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**Abstract:** Spacesuits are highly valuable artifacts made of sensitive synthetic materials, including rubber, polyvinylchloride, polyamide, or polyurethane. The main concerns for preservation are off-gazing from the objects themselves and the exterior agents of deterioration humidity, high temperature, UV radiation, and visible light. This study addresses the implementation of preventive conservation in the Deutsches Museum spacesuit display and the evaluation of the atmosphere with monitoring methods. The focus lies on innovative RFID corrosion sensors developed by the Lab-STICC and used in an exhibition for the first time. In addition, commercial devices (climate logger, UV and light meters, infrared thermal imaging) were used to check the conditions in the spacesuit showcase. The source for off-gazing coming from a suit could be located through the sensors, and the low corrosivity inside the showcase showed the effectivity of the installed charcoal absorbers. Humidity, however, was unable to be reduced to the recommended 30–40% in the large-scale showcase with silica gel. The LED lighting in the dark exhibition excludes any harmful high-energy radiation, but thermal radiation is produced by lighting and electrical devices. The applied methods were effective in evaluating the current situation in the exhibition and form a good basis for future improvements on the display.

**Keywords:** environmental corrosivity; air quality; monitoring; preservation; spacesuit

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## 1. Introduction

Air pollution monitoring is of crucial interest for the conservation and protection of historical artifacts in museums. In this study, the emphasis is put on pollutants, light, and climate, based on previous studies into the causes for damage on the Sokol-KV2 spacesuit in the Deutsches Museum [1]. Other agents of deterioration [2] could be prevented or blocked by the exhibition installations. During display preparation, all objects are surface cleaned and visually inspected for signs of deterioration, including microbiological growth.

Gaseous pollutants in the air are responsible for the degradation of many types of objects and materials. They are of diverse nature (organic acids, ozone, $H_2S$, $NH_3$, $SO_2$, $NO_2$, etc.) and are produced either internally in the building and in artifacts or externally due to outdoor pollution [3]. Internal pollution is a quite complex problem since it involves many pathways of volatile compound formation such as evaporation of solvents, off-gazing from construction or furnishing materials in the museum, and degradation of objects. Museum staff and visitors, as well as personal care products, are also a source of pollution. Typical signs of pollutant-induced damage in spacesuits are, e.g., corrosion of metal parts, formation of crystals, discoloration of the material itself, and adjacent object components [4]. The problem is amplified in showcases in museums since, in comparison to outdoor conditions, they create microclimates. Only traces of pollutants can accumulate in such areas, leading locally to high corrosivity levels. For spacesuit display construction, materials with verification of low-emission are chosen: powder-coated metal, glass, silicone-based sealants, adhesives, and medium density fiberboards (MDF) B1. Some materials used in the objects, such as rubber, polyvinylchloride (PVC), or polyurethane (PU), emit pollutants themselves and thereby contribute to contamination inside the showcase.

High temperature and electromagnetic radiation (UV radiation, blue visible light) significantly increase degradation rates, mainly in organic materials [5,6]. High humidity levels lead to hydrolysis in synthetics, corrosion of metal, and microbiological growth [7], which can highly affect the preservation of spacesuits. By-products formed in chemical degradation reactions or released additives then play a role in pollutant formation [4].

Consequently, it is of worldwide interest to provide effective monitoring solutions in museums that include pollutants, temperature, relative humidity, and light monitoring. Commercial sensors or monitoring systems dedicated to the measurements of temperature, relative humidity, and light exist and can be applied to museums. In contrast, concerning air pollutant monitoring, most of the commercial solutions are limited, in particular due to their cost. Recently, a cost-effective solution affordable for all museums including small ones was proposed to evaluate the indoor corrosivity (IC) level. It is based on the development of low-cost and low-visual nuisance RFID (radiofrequency identification) corrosion sensors [8], which detect a metallic loss of sensitive materials such as silver or copper and thus the IC index from standards [9]. This novel technology was successfully tested in storage and conservation rooms [10,11]. However, its application to real museums open to the public has never been proven, and some related questions arise. In particular, the possibility to install these autonomous sensors in showrooms and to interrogate them from outside is a challenge. One of the aims of this study is to prove this statement and thus the ability of this method to be deployed in real environments.

For this purpose, the Deutsches Museum Munich, Germany, was selected. It is one of the largest technical history museums worldwide with a great variety of objects and tasks for preservation. A multiple-year renovation process at the Deutsches Museum entailed a re-design of the permanent exhibitions from 2015 until the re-opening in July 2022. In the present study, the display of historic spacesuits and pilot suits, which is a highlight of the permanent exhibition "Astronautics" at the Deutsches Museum, was selected. The objects inside the spacesuit showcase are presented in Figure 1. They were produced in very low numbers and are therefore very rare, due to the complexity and enormous costs of a program to bring humans into space. Spacesuits are connected to the rapid technological development of custom-made pressure suits for the space race between Russia (the former Union of the Soviet Socialist Republic (USSR)) and the United States of America (USA), but also the increasing international cooperation between the nations. While the vast number of American suits remain in the USA today [12], space-related artefacts from the USSR became available on the free market after the fall of the communist regime [13]. Due to the extremely high manufacturing qualities and the association with space, with astronauts or with important historical events, spacesuits have a high monetary but also emotional value for society. In the museum, they represent a great opportunity to educate about the history of space exploration, technical textiles, the development of synthetic polymers, solutions to survive in hostile environments, or the iconic aesthetic of spacesuits, to name only a few topics [14,15]. Researchers worldwide are currently working on new models to be used on the surface of other celestial bodies, such as the Moon or planet Mars [16]. Their work is deeply rooted in the findings of earlier generations, and it might even benefit from the research on the long-term preservation of artifacts in the museum because space travel is planned to last longer and lead outside the protective field of Earth.

**Figure 1.** View into the exhibition area of the spacesuit showcase at the Deutsches Museum.

In a previous investigation of air corrosivity, an observation of color change in a Sokol KV2 spacesuit in the museum was observed [17]. A test with metal coupons (Ag, Cu, Pb), positioned inside the suit for some weeks, indicated off-gazing from synthetic materials [18]. A further XPS (X-ray photoelectron spectroscopy) analysis of silver coupons revealed the presence of sulfur-based pollutants in the showroom [17]. The present study aimed at providing additional information on the spatial mapping of the IC index in the museum. For this purpose, several RFID silver sensors were positioned and interrogated by the Deutsches Museum staff in the described showcase and outside. Commercial temperature, relative humidity, and light sensors were also used since these parameters are critical concerning the degradation of artefacts. As it will be shown, despite the correct environmental conditions in terms of humidity, temperature, and light, a source of production of pollutants was indeed detected in the showroom. However, the presence of pollutants is very localized, and its concentration vanishes rapidly when moving away from the source, certainly due to the presence of absorbent.

More generally, the aim of this study was thus to develop a monitoring program for exhibitions, individually tailored to the sensitivities of the objects and the environmental conditions on site. To make this approach feasible for collections in other museums, the selected monitoring methods should be easy to implement, need low-maintenance actions, are cost-effective, and are used by un-experienced museum employees. The following questions guided the research process:

- Are RFID air pollution sensors suitable to assess the effectivity of absorbers and ventilation in showcases?
- What is the indoor corrosivity (IC) class in the different locations inside and outside a showcase?
- Are the chosen light sources in the exhibition and in the showcase free of ultraviolet light, as stated in the product description?
- Can the low light levels recommended for spacesuits be attained and the visibility of technical details of the spacesuits still achieved?

- Were the required climate parameters achieved and when?
- How can influences on the room temperature, such as thermal bridges, lighting, or heating/cooling systems, be connected to the information of temperature measurements?
- Is passive climate control with absorbers efficient enough to reach and maintain relative humidity levels of 30–40% in a large showcase?

## 2. Materials and Methods

The materials for this study include objects and exhibition installation on the one hand and the monitoring equipment on the other hand.

### *2.1. Description of the Objects Present in the Showroom*

The display of spacesuits in a large showcase provides an overview of the protective clothing to survive in the hostile environment of space. A picture of the showcase is presented in Figure 1. The storyline starts with the origins of the technology in pilot pressure suits, from which the intravehicular (IVA) suits, such as the displayed Sokol-KV2 derived and ends with equipment for extravehicular activity (EVA) to be used outside a pressurized spacecraft. The sleeping bag also presented in the showcase is used in the low-gravity environment of a space station. A detailed description of objects is provided in Table 1.

**Table 1.** Exhibits from the Deutsches Museum space collection and loans from NASM as displayed in the showcase (from left to right). Suits with a multi-layered construction are highlighted in grey.

| Object | Type | Accessories | Date | Place |
|---|---|---|---|---|
| Partial pressure suit | | Separate helmet, gloves, cap, and shoes | 1966 | USSR |
| Full pressure suit | Mark IV | Separate helmet and shoes<br>Removable gloves | 1963 | USA |
| Liquid-cooling garment | | Separate urine bag and fecal bag (loans from the National Air and Space Museum) | 1968 | UK |
| Sleeping bag | | | 1986 | USSR |
| IVA pressure suit worn by Klaus-Dietrich Flade (MIR-92) | Sokol-KV2 | Integrated helmet,<br>Removable gloves, cap, and mirror<br>Associated shock absorbing seat "Kazbek" | 1992 | Russia |
| Liquid-cooling garment | | Integrated cap | 1985 | USSR |
| EVA ventilation test suit | Orlan-DM | Integrated helmet and LSS<br>Removable gloves | 1985 | USSR |

The suits are made of a variety of synthetic materials, metals, and some natural fibers (Figure 2), highlighting the presence of those materials in the showcase that are known for their potential to produce off-gazing [15]: polyvinylchloride (PVC), rubber-based adhesives (RBA), rubber, polyurethane (PU), and leather. The Mark IV, Sokol-KV2, and Orlan-DM suit furthermore show a multi-layered structure, with air-tight rubber-coated polyamide (PA) fabrics on the inside, which is restrained with another fabric. This kind of layer buildup favors the accumulation of off-gazing inside the suits. In a previous work, the materials, manufacturing techniques, and preservation of the Sokol-KV2 pressure suit were identified. Grzywacz, C.M. [19] reports the source of pollutants in museums. Vulcanized rubber and rubber-based materials are known to produce $H_2S$, $SO_2$, COS, $CS_2$, and $O_3$. Other compounds such as PVC lead to organic acid formation. The presence of these polymeric materials explain the odor observed in the showroom, indicating that the main area of concern is consequently the presence of air pollutants in the form of off-gazing and contaminants, which interact with other parts in close proximity. Previous XPS investigations of coupons demonstrate the presence of sulfide on silver materials, in agreement with Holzer et al. [17].

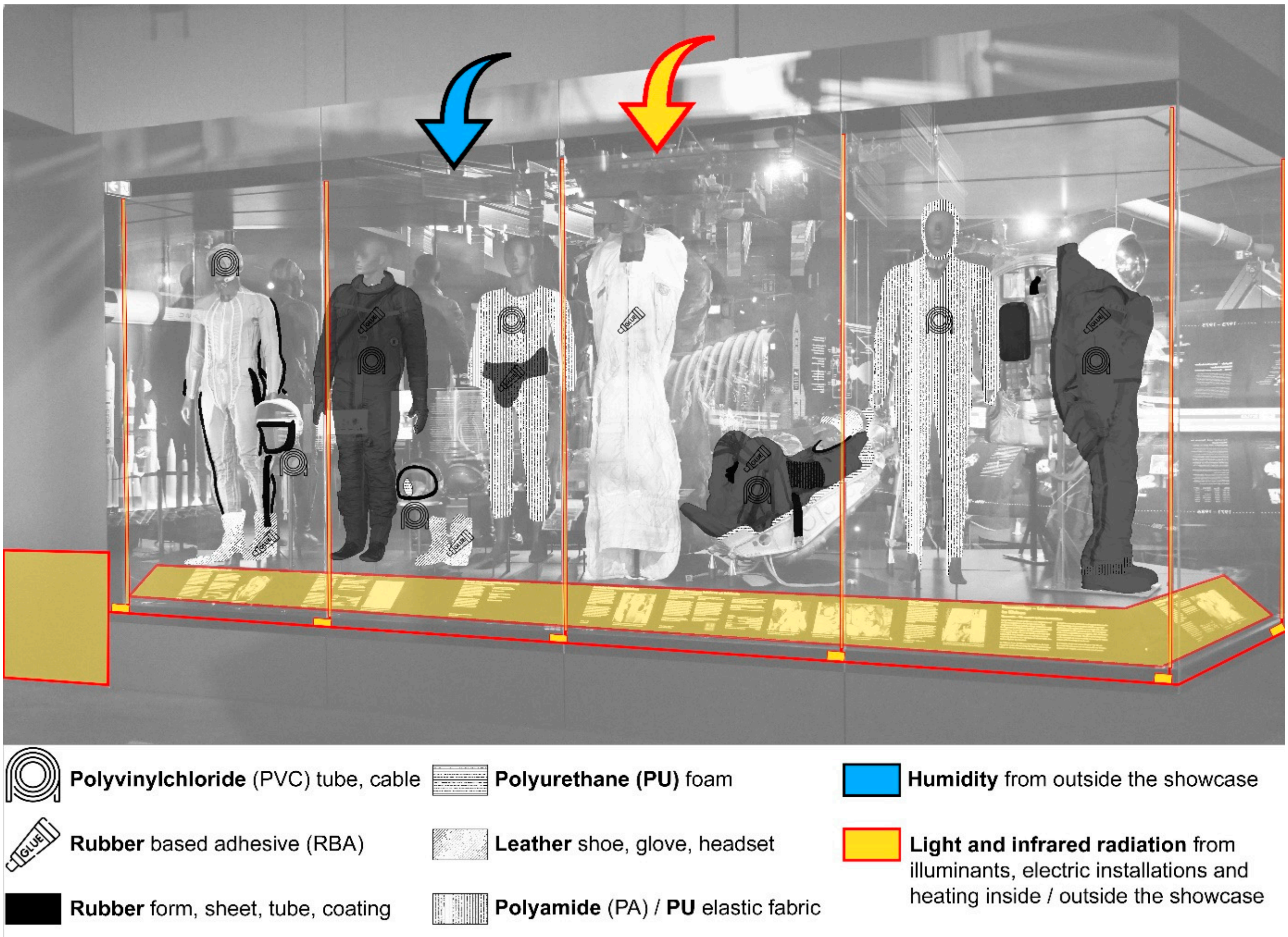


**Figure 2.** Sources of damaging factors in the exhibition from inside and outside the showcase with mapping of the most sensitive materials in spacesuits, PVC, RBA, rubber, PU, leather, PA, and PU. The arrows represent the influence of humidity and radiation respectively from outside the showcase.

The sensitivity of these materials to light also has to be considered. Indeed, radiation can break bonds in polymeric materials, thus leading to pollutant emission such as organic acids. Polyamide textiles and rubber-based materials are considered the most sensitive to light. High temperature furthermore accelerates their aging process, and very low temperatures lead to crystallization and embrittlement of rubber-based components. Humidity acts as a corrosive agent for metals and can react with pollutants, such as chlorides from PVC or sulfides from rubber.

*2.2. Design of the Exhibition for the Preservation of the Suits*

The key publications for the preservation of spacesuits come from the research conducted at or with the Smithsonian National Air and Space Museum (NASM), Washington D.C. Their requirements for the display and storage of spacesuits were derived from the fields of modern materials, metal, and textile conservation. The fundamental knowledge about the materials and their sensitivity is based on conservation science [5,20] and was also acquired through cooperation with production companies and other specialized air and space collections [4,12]. There is no comparable museum research published for spacesuits from other nations, except the project on the Sokol-KV2 suit from the Deutsches Museum [1]. Valuable information about the manufacturing of Russian spacesuits can be extracted from the works of Isaak P. Abramov and Ingemar A. Skoog [13] and the exhibition catalog "Cosmonauts: Birth of the Space Age" [21].

The recommended methods for the design of the spacesuit showcase, the mounts, environmental conditions, and monitoring in the exhibition are therefore based on the NASM requirements and were expanded by other impulses [22–24]. The current version of the Canadian Conservation Institute (CCI) website on "Agents of Deterioration" [2] and the DIN EN Norms on the "Conservation of Cultural Heritage" [25] were consulted for assessing and handling the damage factors pollutants, light, and wrong climate. Specific exhibition requirements for synthetic materials and rubber are provided in [5,26,27] and others. The main issues for preserving metal components in spacesuit joints, valves, and zippers were studied by Lisa Young [28]. In the field of textile conservation, a joint ICOM-CC working group meeting with the "Modern Material and Contemporary Art" group brought together key researchers to present the state of the art. The publication will be available at the end of 2023. The current knowledge and trends in "Museum Lighting" were compiled in the book by David Saunders in 2020 [6]. Marcus Herdin, the preventive conservator at the Bavarian National Museum in Munich, provided further input from practical experience in permanent exhibitions [29].

The spacesuits of the Deutsches Museum are displayed in the exhibition "Astronautics", which is located on the top floor of the aviation and space hall. It is a three-story building with an atrium connecting the ground to the uppermost second floor. The temperature in the museum is actively controlled by cooling-and-heating infrared panels on the ceiling and radiators (target value of 18 °C in winter, 23–26 °C in summer). The outside air entering the building through a ventilation system is filtered and can theoretically be humidified or de-humidified. However, the air exchange rate of 0.5–1.0 is too low to reliably provide the defined climate corridors. Climate sensors measure the exhaust air in the ventilation system. Whether the target value for relative humidity of 50% is achieved depends on the outdoor humidity and other preconnected areas of the museum.

The renovated rooms were newly refurbished with inorganic building materials, such as metal or glass, but also with a variety of synthetic panels, adhesives, sealing, and MDF boards that also can emit pollutants such as organic acids and formaldehyde [30]. Inside the showcase, humidity and pollutant levels are controlled with silica gel and charcoal absorbers, respectively (Figure 3), which are detailed in Section 3.1.


**Figure 3.** Absorbent materials in the showcase drawers to remove pollutants from the atmosphere (grey) and to buffer relative humidity (blue). See also the detail on the right. Control unit for the ventilators and dimming light on the left (yellow).

The space exhibition has no windows and is exclusively lighted with LED spots on the ceiling that have no UV radiation in their spectrum. A major goal of the renovation was to bring the fire protection up to date so the spacesuit showcase does not include any electrical supply lines inside the presentation area. To further highlight the objects inside the showcase, there are LED spots (1 Watt) fixed to magnetic electric rails, with the technical equipment for dimming outside the presentation area. The light level for the pilot and spacesuits was reduced to 30–100 lux, considering both the ceiling and the showcase spots.

### 2.3. Monitoring System

Monitoring of pollutants, light, relative humidity, and temperature is performed by various devices. Table 2 presents the selected methods. The approach favors in situ measurements that can be interrogated immediately and further interpreted with associated software or calculations. This study presents the baseline for evaluating the new exhibition and finding suitable methods to be implemented in the everyday museum life. The energy consumption of sensors is a crucial parameter since no electrical supply is present in the showcase. Autonomous sensors are therefore preferred and continuous measurements with, e.g., $CO_2$ monitors or corrosion monitoring, were excluded until the power supply was ensured. An assessment of airborne fungal contamination and the level of pollutant concentration inside the showcase were not conducted within the scope of the study.

**Table 2.** Methods for preventive conservation and monitoring of agents of deterioration.

| Agent of Deterioration | Preventive Conservation | Monitoring and Measuring Method | | Output for Evaluation |
|---|---|---|---|---|
| Pollutants | Conservation-grade materials in the presentation room of the spacesuits (glass, metal, sealants, adhesives)<br>Charcoal absorbers in showcase drawers and inside object mounts<br>Ventilation for air circulation in the showcase | Sensors<br>UHF-RFID reader<br>Smartphone with Bluetooth connection | Innovative RFID sensors based on silver reactivity<br>Convergence Systems Limited, CS108<br>Apple, iPhone 13 with CS108 RFID Reader application | Evaluation of the corrosivity class through resulting RSSI value |
| Light | LED lighting without UV radiation, dimmable | Light meter<br>UVA + UVB meter | Testboy, TV 333, Vers.1.0<br>Voltcraft® UV-500 (calibrated by the manufacturer) | Numerical value (lux, mW/cm) |
| Temperature | Heating–cooling ceiling and radiators in the exhibition | Infrared thermal imaging | InfraTec VarioCAM® HDx (calibrated by the manufacturer),<br>Software IRBIS® 3.1 | Thermal image |
| Humidity | Ventilation system | Climate logger | Testo® 174H (calibrated by the manufacturer),<br>Software ComSoft Basic v5 SP 6.4 | Variation of T, RH% with time. |
| | Silica gel absorber cassettes in showcase drawers (30–40%) | | | |

RFID sensors were used to define the IC level in the indoor condition in the museum. The latter ranges from ultra-low corrosivity level (IC1) to high corrosivity level (IC4). The principle of the sensors was described in detail elsewhere [8,10,11]. They are based on the electromagnetic coupling between a metallic sensitive thin film, which acts as a coupon exposed to a corrosive environment, and the antenna of an RFID tag. Corrosion of the metallic layer induces an increase in its electrical resistance and, hence, a change in the property of the coupled antenna. The signal strength emitted from the tag to the reader is then modified when corrosion occurs. This variation can be monitored by measuring the RSSI (received signal strength indication) by a commercial UHF-RFID reader. The sensor is constituted of two RFID tags: the reference and sensitive tags. The interrogation of the sensor is made by selecting a value of −47 dBm for the reference tag and by detecting or not detecting the sensitive tag. When a response is observed on the reader for the sensitive tag, it means that the remaining thickness of silver is 7.5 nm. An averaged corrosion rate over the exposure time and the IC level (middle, low, or ultra-low corrosivity) can thus be evaluated. In the present study, an initial thickness of 20 nm was selected to investigate the exposure time needed to corrode 12.5 nm.

Light and ultraviolet measurements were part of the exhibition installation process. The fitters/mount-makers arranged the LED spots, while the conservator controlled the radiation levels and adjusted the intensity by dimming the light. The technical compartment used to modify the light intensity is presented in Figure 3. In that way, details and special features of the exhibits could be highlighted and at the same time attain the accepted levels of illumination. Readings were taken directly on the surface of the objects in various locations and angles of incidence [6]. Light sensors used in the museum are defined in Table 3.

**Table 3.** Comparison of passive and active control methods for the showcase with around 20 $m^3$ volume (price request in October 2019).

| | Passive | | Active | |
|---|---|---|---|---|
| | **Pollutants** | **Humidity** | **Pollutants** | **Humidity** |
| Product | 10 m active charcoal fabric | 40 × 500 g silica gel boxes (1 kg/$m^3$, 30–40% r. h.) | 2 × air filtrations systems with ventilation unit | 2 × constant humidity generators with accessories |
| Price | Around EUR 500 | Around EUR 2000 | around EUR 500–900 | Around EUR 6.000–9.000 |
| Monitoring | No | No | No | Integrated humidity and temperature sensors |
| Maintenance | Periodic exchange | Control and re-conditioning every 3–6 months | Annual filter exchange (depending on monitoring results) | Send in every 2–3 years |
| Longevity | depending on monitoring results | 10–20 years | See above | Longevity under that of absorbers |

The distribution of thermal influences in the exhibition was documented with infrared thermography, which will be shown in the following chapter. Monitoring of temperature and relative humidity started in November 2022 with thermohydrograph devices inside and outside the showcase that were interrogated regularly. Variation of humidity and temperature was measured in the present study by Testo® 174H sensors.

## 3. Results and Discussion

The experimental results describe the implementation of recommended preventive conservation measures to preserve the spacesuits in the exhibition. By applying monitoring and control strategies, their effectivity was evaluated. Any necessary adjustments, based on this study, could mainly target the showcase and less of the surrounding building installation.

### *3.1. Installation of Absorbing Materials and Monitoring with Sensors*

For pollution and humidity monitoring in showcases, passive and active systems are available. Table 3 compares the characteristics of passive versus active approaches, as offered by two different exhibition technology suppliers. For air pollution monitoring, absorbents (charcoal) and air filtration units are proposed. In both cases, either the filters or the absorbents have to be replaced periodically. The cost of both solutions does not differ significantly. Neither of the solutions include measurements of air pollution. The main drawback of the active system concerns its integration within the showroom and the need for electricity. So far, no in situ comparison of pure and impregnated active charcoal has been conducted. Moreover, contrasting active with passive conditions as well as the influence of forced air exchange remains a future task.

For relative humidity, the passive solution consists of using silica gels with additional temperature/relative humidity sensors. In the active system, a constant humidity generator is proposed with integrated humidity/temperature measurements. In this case, the costs of both solutions differ significantly. In 2022, for the re-opening of the museum, as shown in Figure 3, the passive solution was selected. The spacesuit showcase was fitted with absorbing materials in four drawers underneath the presentation room and PC ventilators at the top. The deciding factors to choose passive pollutant removal and humidity control were their longevity; their integration in showrooms; and costs for acquisition, maintenance, and energy. To ensure a stable humidity condition, silica gel in drawers is conditioned to 30–40% relative humidity [31]. In regard to the recommendations of the NASM [4], the decision for purely passive control methods at the Deutsches Museum spacesuit display presents a compromise that was influenced by the exhibition budget and timeline. The results of this study are the baseline data for an informed evaluation and possibly a request for an optimization of the system.

The choice of passive pollutant and humidity control also meant that a separate monitoring program needed to be installed. Figure 4 shows the locations of the RFID sensors in the rooms. Tag #01 is located outside the showroom, while tags #02 and #03 are inside to evaluate the atmosphere around the spacesuits. RFID tag #03 was positioned inside the pilot suit Mark IV, between the outer restraint layer (PA) and the inner bladder (PA coated with neoprene rubber) [32]. Tag #02 is located at about 1.5 m from tag #01. The sensors were put inside black 3D-printed containers, in order to reduce their visual nuisance in the museum. Note that prior to the exposure measurements, the suitability of these locations was determined by placing test antenna tags in situ and interrogating them by the selected portable RFID reader.

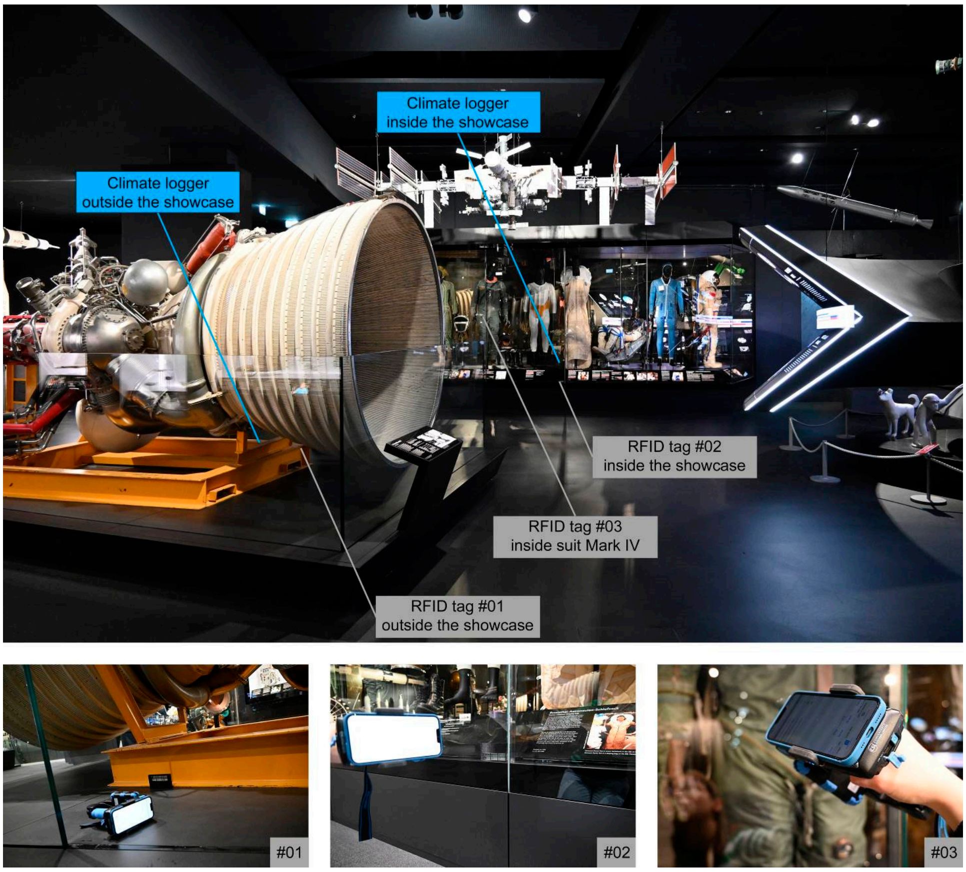


**Figure 4.** Location of the RFID tags #01–#03 and the climate logger in the exhibition (**above**) and the interrogation with the UHF-RFID reader at the three locations (**below**).

Over the five months of exposure, the sensors were interrogated weekly by the conservator, using the hand-held UHF-RFID reader. This device, shown in Figure 4, is connected to a smartphone and is placed during the interrogation at 30–40 cm in front of the tag. A major improvement of the method with respect to the first tests concerns the development of a specific mobile application. Some functionalities are depicted in Figure S1 of the Supplementary Material. As is seen, the application is used first to connect the mobile to the RFID reader by Bluetooth (Connect to the Reader). After this step, it is possible to detect the reference RFID tags responding in the close environment (Search for RFID Tags). To ensure a correct reading of the sensor, the reading distance has to be adjusted during this interrogation task to receive a RSSI value of the reference tag around −47 dBm. As shown in Figure S1 of the Supplementary Material, a green RSSI value on the phone indicates a correct interrogation phase. If the RSSI value is red, the reading distance has to be modified by the end-user. In the present case, one sensor is correctly interrogated, and not the two other ones. Since only a reference was observed on the application, corrosion of the metal thickness had not occurred. In the present case, it was possible to correctly interrogate the three sensors displayed at the bottom of Figure 4.

Tag #01 is close to a metallic object. This object could have an impact on the communication between the sensor and the reader. This was not observed, and the sensor was correctly interrogated during the whole period. Due to regular staff rotation, not every member of the museum guides and cleaning teams were informed about the ongoing research in the exhibition. Therefore, the location of the tag was changed during the test to a position where no further movement was possible. Interrogation of tags #02 and #03 was done through the glass of the showcase and so without removing the tag from inside the pilot suit. Interrogating such battery-less sensors at a typical distance of 50 cm during a very long exposure time is their main feature. Additional RFID sensors were tentatively positioned inside the showroom, and in particular in the drawer. However, due to the metallic shielding of the drawer, the communication between the tag and the reader was strongly reduced, leading to some difficulties during the interrogation task. This highlights the importance of providing RFID sensors well adapted to their locations. Work is currently in progress to provide RFID sensors less sensitive to the local environment. Embedding sensors in materials has for example been considered [33]. Table 4 identifies the tags and presents the results. No signal from the sensitive tag located outside the showcase (tag #01) was detected within the test phase duration of five months, indicating an ultra-low or low corrosive atmosphere (IC1 or IC2). This result can be connected to high-air-exchange rates in the exhibition through the ventilation system. Note that an ultra-low corrosivity class (IC1) can be attained at this location. Indeed, in this case, the metallic loss would be less than 16 nm/year, leading to a tag's detection after 9.3 months of exposure, a duration that was not reached in the present study. In the showroom, the tag #03 inside the pilot suit Mark IV was detected after 39 days, resulting in an IC3 level (medium corrosivity index). At about 1.5 m from the suit, an IC2 level (low corrosivity) was achieved, demonstrating a rapid decay of pollutant content, certainly due to the presence of absorbers in the showroom. This example highlights the interest of RFID sensors to identify the sources of pollutants in showrooms and more generally in museums. Other methods were applied in the past for similar tasks. M. Dubus et al. [34] used electrical resistance sensors in several museums to define the IC levels and thus the suitability of several showcases for conservation. In this case, similarly to the present study, the sensors were based on the chemical reactivity of metals such as silver or copper to pollutants. Other studies focused on the determination of the sources of gaseous pollutants in museums or archives by using sampling methods [35] or gas sensors [36]. The main differences between these previous studies and the present one is the ultra-low cost and low visual nuisance of RFID sensors.

**Table 4.** Results from the RFID sensor interrogation in the space exhibition (15 December 2022–16 May 2023).

| Tag | #01 | #02 | #03 |
|---|---|---|---|
| Metal | Ag 20 nm | Ag 20 nm | Ag 20 nm |
| Location | Exhibition room, floor | Showcase, center | Object, Mark IV |
| Object(s) | Rocket engine J-2 | Spacesuits | Pilot suit |
| Detection time | Not detected | 150 days | 39 days |
| Corrosion rate | <0.07 nm/day | 0.08 nm/day | 0.32 nm/day |
| IC | ≤IC2—low corrosivity | IC2—low corrosivity | IC3—medium corrosivity |

As shown previously in Figure 4, climate loggers (testo® 174H devices, Testo SE & Co. KGaA, Titisee-Neustadt, Germany) were located inside and outside the showcase. Results are depicted in Figures 5 and 6. Only a slight fluctuation of relative humidity and temperature was observed within the enclosed space, thus demonstrating its protective functionality against climate changes from outside. The temperature was well within the required 15–25 °C in the whole exhibition area, with maximum daily fluctuations of ±1 °C in the showcase. The relative humidity in the presentation room of the spacesuits was more influenced by changes in temperature than it follows the outside humidity levels (Figure 6) and evened out above 45% with ±2% fluctuations during the day. It can be concluded that the silica gels help to buffer the relative humidity, but are not efficient enough to dehumidify the atmosphere inside the showcase down to 30–40%. The observed temperature values are connected to museum opening times. Indeed, as shown in Figure 6, temperature and humidity change within a day. During closed days around Christmas and New Year, such daily variation disappeared. A likely explanation for that phenomenon is the lack of heat production from lighting and other electronics in the exhibition during those days. This is highlighted by the slightly higher temperature difference inside the showcase, which is caused by the internal lighting. Judging from this dataset, the pilot and spacesuits are displayed in an environment that can be characterized as climate class AA, according to the Canadian Conservation Institute. It has to be noted that seasonal changes can not yet be evaluated. There should be no or only small risk to mechanical damage induced by incorrect climate conditions and chemically unstable materials, such as rubber, PVC, PU, or PA, which will be unusable within decades [37].

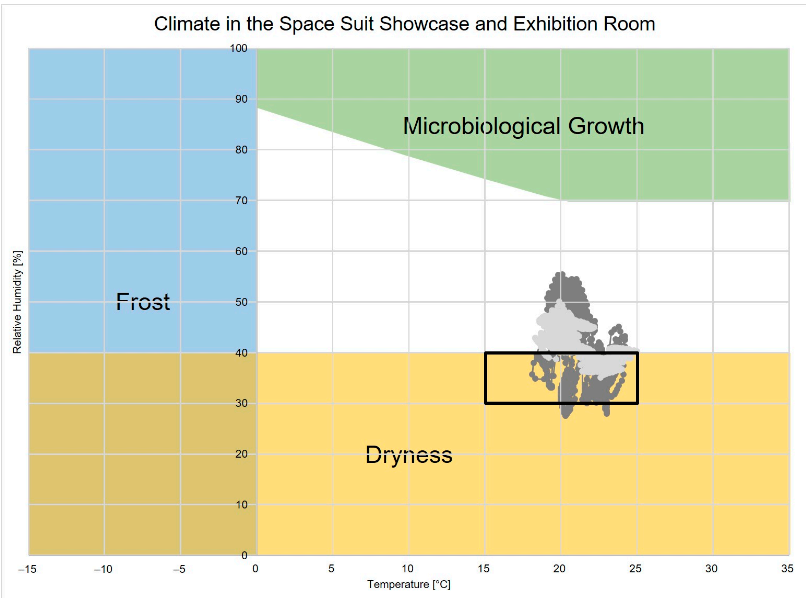


**Figure 5.** Results of the climate measurement from November 2022 to March 2023 inside (light grey) and outside (dark grey) of the spacesuit showcase. Target value marked with black frame.

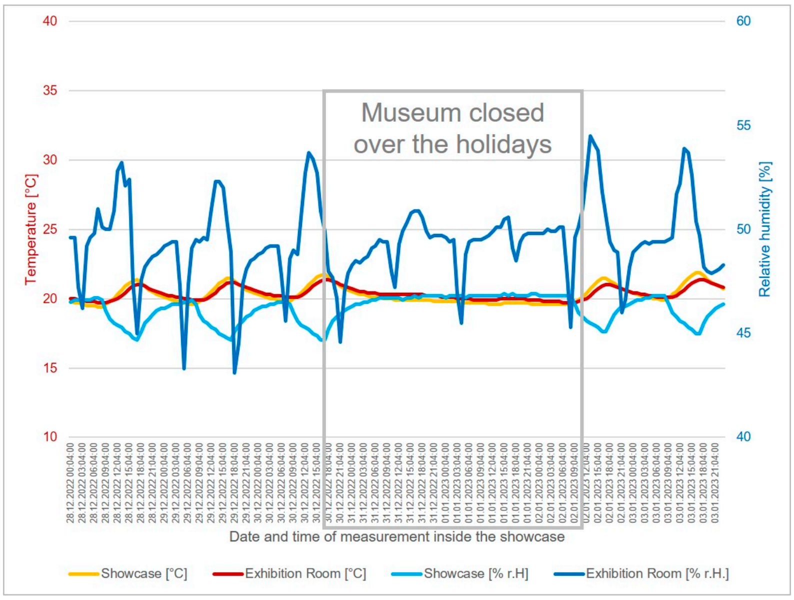


**Figure 6.** The climate inside and outside the spacesuit showcase over New Year's Day 2022/23. Data recorded in the exhibition room with a shift of 30 min from the shown time.

In the exhibition "Astronautics", there are two main sources of radiation: the lighting on the ceiling and inside the showcases as well as the heating-cooling panels on the ceiling (Figure 7). High-energy UV radiation was completely excluded from the surroundings of the spacesuits by forgoing daylight and choosing suitable warm light LED illuminants. The properties of these latter are provided in Table 5. The absence of UVA and UVB radiation (290–390 nm) was confirmed by punctual measurements (Voltcraft® UV 500, Conrad Electronic SE, Hirschau, Germany). The recommended levels of 30–100 lux of visible light (around 400–700 nm) were adjusted during the installation process. The whole outline of the objects as well as detailed structures, such as textile weave, small metal parts, or writing on mission patches, are readable to visitors of different age groups [6]. With a color rendering index (CRI) value above 95, the LEDs have an excellent color rendering capacity [29].

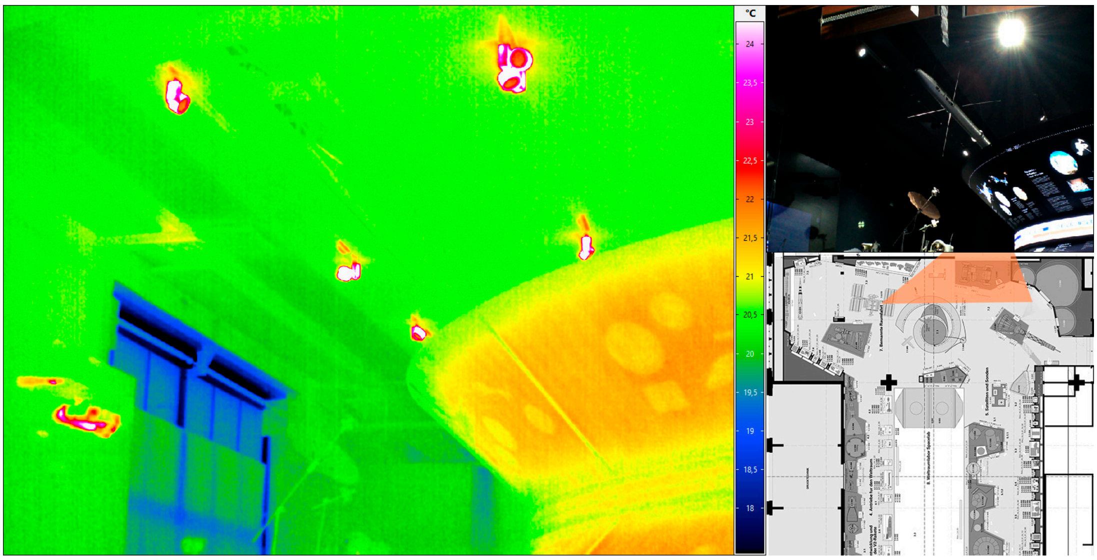


**Figure 7.** Infrared thermal image of the spacesuit showcase surrounding (**left**) with the location of the camera marked on the exhibition plan (**below right**): heating–cooling ceiling, installations, lighting, and a large portal. Image on the upper right shows the area in normal light.

**Table 5.** Features of the showcase LED illuminants and control measurement with an ultraviolet meter.

| Illuminant | Warm Light LED Spots | |
|---|---|---|
| Type of fixture | Magnetic LED zoom spot |  |
| Type of LED | Luxeon/Philips | |
| Number of LEDs | 1 | |
| Lenses | 12°~60° zoom (stepless) | |
| Color temperature | 3000 K | |
| CRI | 95 | |
| Power | 2.5 W | |
| Dimmable | DMX, Dali, 0–10 V, Mains | |
| Fixture color | Black | |
| Fixture material | Aluminum | |
| Fixture size | 20 × 62 mm | UVA and UVB radiation |
| Mounting | Magnetic rail | (290–390 nm) not detected |
| CE and RoHS certified | | |

## 4. Conclusions

Within the scope of this study, an evaluation of the exhibition conditions inside and around the spacesuit showcase during the first months after the re-opening of the museum took place. The chosen methods proved to be easy to conduct, needed very little maintenance, and were cost-effective, because of the use of existing instrumentation and cooperation in testing the innovative RFID sensors. Already within months, the major source of pollution was identified, and the corrosivity of the exhibition environment was found to be low or very low. The choice of LED lighting in the room and inside the showcase was successful insofar as no ultraviolet light was detected and acceptable light levels of 30–100 lux were reached by dimming. Infrared thermal images highlighted a slight heating effect of the illuminants on the temperature and the effectivity of the heating–cooling ceiling. Climate diagrams revealed significant fluctuations of temperature and relative humidity in the first months and an increasing leveling of the values, about half a year after the museum' opening. Relative humidity arrived in an acceptable corridor for the general museum object, but despite silica gel buffering, the recommended values for synthetic materials and metal (30–40% r.h.) had not yet been accomplished in the showcase. Room temperature is controlled by a heating–cooling ceiling, which results in constant values with small daily fluctuations that can be linked to museum lighting and electric installations used during opening hours.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15129442/s1, Figure S1: Mobile application for interrogating the RFID sensors.

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