Requirements for A Vacuum Chamber to Replicate the Space Environment

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Space weather presents unique challenges for aerospace systems. The space environment introduces several factors that must be considered throughout the entire mission lifecycle of a spacecraft, from design to implementation. These factors include vulnerabilities due to radiation exposure, high energy particles risking astronaut safety, and single event upsets of onboard electronics. To be able to accurately test equipment and spacecraft for the space environment, a combination of physical simulations and computational modeling is required to replicate the harsh conditions beyond the Earth's atmosphere. An effective method for simulating these conditions is through the use of a plasma vacuum chamber which creates a high-vacuum environment while introducing charged particle interactions similar to those experienced in space. The authors propose a design for a space environment testing facility, namely a plasma vacuum chamber, to conduct experiments that enhance spacecraft design and increase the widespread use of space weather instrumentation. The general criteria for the chamber are investigated, including chamber dimensions, necessary vacuum, and pump type. Planned projects for this space environment replica, from spacecraft materials to instrument testing, are presented to indicate what modifications would be necessary to create an accurate model. These modifications are further explored to create a finalized list of requirements for the vacuum chamber. This finalized list includes a vacuum chamber and pump system that can provide a space-like vacuum, an electron source to replicate suprathermal and energetic electrons, a proton source to simulate solar energetic particles, a system to create a controlled magnetic field, and instruments to measure the levels of these sources.

I. Introduction

Space weather refers to the dynamic conditions in space, driven by the Sun's activity, including solar wind, radiation, and geomagnetic disturbances. These phenomena interact with the Earth's magnetosphere, ionosphere, and thermosphere, potentially affecting both spacecraft and ground-based systems [1]. Key phenomena include coronal mass ejections (CMEs), solar flares, and solar energetic particles (SEPs). Each of these space weather phenomena contribute to the extremely harsh space environment, each posing unique risks to spacecraft systems. Beyond the direct influence of the Sun, there are additional challenges in the space environment itself, including extreme temperature fluctuations as well as constant exposure to high levels of ultraviolet (UV) radiation. Space weather events can be difficult to predict. Currently, to mitigate these risks, forecasting models and space weather monitoring systems play a crucial role in predicting solar activity and warning spacecraft operators. By predicting these events, protective measures can be implemented to help mitigate the impact. Such measures may include adjustments to spacecraft orientation or orbit, entering safe modes of operation, or activating onboard shielding systems.

The extreme and unpredictable space environment poses significant challenges to spacecraft through its ability to degrade materials, interfere with electronics, and cause serious damage to spacecraft. Charged particles from space weather events can lead to critical failures, including single event upsets (SEUs), single event errors (SEEs), and spacecraft charging. These particle interactions can directly penetrate the onboard systems, potentially causing catastrophic damage to communication platforms, navigational systems, and, in extreme cases, complete loss of spacecraft life. Resulting anomalies can include: bit flips in memory cells, software malfunctions, navigational errors, and damage to solar arrays [2]. Space weather can also result in life or death for astronauts as a result of radiation penetration, leading to the complete failure of a mission. The damage caused can be detrimental to mission objectives and spacecraft functionality. As we advance toward farther and longer-duration space missions to the Moon and Mars,

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the risks become even more critical as we leave the protections of the Earth's magnetosphere-ionosphere-thermosphere, exiting geostationary orbit. Therefore, designing for these challenges requires careful consideration of space weather effects to ensure resilience and mission success in any scenario [3].

Testing for the modified environments that these spacecraft may experience is critical to improving our understanding of space weather, its effects on spacecraft systems, and spacecraft design. Small satellites have been designed to minimize weight, volume, and cost, often at the expense of shielding, reducing their ability to withstand space weather. As small satellite programs propose longer-duration missions, ensuring their survivability against radiation, extreme temperatures, and charged particle interactions becomes even more critical to extending their operational lifetimes [4].

The motivation for developing a vacuum chamber to simulate the space environment within the Space Weather Impacts Forecasting and Transit (SWIFT) Lab at the University of Florida is to advance our understanding of how spacecraft materials and systems respond to space weather conditions, as well as to study the behavior of the space environment itself, including plasma interactions and charged particle dynamics. The design criteria and instrumentation details of the Space Environment Vacuum Chamber (SEVC) are outlined, with the goal of initially simulating Low Earth Orbit (LEO) conditions and progressively advancing toward replicating the deeper space environment. These testing capabilities will allow one to evaluate radiation shielding effectiveness, material durability, and instrumentation in response to various effects of space weather.

II. General Criteria for a Space Environment Vacuum Chamber

The experimental setup of a vacuum chamber that models the space environment can vary greatly depending on the requirements of the project being conducted. However, there are some core demands that remain consistent regardless of the experiment. These base requirements are tied to the vacuum chamber itself, including size and layout, vacuum capabilities, and temperature control. For the initial nominal setup of the SEVC described here, we have chosen to focus on creating conditions similar to LEO, as opposed to other orbits, as this is the predominant orbit for small satellites.

The inner and outer dimensions of a vacuum chamber greatly impact the possible uses of said chamber. Large chambers have higher power requirements and maintenance needs, whereas smaller chambers have a limit on the variety of experiments that can be conducted. In order to properly conduct future space environment experiments, the SWIFT Research Lab decided that the SEVC will have the internal dimensions of 20" X 20" X 28". This allows the SEVC to be small enough where SWIFT Lab can properly maintain the chamber, while still sufficiently large enough to house a 16-Unit CubeSat, allowing for the full range of desired testing discussed in this paper.

The ambient pressure at LEO ranges from 1×10^{-10} Torr to 5×10^{-8} Torr [5]. In order to properly model the space environment, the vacuum chamber must create sufficient vacuum to fall within this range, therefore requiring a high vacuum pump that can reach at minimum 10^{-8} Torr. A dry vacuum pump is preferred as it runs oil-free, ensuring that the SEVC stays sterilized, thereby reducing maintenance needs.

Spacecraft in LEO experience a wide range of temperature extremes, ranging from –65 ºC to +125 ºC depending on spacecraft orientation and location with respect to the Sun and shadows from the Earth [6]. Despite these volatile temperature changes occurring naturally in LEO, when modeling the space environment, a stable and controlled temperature is desired. Uncontrolled temperature and shifts can interfere with experiments and can alter findings. It is for this reason that despite the real-life inaccuracy, the SEVC includes a temperature controller. A temperature controller that can bring the chamber to and maintain any temperature ranging from –75 ºC to +250 ºC is recommended as it would allow for testing in any temperature that can occur in LEO. A depiction of the SEVC's nominal hardware is shown in Figure 1.

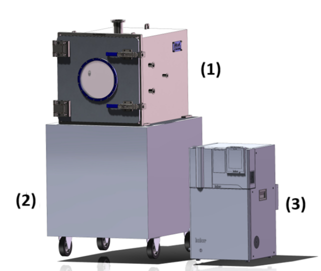

Fig. 1 CAD model of the SEVC: Chamber (1), stand (2), and temperature control unit (3)[7, 8].

III. Overview of Projects to be Conducted with a Space Environment Vacuum Chamber

There exist a multitude of uses for a vacuum chamber that can accurately model the space environment regarding both spacecraft development and space weather monitoring. The following depicts a few projects that the SWIFT Research Lab has planned with the SEVC.

A. Materials Testing

1. Spacecraft Radiation Shielding

It is of high importance that a spacecraft be properly equipped with shielding from the hostile space environment. Each spacecraft launched into orbit has an important mission assigned to it. Improper shielding from radiation means that during a space weather event a spacecraft payload or sensitive electronics can be damaged by SEPs, leading to premature mission failure.

There currently exist multiple commonly used materials for the purpose of spacecraft radiation shielding, the most common of which is aluminum and the most effective of which is Atomic number (Z) grade (Z-grade) material [9]. The SWIFT lab has plans to use the modeled space environment to test both Z-grade and other composites to continue developing more effective radiation shielding solutions. While aluminum has been a commonly known choice due to its lightweight nature, structural reliability and ease of manufacturing, its effectiveness against high-energy ionizing radiation is limited [10]. In contrast, composites are lightweight, durable, flexible and have a superior strength to weight ratio, while demonstrating superior radiation resistance capabilities. They also have low coefficients of thermal expansion, making them more stable to the extreme temperature fluctuations in space [11]. Z-grade is a sandwich composite composed of multiple layers of metals with different atomic numbers. By alternating between low-Z and high-Z materials, Z-grade manages to cuts down radiation energy significantly. Higher atomic number materials provide greater shielding effectiveness [12, 13]. Additionally, advanced composites such as hydrogen-rich polymers, including polyethylene, and plasma treated composites, including carbon fiber reinforced polymer (CFRP), have been utilized due to their potential to mitigate secondary radiation while maintaining mechanical properties[14]. Plasma treatment enhances adhesion and structural integrity, further improving their effectiveness in radiation shielding applications [15].

By testing composites in the SEVC, the Swift Research Lab will be able to validate their strength in the space environment. These composites can also be adjusted to better meet design requirements by altering the composite's matrix and fiber composition, optimizing the composite for radiation resistance, thermal stability, and mechanical performance [16]

Despite composites' effectiveness as protection from radiation, the cost of creating these composites is high due to their intensive processing. The cost of manufacturing only increases when the composite has to be custom shaped to fit hard to shield locations. It is for this reason that the SWIFT Research lab is looking to use the SEVC to test additive manufacturing materials' space weather resilience. There are current plans to test Polylactic Acid (PLA), Acrylonitrile Styrene Acrylate (ASA), Polycarbonate (PC), and Polyethylene Terephthalate Glycol (PETG) with metal components/mix-ins. If these materials prove to provide effective radiation shielding, then the cost of keeping spacecraft protected would decrease significantly. Difficult to manufacture custom radiation shielding panels could be replaced by simple 3D printing.

2. Solar Cell Coverglasses

SEPs can damage the solar cells that spacecraft use for power generation. Coverglasses can be secured onto solar cells to shield from SEPs and prevent solar cell degradation. The SWIFT lab is looking into testing how different types of coverglasses and UV coatings protect solar cells from damage in the SEVC. This would allow for research into the most effective combination of coverglass and coating types for the best degradation prevention.

B. Space Weather Instrument Testing

Most space weather monitoring instrumentation currently in use is restricted to large, space weather specialized spacecraft. This results in a lack of widespread on-board monitoring amongst all spacecraft. If a light-weight, simplified space weather monitoring instrument was developed that could be used on small satellites, like CubeSats, then a more reliable and in-depth understanding of the current state of the space environment would be gained. This would allow for the improvement of space weather forecasting through constant and accurate instrument readings. The SWIFT Research Lab has plans in place to work on developing this monitoring instrument. The SEVC would be used to test said instrument's abilities to accurately detect SEP levels and determine its functionality.

C. CubeSat Testing

Launching a spacecraft into orbit is a lengthy and expensive process. It is for this reason that a spacecraft needs to be properly prepared to function in the space environment before its launch. The SWIFT Research Lab will partner with other members of the UF Astraeus Space Institute, and other academic labs and teams to use the SEVC for environmental tests of instrumentation and small spacecraft, such as CubeSats, to test they operate properly in high vacuum and extreme temperature environments.

IV. Project Specific Criteria for a Space Environment Vacuum Chamber

A. Electron Source

Energetic electrons are a type of SEP that contribute to solar ionizing radiation. The typical range of energetic electrons can vary from a few keV up to a few MeV [17]. The interplanetary solar wind also includes suprathermal electrons, which can range from 60-70 eV through hundreds of eV and are far more common than energetic electrons. High-energy electrons can breach through the shielding of a spacecraft and bury themselves in the spacecraft's electronics, discharging and creating permanent damage [18]. Their radiation can also lead to surface degradation and cause components to become radioactive. Due to the significant role and impact of energetic electrons on space weather, accurate tests of the space environment should include energetic electrons [19]. Suprathermal electron prevalence in the everyday background space environment also warrants their inclusion in the SEVC. The SEVC introduces these electrons through the use of an electron beam gun. This electron source has the ability to produce electrons in the range of 200 eV to 30 keV, spanning both suprathermal and energetic electron ranges, with a uniform flood spot size of 15mm to 500mm, allowing for the full coverage of the SEVC with electrons.

Due to the damage that energetic electrons can cause, in order to accurately assess how well a material shields from space environment radiation the electron source must be included in the SEVC during materials testing. In spacecraft radiation shielding testing, the electron source at high energy output, 30keV, and wide spot size, enough to fully envelop the material, would be aimed directly at the test material. The amount of radiation that breached that material would be measured along with the material's general composition and state after exposure to radiation, determining the material's compatibility with the hostile space environment. The setup used for materials testing is mimicked for coverglass testing, however solar cell degradation would be measured instead of radiation breach.

To properly calibrate and test a space weather monitoring instrument, the SEVC's electron beam would be used through its entire range of energy levels with a small spot beam aimed specifically at the instrument. Using the entire range allows for the development of both a suprathermal electron instrument and an energetic electron instrument. Knowing the electron beam's output would allow for a comparison and test of the instrument's reading accuracy. With this test, any calibration or adjustments would be possible to assure the instrument's functionality prior to launch.

B. Proton Source

Solar energetic protons are another class of SEPs. They are energetic and high energy protons that are primarily accelerated by solar flares and CMEs originating at the Sun. [20]. The typical energy range of protons can be from 20 to 80 MeV with extremely high events exceeding this range. While these more extreme events are relatively rare and occur mainly during solar maximum, high energy level events can pose significant risks by interfering with electronic systems, material surfaces, and significantly affecting spacecraft operations. Due to these potential risks, modeling and testing their effects in the SEVC is important.

To simulate solar wind plasma a low energy proton source can be employed to replicate key characteristics of solar wind protons including their bulk velocity, density temperature, and energy [21]. Bulk solar wind protons are on the order of 0.5 to 10 keV. To achieve this there are plans to make a bulk proton source using a penning trap, which utilizes a combination of electric and magnetic fields to confine and control protons, following for precise replication of solar wind conditions [22].

C. Magnetic Field Source

The dynamics of SEPs are governed by the magnetic field, be it the solar magnetic field in the solar wind or the Earth's magnetic field in the geospace environment. In order for the SEVC to properly model how SEPs will behave in space, the SEVC must have a controlled magnetic field. To achieve this there are plans to use a high precision energy source to power a Helmholtz coil. Helmholtz coils create a volume of uniform magnetic field in their centers [23]. This magnetic field has a defined and controlled strength, and adjustments can be made to cancel out the Earth's magnetic field, creating an accurate model for space in the SEVC.

The generated magnetic field would be used in conjunction with the proton and electron sources for solar wind tests by adding bulk plasma particles, whether electron or proton. For space instrument testing, since the magnetic field inside the Helmhotlz coil is known, the readings from the instrument can be cross compared with the actual magnetic field strength to determine instrument accuracy. In CubeSat testing, a controlled magnetic field can be used to predict how the small satellite and its electronics will react in a varying magnetic field.

D. Sensors

When materials testing in the SEVC, there needs to be a qualitative way to measure a material's propriety for the space environment. When testing coverglasses, the base solar cell's ability to produce power after exposure to energetic particles would be measured at uniform intervals of time. This would allow the SWIFT lab to measure a coverglass's effectiveness through its ability to prevent power degradation over time. However, radiation shielding tests require more intricate methods of measuring effectiveness. In order to measure how much radiation passes through each material there has to be a sensor placed behind said material. Due to its simplicity, cost effectiveness, and accuracy, radiochromic sheets will be used as sensors in initial spacecraft materials radiation shielding experiments. Radiochromic sheets react to ionizing radiation and change shades depending on the dosage they are exposed to [24]. The change in shade can be analyzed using a film scanner and specialized radiochromic analysis software to determine how well each material shields from radiation. Figure 2 depicts EBT3 Gafchromic® Film being used in a medical setting to measure the dosage of radiation that crossed patient shielding, mirroring what would be done with spacecraft materials in the SEVC [25].

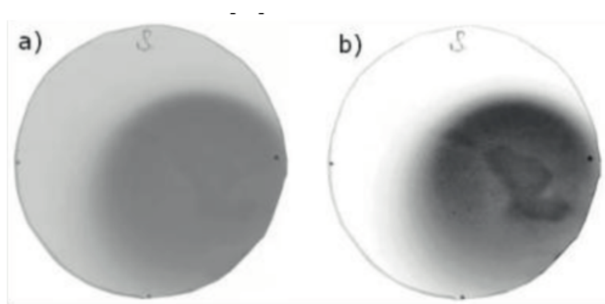

Fig. 2 a) Original image; b) Enhanced dishomogeneities [25].

V. Conclusion

An overview of the SWIFT Research Lab's SEVC was discussed and a schematic of the SEVC's setup is depicted in Figure 3. In order to create a moderately accurate space environment model, the SEVC requires a vacuum of at minimum 10^{-8} Torr, temperature control for any temperature ranging from –65 ºC to +125 ºC (although a wider range is recommended), an electron beam gun or any electron source capable of replicating the common energy levels of suprathermal and energetic electrons, proton sources that can replicate solar energetic proton events and solar wind protons, a Helmholtz coil and stable power source to control the magnetic field in the chamber, and sensors tailored to the experiments being conducted. Research into the effectiveness of the SEVC will be conducted as its planned projects are carried through and completed.

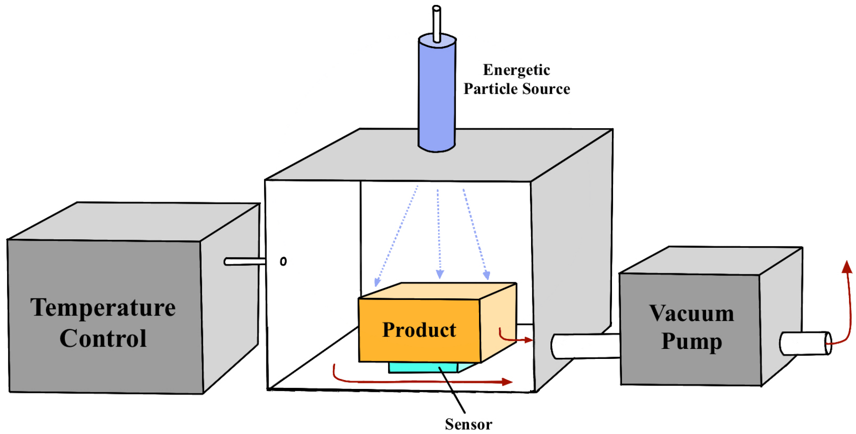

Fig. 3 Scheme of the SEVC

The SEVC offers a small lab solution to modeling the complex space environment. The SEVC's use is rooted in its feasibility and ability to create opportunities for a variety of space environment experiments and testing.

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