variations, radiation from the Earth, and leakage flux from the internal sources. The combination of such effects in any space environment (geostationary, low Earth orbit, and planetary orbit) leads to enhanced temperatures that must be somehow dissipated to avoid permanent damage and loss of mission objectives.

Efficient thermal control management is of crucial importance to prevent thermal control problems. In a basic approach, the general function of the spacecraft thermal control system is to maintain the internal components of the spacecraft within the operating range of temperatures, in suitable thermal energy conditioning. This function is often achieved mostly using passive thermal control equipment that is easily installed in the spacecraft itself and is non-expandable.

To achieve this, systems capable of providing the desired passive thermal control should be used, and the ground and internal qualifying thermal design operations must be performed. The adoption of a proper passive thermal control approach may reduce the complexity of the active thermal control system and demands two additional thermal control management issues, which creates substantial potential for an improvement over overall spacecraft performance. This may mean increasingly larger energy savings in protection, dissipation, and redistribution of thermal energy within the equipment volume and, in some specific cases, enhance the operational lifetime of the spacecraft.

5.8. Types of Thermal Control Systems

Spacecraft require thermal control systems to manage the transfer of heat to and from the spacecraft to maintain the structural and electrical integrity of internal systems. When on orbit, passive thermal control systems reduce the waste heat of equipment and instruments to space. There are two general types of active thermal control loops used to move heat from the spacecraft to a thermal rejecting surface: 1) Two-phase loops use evaporation at the waste heat source followed by condensation at the radiator; and 2) single-phase loops use conduction, in conjunction with heat pipes, to conduct heat to the radiator followed by heat transfer to the surrounding space.

The transition from an active to a passive approach to the design of these heat flow paths is usually a smooth one. Most active systems make use of passive heat transport and heat rejection components, such as radiator fins and heat pipes, that continue to function passively once they are launched. In addition to this indirect passive TCS hardware, several direct passive TCS designs can be used for space missions, including off-the-shelf components, thermally connected isolated components, active-thermal-strap equivalent designs, and technologies such as hermetic-sensitive or heaters-sensitive materials. These components can be utilized to reduce program risk and simplify design by reducing the need for active TCS in high-impact areas. The following are representative examples of passive TCS approaches that can be used in mission architectures.

- AI plays a crucial role in maintaining and repairing spacecraft, especially during long-duration missions. Predictive maintenance algorithms can monitor the health of spacecraft systems, predict potential failures, and suggest preventive measures.
- MLI, coatings/surface finishes, interface conductance, heat pipes, sunshades, thermal straps, interface materials, and louvers are some examples of passive thermal control technology. Structural component materials are chosen based on needed heat transfer through the structure.

6. Materials and Components Selection for Space Applications

During the last 50 years, more than 500 manned and unmanned missions have been carried out conducting scientific experiments and exploring the Earth's environment, near-Earth space, and other planets. Since plywood was utilized in the disassembled parts of the first V-2 missile, most of the interplanetary probes and spacecraft's systems became more and more complex, having larger power and mass. Only a proper selection of materials and components existing in space structures, payloads, and spacecraft subsystems allows for realizing the increasing demands on mission duration, modularity, performance, life-cycle cost, and space operations. In fact, the operation time and the reliability of systems crucially depend on the good performance of materials, parts, and components exposed to the space environment with constraints that are becoming stricter throughout the years.

Attending to system requirements, different scientific and application missions need propulsion, pointing, power, thermal control, communications, and payload systems operating in many orbits with different life expectancies at critical temperature, humidity, and ionizing radiation levels.

Large, medium, and small Earth-orbiting space infrastructures are used to operate scientific experiments, search communication services, Earth observation applications, and remote sensing missions. Moreover, near-Earth space infrastructures have been used to validate new technologies, rendezvous and docking space operations, repairing techniques, and health monitoring devices for future applications requiring a more sustained human presence featuring either commercial or exploration purposes.

6.1. Importance of Materials and Components Selection in Space Applications

Materials and their proper use, along with component selection, are two primary important decisions that lead to successful and cost-effective payload missions. Materials and components are subjected to stringent environmental constraints and must satisfy the most severe operating conditions for manufacturing, launch, and space. Strict performance requirements, the cost of developing materials and components, and associated verification testing should be considered. High reliability of materials and components during the entire lifetime of a mission is mandatory and only achieved through a rigorous selection process from the variety of options available within the space industry.

In general, aerospace legislation and related industrial behavior are evolving to maximize the competitiveness of the space industry through deregulation and new management laws. However, monitoring is conducted by means of specific standard procedures and test rules that are strictly based on the precautionary principle. Despite the extensive attempts of the space community to ease these rules and obtain a more realistic ground environment, in-service performance data are quite limited, and the full realism embodied within space missions and conditions is rarely attainable at ground level. This situation makes the choice of materials and components the crux in enhancing the likelihood that future, challenging space missions will be successful; if not, technologies and design solutions will be obsolete, or at best unreliable. These aspects have a direct impact on architecture design, considering the growing demand for more competitive missions as driven by the increasing societal demand for lower and shorter data solution times. Furthermore, many challenges regarding the need for predictive methods linked to aging effects, exposure influences, and interaction among the mixed environment are emerging, indicating that materials and components will be at the core of the next generation of space missions.

7. Introduction to Space Resilient Materials

The operational lifetime of a spacecraft is defined by the reliable and durable operation of built-in systems in the harsh environment of outer space. The construction of space vehicles and spacecraft is based on the use of space missile-resistant materials. Systems are adapted and tested for operation in the conditions of the near-Earth orbit. Research has been carried out at the stages of production of materials, components, ground control, and operation of space-based products to assess the behavior of materials, designs, equipment, and mechanisms in space. With each new stage of work on spacecraft, there is an evolution of the space-resistant purposeful materials that meet the specified technical requirements.

The work on the improvement of space-resistant materials has produced not only predictable consequences and results, but also discovered new effects observed in laboratory and on-board spacecraft studies. These phenomena, detectable under low-gravity conditions and intense cosmic ionizing irradiation, are not typical of ground objective conditions. The study of these phenomena is the basis of the concept for the development of a fundamentally new class of materials containing structures – space-stimulating structural materials – which are analyzed for use in the construction of new radiation-efficient spacecraft.

7.1. Materials in Space

The behavior of materials and the response of subsystems to the space environment are critical. The space environment imposes unique stresses to which materials must respond. These are that there is no atmosphere, no gravity, and a higher radiation environment, both in particle flux and composition, coming primarily from the sun, and for longer-duration spaceflights, from outside of our solar system; the space station environment includes periods of exposure to the ionosphere for high-power operations. Whereas these characteristics are met uniformly by all materials that are exposed to space, we stress here that it is the duration and the expected performance degradation in some materials that can pose a threat to the mission owing to the absence of terrestrial replacement parts, as is often the case.

The behavior in the space of a material may be certified beforehand only by careful qualification and testing under the most representative conditions that are available on the ground. Concerning the certification of the structures, the constant high cost of mass launched, and the special challenge for materials that are functionally graded, may open a wider interest in the new field of "in-situ certification" of materials performance. These material properties and the specifics of their response to the environment must be known to a considerably higher level of accuracy than is normally required for terrestrial application. Rather than assuming that well-known material properties will be performed, it may be necessary to use less-well-understood and characterized materials to minimize weight or cost, including special orbit maintenance.

7.2. Physical Properties of Materials Used in Space

We have been engineering materials for use in space since the early advent of rocketry. Yet, 50 years after the space age began, it remains the case that neither the conditions in outer space nor the critical role of materials in space systems are intuitive for many scientists and engineers. The truly adverse space environment, which has consequences for almost all materials, includes extreme thermal swings, vacuum, harsh ultraviolet (UV) radiation, and impacts by micrometeoroids and space debris, to name a few. These have led to a substantial database of materials-related anomalies, dating back to the first reports of painted surfaces becoming covered with extravehicular activity (EVA, or "spacewalk") cooked residues, through numerous equipment failures caused by the stress of cycling from boiling to freezing for days at a time, and up to the more recent problems observed on solar cells, thermal controls, and spacecraft coatings.

This article is aimed at readers with an interest in how physical properties of materials influence their performance in space, or how their properties are altered by the space environment. We start with some general notes on materials present in space and the mechanisms of space environmental effects. Then, we will look at the basic physical properties that influence the performance of the materials in space, highlighting those for which the space environment is particularly noteworthy. More details are provided for common problem categories necessary to understand some of the more extreme aging, degradation, or malfunction modes that might be observed and, therefore, require mitigation at the design stage. Where possible, the reader will be referred to reviews and monographs for further information and details, to avoid significant repetition of the known and the basics. Given the fact that space agencies use only a small fraction of all materials on Earth, most of the topics covered in the article are linked to materials used in space. However, many of the issues existing in space also apply to a variety of terrestrial environments, thus justifying the wider interest. The discussion should be particularly helpful to those who are not familiar with the characterization techniques used in the field and the vocabulary of space agencies, making it easier to engage in the necessary dialogue with space discipline experts.

7.3. Importance of Material Selection

Selection of materials is an important part of space design. Design can proceed by selecting materials that are readily available, or by specifying the essential properties and characteristics that the materials must have. The selected materials must be compatible or tolerably combinable together. It is a common practice to design component containers in space from the inside outward with as few materials as possible that are sensitive. The objective of such design practice is to prevent the failure of a sensitive material by shielding the substance from it. The effect of sensitive materials, which constitute a problem, is subdued, or eliminated by the judicious use of other materials with which such substances are compatible.

To build a structure in space, each connecting part must have proper strength, together with other necessary properties and characteristics. Proper strength is not always the nominal prime consideration for selecting appropriate materials. The mean need not always be to have the strength of the mating parts of the joints. Other properties, such as density, workability, specific strength, and coefficient of expansion, contribute to the design of lightweight structures at which superior fastening methods and organizational simplicity are essential. Since load-carrying capabilities depend on both materials and structural principles, the most suitable selection of design conditions for material properties, in terms of requirements, must be met through the process of material selection.

7.4. Challenges of Operating in Space Environments

Space is one of the harshest environments. It is characterized by the absence of air, the presence of a vacuum that can cause outgassing of materials, high levels of cosmic and solar radiation, the presence of micrometeoroids and orbital debris, and extreme temperatures due to irregular illumination from the sun and the absence of an atmosphere. Rockets also must endure the burning hot temperatures on the way back to Earth. These extreme environments challenge the performance of materials. It is important to select materials that function perfectly in these environments because of the cost of sending materials to space and the difficulties of replacing or repairing them.

Operating outdoors in space requires a thorough study of how the environment acts on the materials. The International Space Station contains many scientific instruments permanently open to space. By studying the effects of space on specified materials, it helps space agencies to supply efficient and long-lasting materials for future devices. It can also inspire new protective materials or additives to enhance the properties of other materials. The first citizens of space wore silvered garments due to the high reflectance of silver. Nowadays, aluminum has replaced silver as the material of choice because of its efficiency as a solar reflector.

7.5. Advancements in Materials for Space Exploration

Space exploration, whether in the form of manned or unmanned missions, generates events - the combined conditions and experiences that provide the opportunity to learn about matter in extreme environments. The unique properties of matter derived from conditions that cannot be replicated in terra-based laboratories are distinct behaviors known as space-materials interactions. The exact response of a given material under a given set of conditions may not be known from laboratory test data, and so components and systems are generally overdesigned to ensure missions can achieve an acceptable level of success. In some cases, the effects of space exploration can be observed through Earth-based telescopes, thereby potentially increasing the range of materials that can be included in the study, the duration of the experiment, and the precision that may be applied to different measuring techniques. The commercial exploitation of space also generates a significant need to solve medical, economic, infrastructure, biological, and physical problems, as increased space exploration is essential for Earth's continued development and increasing population.

The materials scientists aim to ensure that materials either perform sufficiently well under space exploration conditions for the length of the mission or that they are 'spent' as intended for both safety and function, such that resources can be reallocated to other mission-specific tasks. The materials used in space must endure severe conditions, typically caused by the potential for exposure to atomic oxygen, atomic nitrogen, ultraviolet radiation, extremes of temperature and humidity, contamination, microgravity, and biological and engineering environments. A major concern is the potential for degradation in such environments, particularly where materials are expected to provide serving functions. Consequently, the development of new materials that demonstrate novel properties under such conditions has become a field of major interest. These advancements in emerging technologies have provided new opportunities to design and prepare new materials. In addition to improvements in existing materials, replacement alternatives to other technologies are beginning to emerge that offer performance improvements through innovative solutions applied to some of the numerous challenges presented by space characteristics.

7.6. Significance of Materials in Space Exploration

Materials have been an essential part of human space exploration since the beginning of the space age, and it will remain so for the future human exploration of space. The spacecraft, habitats, life support systems, goods, and research labs which are part of human settlement extraterrestrials have all been tailored from a variety of materials. Materials have defined much of what human space capability has been to date, will be such for the immediate future, and will continue to enable and shape what capabilities can be feasible going further. However, as with so many aspects of space, materials technologies are being transformed quickly.

While the value of materials utilization has always been closely linked to the value of the items made in space, significant enabling advancements in implementing many materials technologies have inspired research and experiments beyond Earth. Some fields are already offering real tools that could be of near-term benefit to the space exploration enterprise. Further advanced materials expansions offer the promise of significantly altering the development of meaningful space capabilities – most notably the process of human settlement beyond Earth. Some game-changing capabilities are nearly here. These fields can be explored within relatively short-raised horizons, guided by progress in Earth-side applications.

8. Space Radiation-hardened Electronics

8.1. Introduction

Space radiation effects on microelectronics can significantly disrupt the performance of spacecraft and space-based computing systems. There are two main threats of space radiation in the electronic equipment of satellites: single event effect (SEE), which is induced by charged ions striking sensitive points of the device, and total ionizing dose (TID), which is related to the accumulation of energy during satellite operation. As technology scaling continues, radiation-induced soft errors become increasingly common in this era of nanotechnology.

On the ground, cosmic rays are also the largest background event in large experiments. The single events can result in transient effects, which increase the missile probability to an intolerable level and compromise the performance of electronic components. Accumulation of charged particles and stress does not disappear when passing through the material, resulting in the establishment of ion tracks caused by ultimate damage effects.

Intense cosmic rays and radiation belts encircle the Earth. When cosmic rays encounter the components of spacecraft, they also create many secondary particles, especially protons, helium ions, and low-energy particles. The primary particles in the cosmic ray are heavy ions, and these ions are accompanied by electrons, protons, and other charged particles. All high-energy particles are directly or indirectly related to the sun, mainly hydrogen protons and 4He, and highly charged 4He. However, compared with the high-speed cosmic rays on Earth, the number of secondary particles produced in the components of the spacecraft is higher. In space, the properties of primary high-energy particles and secondary charged particles created in the spacecraft can be substantially affected by the passage of the medium to the substrate.

Unlike ground neutron irradiation, when the irradiation of non-insulated current and bulk material occurs, the thermal contact part of the substrate is also involved in energy dissipation. When a certain primary particle passes through a specific material, energy is continuously attenuated and distributed uniformly during interaction. The probability of stochastic interpretation of individual interaction events is determined by the specific cross-sectional value of the physical process type concerned.

8.2. Fundamental Effects of Radiation on Electronics in Space

Space radiation effects constitute a significant concern in the design and operation of most electronics employed in any space environment. The ability of modern microelectronic devices to process many complex tasks rapidly and accurately is largely due to their miniaturization—features on the order of microns and tens of microns in size have now been realized in very large-scale integrated circuits (VLSIC). However, advances continue to be made in the design of microelectronic elements which increase the sensitivity of these devices to ionizing radiation—effects which are deleterious in the presence of harsh radiation environments. The performance of the Institute d'Estudis Espacials de Catalunya (IEEC) Charge Energy Loss Measurement (CHELM) Total Ionizing Dose (TID) and Single Event Effects (SEE) Monitors developed for the TRITEL, TRIple Ion and Electron Telescope project, flown in June 2015 on board the BEXUS26 stratospheric research balloon, and improvements have been made to the software and control electronics since that flight, leading to improved performance.

Electronics on spacecraft are exposed to low-Earth orbit (LEO) ionizing radiation including secondary radiation produced in the spacecraft and atomic oxygen present in LEO. In particular, these are of concern for low threshold total-ionizing radiation dose (TID) and single event upsets (SEU). Electronics on spacecraft traveling to other planets or solar-system objects are exposed to solar and galactic cosmic particles, but also to secondary radiation produced in the reaction of solar particles with the planetary atmosphere and surface. These secondary particles have kinetic energies and masses much larger than those of solar particles resulting in interactions with electronic devices producing TID and Single-event effect (SEE) including single-event upset (SEU). The CHELM monitors and hardware considerations are described, and the data obtained during the BEXUS26 flight are presented.

8.3. Sources of Radiation

We distinguish between two sources of radiation that can significantly influence the performance of most electronic systems in satellites or high-altitude balloons. These two sources are simply the natural radiation environment and the radiation generated by scientific experiments in which electronic equipment is an essential component. Solar cells supply electricity and electronic equipment processing and transmitting data, and lines of sight protect the other components of the scientific experiment from radiation. Usually, there are some aspects in which each source of radiation resembles the other - neutrons, protons, alpha particles, and cosmic rays - such as the energy of incident particles, their angular distribution, or their fluence. On the contrary, there is almost no similarity in other specifications - i.e., ionization density or ionization space charge produced in the silicon.

For basic research purposes, on the one hand, it relatively seems easy to evaluate the different expected radiation effects caused by the various sources - but, conversely, on the other hand, the many factors which interact, makes it difficult to foresee the sensitivity of electronic devices. We highly appreciate the tremendous efforts made by various scientists, in the world, to carry out careful and often delicate assessments for the future scientific space experiments in which their electronic systems will be employed: e.g., substantial hardening is about to be performed for the HERD and GAPS experiments by the ASM collaboration. These practical and sometimes intricate activities are made possible by the strength of very advanced, cutting-edge simulations and experimental techniques which have been developed for high energy accelerator and other physics experiments - and which are the subject of this course. Both the requirements of the various components of these experiments and the solutions arrived at will be fully reviewed in the following ranging from the feasibility pre-check of the electronic systems in collaboration with experimental physicists, in the early stages of hardware developments, up to the validation of the completed electronic system.

8.4. Types of Radiation

Space radiation can be harmful to microelectronics in several ways. Effects that occur within a matter of minutes to a few days of exposure, such as Single Event Upsets (SEUs) and Single Event Transients (SETs), must be handled by the normal real-time response mechanisms of the spacecraft and its subsystems. In today's systems, this means the data must be protected in such a way that these effects will not accumulate to levels that exceed the mission's reliability requirements. On the other hand, effects that occur after days of exposure, such as total dose damage and displacement damage, must be minimized by suitable design rules because the real-time techniques cannot generally cope with these cumulative effects. As semiconductor technology and operating voltage continue to evolve, this will not be completely true, but it will usually be true enough that the associated design rules are a significant concern.

Radiation Environment in Space: Shielded by the atmosphere, biological organisms are not affected by any of the particles and fields present in the near-Earth space environment except ionizing radiation. However, both relatively low-energy protons and electrons penetrate the atmosphere and produce cascades of secondary particles through nuclear interactions. High energy cosmic rays penetrate both the Earth's upper atmosphere and the spacecraft shields, potentially damaging microelectronics. These primary and secondary space radiation fields are sketched in. Additionally, high energy heavy ions trapped in the terrestrial magnetic field produce exposure hazards for orbiting satellites if magnetic shielding is not included as part of the spacecraft design. The single most important effect of the environment on the performance and reliability of spacecraft microelectronic systems is the potential for radiation-induced upsets and damage.

8.5. Impact of Radiation on Electronics

In the 1940s, several experimenters using techniques of electronics and radioactivity discovered first-hand the effects of ionizing radiation on electronics. They observed changes in transistor characteristics when the material was irradiated with the α, β, and γ radiation that impinged on it. As is commonly done, they assumed that the changes they observed were a result of the energy that they had raised the temperature of the semiconductor material while it was being irradiated.

Physicists at the time and since have recognized that the source of this heat was the ionization of the material by the ionizing radiation, which was converting into free charge lattice motion by releasing electrons and holes. Over the years, the body of knowledge related to the damage caused to materials and especially silicon devices by ionizing radiation have grown. These effects have been called total ionizing dose (TID) effects in silicon materials.

The purpose of this guide is to help you in understanding the effects of ionizing radiation on the devices that are and will be used in the control and safety of nuclear processes. The first part of this guide will introduce the principles by which ionizing radiation propagates in materials and why it affects semiconductor materials. Following the explanation of the TID effects is a description of the principles and common methods used to measure the effect ionizing radiation has on electronic devices.

Following these introductory comments, a description is given of the methods used by AT&T Technologies to qualify various circuits for NRC licensing and to demonstrate to customers that they meet the design basis coverage of the environmental qualification required by the customer. The information given in this guide will allow you to determine whether the methods proposed to qualify devices and circuits are appropriate and adequate.

9. Spaceflight Material Mitigation Strategies

9.1. Future Spaceflight Trends

The U.S. Federal Government, about half of operating satellite customers worldwide, and response control for 90% of intelligence, communications, global positioning services, and space traffic management are all dependent on the infrastructure accomplished by fifteen commercial space companies in cooperation with military, research, and university laboratories. "Guaranteeing space access, to guarantee prosperity, security, and scientific investigation," according to the National Strategy for Space Traffic Management, consummates U.S. space policy. The largest Jefferies indices, managed by a handful of telecommunications companies, represent the foundation reflected in military commands and undisclosed ventures. A OneWeb security advantage, both critical and uncritical, has occurred recently.

2. "Vigilantly protect and manage capacity, diversity, and timely temporal use" in the future. Dependent directly on space surveillance, intelligence, surveillance, and reconnaissance to counter U.S. "imperial support of it (command and control)" is a country unable to proceed with its business model. The U.S. economy will face a trade of $250 billion and 1¼ million jobs. Fearing reliance on vulnerable space assets, the United States must "safeguard businesses, consumers, and U.S. national security interests" by presenting secure, agile access to space. Official responsibility cannot fail as a service provider to these stakeholders; instead, to reserve legislative, philosophical, and diplomatic heritage and endorsement of open international cooperation.

9.2. Overview of Materials Used in Spaceflight

The described phenomena are based on issues that occur in the low-Earth and geostationary environments, so there currently is limited exposure and understanding of manmade and natural orbits. Designers and satellite operators must understand the strategy for mitigating failures due to material interactions because these types of degradation can occur unpredictably, leading to system failures. Reaction control thrusters and xenon ion engines are the most sensitive components to environment-induced failures because they subject spacecraft to continuous exposure to the contaminated environment, magnifying the response. Reaction control systems are responsible for station-keeping and repositioning, using high-pressure hydrazine propellant thrusters for maneuvering, and may require ongoing propellant firing throughout the lifetime of a satellite. Xenon ion propulsion engines provide efficient, low-thrust, high-velocity services for north/south station transfer and for deep space missions, and their use is limited by the quantity of stored xenon gas.

Materials used in spacecraft construction are selected for strength-to-weight ratio, thermal insulation, heat transmission, optical coatings to modify emissivity, reflectance, and absorptance properties, and electrical conduction or insulation. They are designed to hold useful lifetimes over a certain temperature range without distortion, embrittlement, or solar state curing when exposed to radiation. They are thought to be stable at temperatures exceeding 160°C and to operate at temperatures below -150°C. These operating temperature gaps allow for some temperature cycling without noticeable impacts. However, this temperature range does lead to changes in surface physical properties.

9.3. Types of Degradation Mechanisms

All different circuits, components, and systems that make up an electronic assembly have very specific functions which contribute to the overall operation and performance of a product. These components, however, are not immune to changes in performance over time. There are several mechanisms that influence the performance of components, all of which can be termed degradation mechanisms. The degradation can lead to failure if not detected early on. To be able to detect degradation early and take appropriate corrective and preventive action, it is crucial to understand what mechanisms of degradation are active in the assembly.

The reliability of the overall system consists of both electronic assemblies and their constituent components. This in turn relies on the reliability of the component. The release of energy of failure and the capability of this energized failure to cause any form of hazard to the equipment and/or personnel is the threat that the components give rise to. The effectiveness of any component design and the electrical, thermal, and environmental design also put forth a significant effect on these characteristics. Component mechanical, thermal, and electrical characteristics can drastically degrade during both in-service and test handling, sometimes causing trigger mechanisms without any inherent failure mode. The role of the components' Attachmate and the materials used for encapsulation and protection, especially in extreme conditions is also a point of discussion. The design and fabrication of microelectronic components has to take into consideration both the activation of any of the mechanisms of degradation and the possible failure mode. Moreover, the operation of components under stress may lead to either degradation of specific parameters, called drift, or to catastrophic rupture. Both manifestations have an impact on the encoded response of systems, thus leading to potential hazards. The paper presents a list of the basic mechanisms of degradation and their effects experienced by microelectronic components. The relative importance of each mechanism and failure mode depends on the life conditions and the operating environment.

9.4. Mechanical Degradation in Materials

The mechanical load-carrying structure of a material is controlled by its microstructure or physical structure. Changes in deformation mechanisms or new deformation mechanisms often evolve from these microstructural changes. Consequently, it is the mechanical degradation and its impact on the material's deformation and loading behavior. Mechanical degradation in materials. A real need exists to be able to assess materials quickly and reliably, over the full property space, to avoid failure. This is especially the case in demanding service environments. For example, in the aviation field, the ability to predict the initiation of damage can lead to significant savings.

One possible approach, and one that has attracted considerable interest, is the measurement of the Atomic Force Microscopy (AFM) Young's modulus by the technique of nanoindentation. This has been used to measure the Young's modulus of various phases of polycrystalline cast cuprous base alloys. It follows that any changes in the microstructure would have an observable effect on the mechanical properties of the material. Some of these effects arise because of the change in microstructure, which may also control the hardness. In the following, we review some of the many different types of mechanical degradation in materials before focusing on the influence of the microstructure of commercially pure aluminum on some expected performance-related mechanical properties.

9.5. Definition and Types of Mechanical Degradation

Mechanical degradation is a type of physical deterioration that can occur in engineering and construction materials. While other forms of deterioration (such as thermal or chemical degradation) occur because of the reactions of atoms, molecules, or ions with the surrounding material, mechanical degradation occurs as a result of excessive physical forces. In engineering applications, these forces frequently consist of the recurrent or sustained stresses that materials experience from loads, thermal gradients, environmental changes, and wear and tear.

There are numerous types of mechanical failure and considerable overlap between some of them. Frequently, there are several different classifications and definitions of various failure processes available in the literature, depending on the source of the information and the particular interest of researchers. The underlying understanding is often similar, but the definitions are specialized for widely varying technical points of view. Briefly intense and rapid mechanical overstress may produce so-called dynamic failure. High, but not instantaneous, overstress stimulates what is commonly referred to as fatigue failure. Surprisingly, low overstress may give rise to wear failure, which is repeated daily in many pieces of equipment. Another type of failure is creep, which is slow and usually occurs under constant loading and high temperatures. Its occurrence requires no prior fatigue history and may be so insidious that crept components must be annealed, perhaps in a vacuum, to restore their original strengths. In addition to these well-documented degradation processes, mechanical damage and corrosion fatigue are often observed in practice.

10. Spacecraft Material Redundancy and Backups

10.1. Introduction

Material redundancy in spacecraft structural components has been employed to improve reliability and mission success for nearly the entire half-century history of crewed spaceflight. Originally, this involved using multiple pieces or layers of material to absorb or spread out the energy caused by a particular hit of micrometeoroid or space debris (MMOD). When humans are accidentally afloat in the vacuum or ionizing atmosphere of outer space, the off-nominal penetration of an intact vehicle's pressure shell and crew cabin is always a bad day in space. The same is relatively true when the vehicle's fragile solar cells and fuel tanks contest against the hypervelocity and ram-breasting MMOD. Enough little collisions create a lot of damage. Additionally, the fact that a significant percentage of the MMOD population is of unknown size and direction means that the current inventory of MMOD-destroyed spacecraft is a poor tool for predictive structural design.

An intact human-tended spacecraft is a unique thing, now and for the foreseeable future. It is uniquely expensive to design, build, and operate. It is uniquely dangerous even when nothing goes change-of-nominal. Those facts lead nearly all responsible engineers to a similar optimization or risk metric: the fewer bad days we allow, the more intact days we get. In the real world of limited fiscal and mass-allowed-for-the-converted-dollar, the trade between complete redundancy and risk management must be made. But that trade can be made only with confidence and from a position of really understanding the relative benefits. This paper has a narrow focus. It is not about MMOD impact crater scaling laws or the derived mathematical form of the extremum (1- or 2-layer) in any given energy dissipation process. The extraordinarily high speed and nearly non-existent relative probability of a human spaceflight disaster work against phenomenological experimentation over the flight readiness program's expected decades of useful life. After launch, flight operations are based on best-guess (nearly-done)-right computational models.

10.2. Overview of Spacecraft Material Redundancy and Backups

In the development of modern spacecraft, redundancy, and hardware independence are used to ensure high reliability, safety, and secure promising connection of all systems on board. The failure of one or another unit on the spacecraft can lead to fatal consequences. Therefore, methods of reliability increase, and the use of backup equipment have been developed for many years. They are one of the key issues for the life of astronauts on the spacecraft or for communication systems reliability.

The basis for redundancy is built at almost all stages of the life cycle of the spacecraft. This begins with its development and production and continues until its launch and operation. In the design stages, the principles of redundancy error and damage tolerance are taken into account. At the production stage, the control of all units is carried out, but after the launch, serious difficulties are encountered in repairing the installed systems or malfunctioning components of the space vehicle.

New solutions must be developed for repair. Therefore, a detailed system of redundancy and backup is developed for each new spacecraft. It is worth noting that unmanned spacecraft are periodically launched. Therefore, accuracy and precision may have some additional requirements, but the guarantee of the spacecraft could be doubled. Therefore, certain levels of redundancy are included in the design of unmanned vehicles.

For manned spacecraft, the principle of hardware independence was formed in the years of development of the first spacecraft. This cannot be otherwise, since the fate of astronauts depends on the reliability of all systems of the spacecraft, which are at a great distance from Earth. In this case, there can be no help rescue using airplanes, helicopters, or other means if an abnormal situation occurs. Therefore, it is necessary to carefully provide for the emergence of such forces in the crew, and in the design of the spacecraft, it is necessary to provide not one but several reliable rescue systems.

11. Spacecraft Material Shielding Techniques

11.1. Introduction

In the space environment, prolonged exposure of human beings to harmful radiation, particularly cosmic rays, and solar energetic particle (SEP) events, remains the greatest obstacle for future space exploration. Galactic cosmic rays are primarily composed of a mixture of highly charged, heavy ions and energetic protons with energies spread from the thermal limits of sources out to a few times the speed of light. These cosmic rays are a major source of radiation exposure to astronauts on long-duration space missions, carried to the Earth's atmosphere by the solar wind. The second major space radiation threat is from sporadic and unpredictable solar energetic particle events, which feature a sudden increase in the intensity of galactic cosmic rays at energies from a few MeV per nucleon. Fighters are the first products of solar particle events and may reach the Earth within minutes to a few hours of the flare.

Several materials-based protection techniques have been suggested with varying degrees of merit. For example, aluminum is popular as its primary advantage is its low mass (lightweight) while having a high surface charge density (aluminum is the most used material for spacecraft central and cabling shielding). Carbon-composite materials are another popular space radiation protection material, used both within the construction of spacecraft and in ancillary equipment worn by astronauts (which also protect against solar radiation). However, both aluminum and carbon are inefficient at stopping ionizing radiation. Low mass and low surface charge density provide low protection from ions because a minimal density of columnar electrons is presented, with the low stopping power providing little radiation shielding benefit beyond a few mm thickness ankle sufficient backscattering is also provided for higher-energy particles.

11.2. Spacecraft Material Selection Criteria

Materials form the basis for all engineering designs and where a material is in contact with a different material, an interface is necessary and thus also influences the design. Even when the parts are identical, the interfaces are necessary. Unique materials such as monolithic glasses, ceramics, and single crystals of metals are not standard engineering materials as they are reserved for special applications such as spacecraft, rockets, and electronics. These materials are critical to understanding the engineering design around space hardware. Use of these materials can allow engineers to design lightweight, high-strength, and high functional performance systems such as electronic packaging, thermal protection systems, and high-precision optics. Yet, other materials such as polymers are like vanadium, nickel, and steel in that they can be used in the majority of spacecraft systems and as a result, the major focus of this book will be these materials.

Spacecraft applications vary widely including rockets, occupants, electronics, solar power, thermal protection, cryogenics, magnetics, power storage, and other special components. As a result, where the spacecraft materials literature is very large and often specific to very narrow design regimes and applications, the purpose of this book is to examine each material in an orderly fashion to promote an understanding of the special characteristics of the material itself and to apply the information to the peculiar requirements of spacecraft and its unique operating environment. To design, test, and thereafter choose a suitable space vehicle material often requires several unique aspects peculiar to these spacecraft applications mentioned. In this introductory chapter, we will outline some of the basic considerations of material behavior so that the reader can appreciate both the complexity and uniqueness of this most complicated kind of problem.

12. Analytical Study of Spaceflight Materials: Case Studies

12.1. Introduction to Spaceflight Materials

Materials used for spacecraft must fulfill very stringent requirements. They must be strong and capable of withstanding the high forces to which they are subjected during launch, and highly resistant to fatigue and degradation in the hostile environment of space. For example, metals used in satellite structures must be particularly stable in space conditions, and plastics such as polycarbonate are preferred for use in space due to their superior resistance to both gamma and ultraviolet radiation, as well as their bond strength, toughness, and optical properties. Space applications require that materials should be as radiation resistant as possible in order to minimize replacement, maintenance, or downtime. To anticipate and prevent such costly failures, a range of analytical techniques is being developed to accelerate improvements in material specifications. The overall objectives of current spaceflight materials research are to develop more accurate life prediction methods and enhance associated design practice, as well as identifying and initially developing new materials that might bring substantial performance benefits, such as improved radiation resistance.

This chapter looks at the use of materials and space structures in very low Earth orbit for the special environment of the International Space Station. It reviews, in turn, the space environment, the radiation environment and its causes, the sources of particle flux and energy, the space environment due to natural causes, the interaction of the particle and environment with materials, the physical processes of material degradation, the processes and materials degradation of electronic equipment carried in the space environment, transistors, and the radiation environment. The last section introduces the biological impacts of space weather as a result of the interaction of the space environment with spacecraft and space passengers and experiments.

12.2. Importance of Materials in Spaceflight

Material selection for a specific application is known to be among the performance-limiting factors for the safety and success of spacecraft. The appropriate selection reduces to a minimum both mass and payload volume, which are ultimately relevant to extraterrestrial missions. In Earth orbit, however, such parameters are crucial for setting the mission lifetime and maintaining it in operation. Mass significance is attributed to reducing the launch cost, a fundamental issue for commercial space utilization. The effects of weight in connection with structural performance depend in part upon the materials used in the spacecraft structure. Those materials must serve in wide limits of temperature, radiation, atomic oxygen, and micrometeoroid and space debris to endure the stiff, combined requirements of the extraterrestrial environment.

13. Spaceflight Longevity of Solar Panels

13.1. Introduction

The longevity of space solar panels (SSPs) under the combined influence of thermal cycling, ultraviolet, and charged particle radiation, as well as micrometeorites and atomic oxygen, will determine the service lifetime of future space missions. The photovoltaic arrays used on current-day spacecraft have, in general, shown a reasonable in-orbit operational lifetime but are not designed for very long missions in harsh radiation environments. Twenty to twenty-five-year mission lifetimes may be part of the planning horizon for at least some future space missions, but industry has little experience base with long-duration high-voltage photovoltaic devices.

The voltage-current performance degradation mechanisms of a representative high-efficiency (triple junction) monolithic SSP have been investigated. The initial results show that potential power losses from dark-space limited voltage-current degradation are significant for missions lasting more than 5 years. However, at least for radiation-hardened single-crystal silicon wafers, the voltage-current performance degradation from moderate fluence electrical proton irradiations was substantially reduced compared to initial experiments. The long mission life degradation processes can be faster, slower, and/or additional from the mixed radiation environment of a given orbit of interest in comparison.

High-voltage monolithic multiple-junction SSPs have been flight-qualified with standard industrial materials. However, the standard high-efficiency triple junction SSPs have been qualified for space application using production techniques that were intended for low expectance laboratory lifetime like the SSPs on GeoSTAR, Space Technology Research Vehicle (STRV) 3, Military Communications Satellite (MILSTAR), Space Infrared Telescope Facility (SIRTF), Advanced Communications Technology Satellite (ACTS), and the International Space Station (ISS). The need to ensure the reliability of cost-effective high-efficiency SSPs for 20 to at least 25-year low-cost service lifetimes on such missions as the Space Solar Power Satellite (SSPS), SunTower-SI, Solar Electric Propulsion (SEP) vehicle, incipient phase of the solar cycle research probes, and the Solar Monitor Accelerometer Solar Electric spacecraft require more in-depth and comprehensive ground laboratory candid mission environment simulations.

13.2. Significance of Solar Panels in Spaceflight

Solar panels (SP), as a de facto power generator in space, serve as the cornerstone for all kinds of long endurance, long distance, and laudable physical ambitions and endeavors, such as satellites, space stations, probes, planetary rovers, and space telescopes. Furthermore, SP is the only means to generate electricity reposed on SC, to charge loads and recharge batteries, keeping power usage size and stability. Therefore, the robustness and durability of SP are essential under the harsh space environment. When designed, SP was suggested to fulfill the ideal service life of 30 years in Geostationary Transfer Orbit (GTO). Although SP has only serviced for 4 years in the GTO orbital region since the SJ series began to be launched in 2006, and SP lifespan is continuously promulgating, 30 years is far from the true service longevity of SP in GTO. The ambitious success of the Chinese Lunar Xisha with Chang'e 4 not only demonstrated that SP could fulfill its power supply No MTF (Mean Time to Failure), but also verified that SP with LEP (Low-Energy Particle) radiation-proof technology could ease the MTF life limit to sub-TLE (Trans-Lunar Injection) destiny.

The power leaf-likelihood that SP basked in the sunlight is usually proportional to the solar collector area and the optimal incident solar angle. Regarding GTO orbit, the incident solar angle converges on a fixed value, namely 2.67° for inclined orbit or 0° for geostationary orbit. Therefore, if an optimum irradiance could be maintained, SP sailing in the GTO route have everything they may need for fancy power production and a very long life together with their science experiment and exploration target companions.

14. Life Expectancy of Spaceflight Communication Systems

14.1. Introduction

Quantifying the expected life of a communication or other spaceflight system component is fundamental to the design of the system. It provides a measure of the likelihood that the system will be operational at some time after launch. It may be used as a measure of system performance. If at or near the end of the system's life (or earlier if there is a known life history), the system can be replaced before a failure. Replacement can be accomplished with, for example, redundant hardware on a spacecraft, or by a replacement spacecraft waiting on the ground. The data that is compiled from system histories can be used in many ways. A designer of a new system can rely upon these life data to select components that will have appropriate life expectancies commensurate with costs for what the project needs. Careers in the administration of space systems and management of future scientific missions can also be enhanced by understanding how long systems are operational.

A review of analysis methods and other means of estimating space system operational life has been presented, with emphasis on photovoltaic devices and systems. Two general lifespans have been used to review the life engineering data analysis/archival requirements (LEDA) database of space systems currently consisting of eighty-nine ballistic and communications satellite systems. These parameters are the time to 90% survival and the time at which fifty percent of the total failures to occur are expected. Specifically, the expected life of communication subcomponents PAN, PDA, TWT, VCO, LNA, and MMIC were extracted from several depth-of-impact studies. Pan performances remaining from six communication satellite systems were used to describe an empirical transponder performance model. Future missions wanting a specific probability of block success can use these performance functions to describe the effects of different subcomponent lifetimes on a low Earth orbiter communication payload design.

14.2. Communication Challenges in Outer Space

Space is often hostile to human life, yet it can be alluring, providing the backdrop for extraordinary explorations and scientific achievements. Space exploration and exploitation, such as inter-orbit satellite communications, excursions to the moon and Mars, and assembly of the International Space Station (ISS), could not have been possible without the existence of reliable and effective communication systems. Indeed, from the early Apollo era to the present, the role of space communications is as critical as it is central to a wide range of our space activities and endeavors.

While the magnitude, scope, and complexity of space communications systems have evolved with advancements in technology and knowledge, the basic elements of all communications networks have remained largely constant and straightforward. The essential goal and principal objectives of all space communications systems are to transmit signals from an originating earth station to a satellite or spacecraft in deep space, and if appropriate, receive signals or data transmitted back to the originating earth station.

Operating in space with its unique environment, however, can present significant and often extreme challenges to the provision of high-quality communication systems. The celestial profile of outer space, coupled with the fundamental attributes of spacecraft communication systems, makes outer space an unusual and often treacherous medium for implementing and sustaining communication missions. Extreme isolation, great distances, high-velocity objects, severe propagation issues, power constraints, limitations due to orbital rotation, real-time operations, and conflicting demands on precious resources are just a few of the quandaries facing satellite and spacecraft communication systems. As a result, the provisions and designs of communication systems for space applications must contemplate these characteristics and such inherent concerns and constraints, often viewing, establishing, and maintaining contact with spacecraft as the ultimate in remote network access.

15. Scientific Discoveries from Returning Hardware Flown in Space for Extended Periods

15.1. Introduction

Returning spacecraft that have been flown in space for extended periods contain much relevant scientific information that tells us much about the environment in space and its effects on virtually all materials, biological, microbiological materials and systems, cosmic radiation, and man-made environmental conditions of people and the spacecraft in space. This information should be obtained, inventoried, cataloged, and the information refined, summarized, and utilized. Data and refined information on specific topics and issues may save substantial time, risk, and money in developing future spacecraft for specific missions, cargo, and crew, and should encourage the proposal of potential new experiments. In the cases of biological and microbiological matter and systems, data and research may minimize or eliminate potential health risks and hazards for people at work and play in space, and for the general population on the spacecraft itself and Earth.

Returning, specifically reused spacecraft, behave somewhat differently than spacecraft specifically designed for multiple use and reuse. Additionally, experiments located externally on utilized modular-type spacecraft structures might also have somewhat different direct and indirect influences from the environment in space. It is important to recognize these relationships so that all relevant information can be obtained, interpreted, and properly utilized. It can be predicted that essentially no future space program effort will be completely efficient if this approach is not fully incorporated and utilized.

15.1.1. Background and Significance

Scientific discoveries of new knowledge are being accomplished by the science payloads flowing on Mir and Shuttle, space station projects of the future, free flyer spacecraft such as Hubble, etc., and the lunar and Mars rovers. for a discussion of the seven fundamental elements of scientific progress - measurement, validity, relevance, interaction, acceleration, abstraction, and prediction. There is a new frontier to this type of new knowledge activity called "human response to space", which involves the acquisition of basic information on how the human body deals with the space environment at the level of operationally feasible and sustained space experience. Although more bits and pieces of "human response to space" can be obtained from each new flight in microgravity, biological science no longer supports the father fig leaf of having enough hard quantitative data from the months or years of in-flight experience by humans to be able to understand and to rigorously model changes that occur simultaneously in all the body subsystems that are potentially affected.

15.2. Physical Changes in Materials and Structures

To better comprehend the fundamental physical changes in materials and structures as a result of being returned from space, extensive space experiments have been conducted over the past decades with the return of a multitude of payloads, including crystalline solidification of molten phases, casting of non-metallic semiconductor materials and photoconversion solar cells, thermal protection tiles returned from the leading edge of the spacecraft, heat sink fins, rail gun components, and more. Processing conditions for these space experiments included elevated temperatures all in ultra-high vacuum, external application of large normal, shear, or tensile force, and the use of light-emitting diodes and lasers. Analysis of the returned samples was conducted with a variety of chemical and structural tests, such as ellipsometry, X-ray reflectivity, X-ray diffraction, SEM/EDAX, and transmission or scanning beam-type optics.

These extensive space experiments provided new knowledge on the understanding of residual background gases left in the crucibles or evaporator sources, the generation of a degree of perfection at the interface of mixed metal glasses, and the effect of impulse tensile loading in the dislocation structure and microstructures of magnesium crystals. These new findings have generated numerous new models for adhesion that triggered the development of new material and bonding technologies used in the aerospace and commercial sectors. With the recent advancement of the Human and Statistical Unified Thermodynamic of Bernal-Fowler-Cybulsky-Mackerel-Moore-Bernal model, along with the inherent limitation on earth-bound microgravity analogs, additional fundamental knowledge could be generated on the current states of the physical processes unique to ultra-high vacuum when the samples are cooled back to room temperature from liquid temperatures so that new criteria to properly evaluate the extent of model accuracy could be developed. Only then will these valuable tools be recommended for use where the glass transition temperature is approximately less than 0.6 Tg, and when the glass-forming liquid is below the upper critical temperature of the continuous casting rate Isokawa-type model.