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subjected to one of the following conditions: IEAP materials were divided into six test groups. Each group was assigned hazardous environments; the synergism effects—the simultaneous action of several destructive factors that can enhance or reduce the resulting orbit (LEO). The sequence of the experiment consisted of the following steps:

- **Step 1.** The initial performance of each sample was tested during a single measurement cycle;
- **Step 2.** Without operating, the samples were exposed to their pre-assigned hazardous environments;
- **Step 3.** The performance of all samples under continuous loading was recorded until their complete degradation. This step was carried out in an ambient environment (temperature 17°C, relative humidity 30%) after the hazardous environmental exposure was terminated.

The abbreviations indicated with bold text indicate the corresponding series in the graphs given below. Detailed descriptions of the conditions in harsh environments are given in the Supplementary Information.

In addition to the weight, another critical attribute of space systems is reliability because any reliability problems during the mission can lead to complete mission failure. Therefore, any technology design intended for orbit is carefully inspected for potential causes of failure prior to launch. To demonstrate that IEAP actuators survive the space radiation effects, we performed ground-laboratory tests with seven types of IEAP actuators, covering a wide variety of constituents and fabrication technologies. The collection of the test objects was chosen among well-studied IEAP materials at the present time, such as aqueous IPMC, conducting polymer actuators, and nanocarbon-based ionic actuators. The IEAP materials involved in the experiments are briefly compared in Table 1, while a comprehensive overview of their fabrication and properties is given in the Supplementary Information and in the corresponding references.

The abbreviations indicated with bold text indicate the corresponding series in the graphs given below. Detailed descriptions of the conditions in harsh environments are given in the Supplementary Information.

### Table 1 | IEAP materials

| Membrane | Electrodes | Electrolyte | References |
|----------|------------|-------------|------------|
| A GEFc   | Pd + Pt    | Water + Li⁺ | 22, 23     |
| B PVDf-HFP | SWCNT  | EMIBF₄⁻ | 24, 25     |
| C Nafion® | nanocarbon + Au | EMITF | 26         |
| D PVDf-HFP | nanocarbon | EMIBF₄⁻ | 27         |
| E PEO/NBR IPN | PEDOT | EMITFSI | 28         |
| F PVDf | Ppy + Au | PC + LiTFSI | 29         |
| G PVDf | Ppy | PC + LiTFSI | 30         |

Acronyms: EMIBF₄⁻: 1-ethyl-3-methylimidazolium tetrafluoroborate; EMITF: 1-ethyl-3-methylimidazolium bis[trifluoromethylsulfonyl]imide; GEFc: GEFC Co., Ltd; LiTFSI: lithium bis(trifluoromethane)-sulfonimide; Nafion: perfluorinated anionic polymer of DuPont; PC: polypropylene carbonate; PEDOT: poly[3,4-ethylenedioxythiophene]; PEO/NBR IPN: polyethylene oxide/nitrile butadiene rubber interpenetrating polymer network; Ppy: polypyrrole; PVDf: poly-1,1-difluoroethene, polyvinylidene fluoride; PVdF-HFP: poly(vinylidene fluoride-co-hexafluoropropene); SWCNT: single-walled carbon nanotubes.

In the course of the Step 3, performance tests, which lasted 13 working cycles, were performed after every 174 working cycles. The obtained data allows the performance of each sample to be plotted with respect to time as well as the total number of cycles performed. Typical plots with respect to time and the total number of cycles are given in Figure 1. Each point denotes one test-cycle, and...
one point in one graph corresponds one point in the other graph and vice versa.

**Results**

For analysis, the lifetime of an IEAP actuator was divided into two phases, indicated by the three checkpoints in Figure 1: \( B_I \) indicates the sample initial performance at the first test \( I \), \( B_A \) indicates the performance at the first test \( A \) after the sample is removed from the adverse environment; and \( B_F \) indicates the final performance after an arbitrary number of working cycles \( F \) before remarkable degradation begins. Due to the fact that the lifetimes of different IEAP types may vary up to several orders of magnitude, the checkpoint \( F \) is chosen separately for each particular IEAP type.

The long-term degradation experiment was carried out using identical methodology on 320 IEAP actuators of seven types, divided into six test groups. The subsequent survival analysis of the actuators confirmed the deduction of Liu et al. – the distribution of lifetimes cannot be well described by any of the commonly used methodologies of failure distribution characterization, e.g. the Weibull statistics\(^{32} \). Moreover, with small statistical sample sizes (up to 10 samples of each category) of the rather irregular test objects, the formal statistics also become uncertain. Therefore, we explore the common degradation tendencies using visual data analysis methods. The obtained data is displayed graphically by scatter plot pairs, which present the dimensionless relationships between the initial performance and final performance of the two phases. Along the horizontal axes of the two scatter diagrams are plotted the starting performances \( B_I \) and \( B_A \). Along the vertical axes are plotted the degradation due to the environment \( B_A/B_I \) and the degradation during operation \( B_F/B_A \) respectively. The seven scatter plot pairs presented in Figures 2–8 describe the degradation tendencies of all 320 samples of seven IEAP types.

**Discussion**

Though X-ray radiation significantly increases the performance of the Ppy actuators, the higher performance is indiscernible by the next measurement cycle. On the other hand, Gamma radiation had no effect on IEAP materials with conducting polymer electrodes (\( F \) and \( G \)). This indicates that the interim performance peak is due to the radiation-induced doping of conducting polymer electrodes, which improves their conductivity. The described phenomenon has not yet been studied in detail. Furthermore, the few available studies about the ionizing radiation-induced doping of conductive polymers do not cover our specific case\(^{34–35} \). An intelligible explanation to the phenomenon of ionizing radiation-induced doping is given by Boye et al.\(^{36} \) At lower doses, the ionizing radiation acts as a catalyst, allowing excess dopant to attach to the polymer chain. This, in turn, enhances the material conductivity. As the dose increases, damage to the polymer chains will be the dominant result of ionizing radiation, leading to a further decrease of conductivity. However, all studies on this topic deals with a separate conducting polymer. In our experiment, the alternate polarization of the actuator during the next working cycle nullifies the effect of excess dopants.

**Conclusions**

This study confirms that cosmic radiation does not impinge on the prolonged exploitation of IEAP actuators in space applications. Unlike materials used for conventional actuators, IEAP materials do not embody any crystal lattice, the characteristics of which could be sensitive to ionizing radiation or atomic oxygen. Instead, these
Laminates consist of polymeric materials with high-radiation resistance: PVdF, Nafion, carbon powder, noncrystalline noble metals, and nonvolatile ionic liquid electrolytes. Although numerous methods exist to modify the structure of these materials with ionizing radiation, the damaging doses are several magnitudes higher than any object can absorb from cosmic radiation in space near Earth over several decades37,38.

The results of our long-term large-scale experiment convincingly demonstrate that IEAP actuators are fully tolerant to the ionizing Gamma- and X-ray radiation at LEO levels. The IEAP actuators with carbonaceous electrodes as well as aqueous IPMC are resistant to all environmental parameters tested. The most destructive radiation for IEAP actuators is direct UV; hence, devices obscured from direct sunlight can be considered to be fully reliable. Moreover, UV-degradation of the conducting polymers PEDOT and Ppy is described in numerous papers39,40; it also caused harm to the radiation-absorbing black electrodes of IEAP material D. Long-term vacuuming does not affect actuators that have ionic liquid electrolytes. The freezing tem-

Figure 4 | IEAP material C: An ionic polymer membrane with nanoporous carbon electrodes. A Nafion® membrane with electrodes consisting of CDC, which is nanoporous carbon derived from titanium carbide33. The electrolyte is ionic liquid (IL), 1-ethyl-3-methylimidazolium trifluoromethanesulfonate (EMIT), while the conductivity of the electrodes is improved by thin gold foil26. Checkpoint F is marked at 3000 working cycles. In spite of the considerable divergence of the initial performance, none of the environmental parameters has a notable effect on this IEAP material.

Figure 5 | IEAP material D: A non-ionic polymer (PVdF-HFP) membrane with CDC electrodes and electrolyte EMIBF4 27. Checkpoint F is marked at 5000 working cycles. Exposure to UV radiation significantly damages this IEAP material, although it is able to function with lower performance. Vacuuming increases the degradation during operation.

Figure 6 | IEAP material E: a conducting interpenetrating polymer network, based on a non-homogeneous dispersion of PEDOT through the thickness of the PEO/NBR IPN matrix, with EMITFSI as electrolyte28. This material is similar to a layered actuator with conducting polymer electrodes with the advantage that no adhesive interface is necessary. Checkpoint F is marked at 10,000 working cycles. The samples were fabricated in two batches; therefore, the initial performances lie in two intervals. UV radiation destroys this IEAP material. Indeed, the photo-oxidation process leads to rapid degradation of the polyethylene oxide (PEO) partner, which in turn degrades the PEDOT electrodes. All other environmental parameters have no notable effect. Vacuuming slightly degrades this IEAP material; however later the degradation is not noticeable.
Temperature and duration show no difference. Naturally, these materials are not able to work when the electrolyte is frozen or drawn off, but they revive after melting up or soaking in the appropriate electrolyte.

Methods

The experiment involved testing 320 samples. Over the course of the long-lasting experiment, the electrical input and electromechanical output were recorded for each sample. To handle the number of samples, we designed original equipment to automatically perform the testing procedure upon many actuators concurrently. A comprehensive overview of the equipment as well as the methodology used for testing is presented elsewhere. This setup excludes human errors and guarantees that all samples are tested under exactly similar conditions. For that reason, the experiment was setup considering the trade-off between the obtained data and the automation options.

The recorded mechanical outputs were the force gauge output and visual information on the bending. The actuator behaviour was recorded by a camera, which was equipped with a long-focal-length lens. The 640 × 480 pixel images were converted to vector interpretation using the National Instruments LabView image processing package. The vectorial interpretation expresses the curvature as a function of the distance from the input contacts along the sample. The curved line representing the shape of the actuator is divided into vectors of equal length, assuming that the curvature is constant within each vector. A convenient quantitative parameter for estimating the performance of the actuator is the angle \( \beta \), which is the angular spread of the tangent of the actuator tip.

Figure 7 | IEAP material F: Ppy films grown galvanostatically on gold-coated PVdF membrane. The electrolyte is 0.1 M LiTFSI solution in PC. Checkpoint F is marked at 600 working cycles. The degradation due to the environment is perceivable. Direct UV radiation certainly destroys this IEAP material. Moreover, X-ray radiation increases the performance significantly; however, this effect only lasts a few measurement cycles.

Figure 8 | IEAP material G: a conducting polymer IEAP comprising PVdF membrane with Ppy electrodes and PC+LiTFSI (1.0 M) electrolyte fabricated by the combined chemical and electrochemical synthesis method. Checkpoint F is marked at 500 working cycles. The degradation due to environment is much less noticeable than the previous case (F). The influence of UV is not noticeable. After exposure to X-ray radiation, the performance is significantly increased; however, the effect only lasts a few measurement cycles.

Figure 9 | The performance of an IEAP actuator is defined as \( \beta \), which is the angular spread of the tangent of the actuator tip.
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Author contributions

K.J.K. and V.P. fabricated the type A IEAP actuators. K.A. and T.S. fabricated the type B IEAP actuators. I.P. and U.I. fabricated the type C IEAP actuators. F.K. and J.T. fabricated the type D IEAP actuators. C.P., N.F. and A.M. fabricated the type E IEAP actuators. I.P. and U.J. fabricated the type C IEAP actuators. F.K. and J.T. fabricated the type G IEAP actuators. A.P., K.J.K., F.V., G.A. and A.A. planned the experiment and wrote the text. V.V., K.K.J., T.F., P.R. and A.-L.F. performed the destructive environment tests. A.P., U.I., V.V., K.K., A.A. and I.M. performed the long-lasting degradation test. A.P., U.I. and I.M. performed the data analysis. All authors reviewed the manuscript.

Additionally information

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