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Influence of the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) on the local atmospheric environment

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A R T I C L E   I N F O

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A B S T R A C T

A survey around a recently-fueled MMRTG in the terrestrial atmosphere finds a warm air plume with a characteristic updraft velocity of ~1 m/s and a temperature rise of ~4 K. Additionally, a roughly hundredfold enhancement in ion density to ~70,000/cm³ in the vicinity (<1 m) of the generator was observed: air electrical conductivity was measured to be ~10⁻¹³ S/m. No evidence of ozone production was detected. These observations inform the electrical charging environment and possible local perturbation to meteorological measurements on Mars or Titan on MMRTG-powered landers or rovers. On Mars, the effects of any electrical conductivity enhancement are likely small, but on Titan they may be significant.

1. Introduction and motivation

The thermal influence of a radioisotope power source (RPS) on meteorological measurements was observed on the Viking lander (Hess et al., 1997) as well as on the Mars Science Laboratory (MSL) Curiosity rover (Viúdez-Moreiras et al., 2019), although lander perturbations can be detected on solar-powered missions too (e.g. on the Phoenix lander, Davy et al., 2010). The potential for such effects on future Titan landers was also investigated by Lorenz and Sotzen (2014) and Lorenz (2015). These studies have relied on analytic or computational fluid mechanics models to estimate the characteristics of the plume.

Motivated in part by the prospect of meteorological measurements on platforms furnished with RPS, we have made in-situ measurements on a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). The MMRTG is the system that powers the Mars Science Laboratory (‘Curiosity’, carrying the Remote Environment Monitoring Station instrument REMS) and will power the Mars 2020 rover (‘Perseverance’, carrying the Mars Environment and Dust Analyzer MEDA), and is proposed for the New Frontiers relocatable lander ‘Dragonfly’ (carrying the DraGMet – Dragonfly Geophysics and Meteorology package). A narrow window to conduct these measurements arose in early 2020 on the F2 MMRTG unit, between its loading with 4.8 kg of Plutonium Dioxide fuel at the Idaho National Laboratory (INL) and its shipping to Florida for launch on Perseverance in July 2020. In fact, the opportunity to make these measurements turned out to be even more fortunate than expected: they were performed in early March, just a few days before widespread restrictions on government-sponsored travel were introduced as the COVID-19 pandemic accelerated in the USA – they would have become impossible one or two weeks later.

In addition to characterizing the temperature and wind speed of the thermal plume from the generator (which in principle could be simulated with an electrical heat source), the possible influence of the radiation field on the atmospheric chemistry and electrical properties was of interest. The former question is stimulated by the ongoing debate concerning methane on Mars: fluctuations in methane abundance measured by Curiosity have been argued to suggest a local (vehicle) source (e.g. Zahnle, 2015). If so, it is possible that radiation effects on polymers used in the vehicle (e.g. epoxy circuit boards, or Kapton, Mylar or Teflon materials in thermal or electrical insulation) may play a role. However, a seasonal variation in methane has been suggested (Webster et al., 2018), and assessments appear to discount a rover source. Alternatively, noting that methane can be chemically destroyed by oxidants generated by photochemistry or triboelectricity (e.g. in dust devils – e.g. Atreya et al., 2006), the possible generation of ozone by radiation also deserved attention in the present work. The second influence, on atmospheric electrical conductivity, arises in connection with electric field measurements to be made by DraGMet on Titan, to search for possible Schumann Resonance signals (Lorenz and LeGall, 2020), and detect the wind transport of sand and dust. It may be noted also that while Curiosity and Perseverance carry no instrumentation dedicated to atmospheric...
electricity, the adhesion of dust to spacecraft surfaces (which can be monitored by imaging and other optical sensors) is often mediated electrostatically, and thus the vehicle charging environment on Mars may play a role and be different for RPS- and solar-powered landers.

2. MMRTG details

The 45 kg Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is the current generation of US RPS (e.g. Zakrajsek et al., 2016). As the name implies, it is designed for broad applicability to a variety of space missions, and in particular (unlike the RTGs used on Cassini and New Horizons) can operate in a planetary atmosphere. The outer shell of the MMRTG (Fig. 1) is an aluminum housing with eight radial cooling fins. The MMRTG converter housing has an overall diameter of 0.65 m and a length of 0.69 m, including the fins. The housing hermetically seals the converter assembly and cover gas within the MMRTG, and provides the necessary electrical and mechanical interfaces to the spacecraft.

The converter assembly routes heat from the heat source through 768 thermoelectric semiconductor couples of lead telluride (PbTe) and tellurides of antimony, germanium and silver (TAGS) to produce an electrical output. The converter housing has an overall diameter of 0.65 m and a length of 0.69 m, including the fins. The housing hermetically seals the converter assembly and cover gas within the MMRTG, and provides the necessary electrical and mechanical interfaces to the spacecraft.

3. Measurements

Measurements were performed in the SSPSF (Space and Security Power Systems Facility) at INL, with rigorous preparations for security, hardware quality assurance and personnel safety. For obvious occupational health reasons, the exposure of personnel to the radiation field was kept to a minimum and carefully monitored with standard radiological surveillance measures. Measurements were made in two different rooms (103 and 117), about 15 m apart and adjoining the same anteroom with open doors: the atmospheric properties reported here are applicable to both rooms (the MMRTG was transferred from one room to the other in the middle of the day), although the air velocities in the two are slightly different.

3.1. Thermal plume

Since the warm air plume from an MMRTG can influence meteorological measurements, it was desired to measure the temperature and updraft speed in the air rising in free (buoyant) convection from the device (Fig. 2). These were recorded with an Extech Model 407,123 Hot-Wire Thermo-Anemometer. This unit is equipped with a ~1 m wand with a hot-wire sensor at its tip, allowing the operator to stand some distance away and yet access the volume immediately above the MMRTG. After an initial survey ‘by eye’, data were obtained in a regular 2-dimensional grid (the MMRTG is radially-symmetric) by using a levelled laser cross-hair: the laser was moved at fixed (typically 15 cm) intervals marked on the floor and wall, and the anemometer tip was held by the operator in an orthogonal plane (through the MMRTG center) until the tip was at the laser cross.

It was found that there was some fluctuation and drift in measurements: these appear to be due to air handler operation (the facility is nominally under slightly negative pressure for contamination containment) and/or the plume itself, which could develop in the large room (designated room 103, 6 × 8 m, with a 10 m high ceiling). Inspection of the data post-hoc also suggested a hysteresis effect, in that the temperature sensor and wand structure around it had a response time of several seconds, so that measurements made just after being closest to the generator were 1–2 K warmer than those made at the same distance before being closest. Some additional ‘spurious’ warming likely also arose due to radiant heat from the generator, rather than the warmth of the air in the plume.

Correcting for these effects by subtracting an offset to yield a zero perturbation in the far field, the most representative plume profiles (for heights of 15–45 cm above the top of the generator) are shown in Fig. 3. Updraft velocity peaked at about 0.7 m/s, and the temperature perturbation was just under 4 K. The background air temperature for these tests (at about 1000 h local time) was 21–24 °C, and background circulation currents may have been as high as 0.6 m/s. The highest (uncorrected) readings in the plume were 32.8 °C and 1.4 m/s respectively.

Measurements were found to be somewhat steadier when repeated in the early afternoon in a smaller room (117, 3 × 4.5 m, 5 m high). Background temperatures here were notably higher (~27 °C) due to the more restricted circulation, but because the measurements were made more rapidly (due to operator familiarity with the procedures, and the shorter distance to the wall made positioning easier), the hysteresis effects were more significant. Because the Extech unit uses the ‘air’ temperature measurement to derive the wind speed, these effects likely influenced the wind speed too: background winds of 0.8 m/s were indicated. The highest uncorrected readings above the generator were 41.6 °C and 2.0 m/s.

3.2. Thermal image

Thermal images of the generator were obtained with a FLIR™ infrared camera model FLIR-E63900 (contact measurements on the MMRTG are not permitted, not least since this might damage the high-emissivity white paint). The images indicate (Fig. 4) typical external fin temperatures of 70–90 °C, with an increase ~140 °C towards the fin roots at the midpoint of the generator.

3.3. Oxidants

A ‘Smart Sensor’ AS8908 ozone detector read 0.00 ppm, both in the MMRTG facility and outside. However, there was no opportunity to calibrate (or even confirm qualitative operation of) this unit without its sampling pump accessory (not available in time for the test), so this should not be regarded as a definitive nondetection. Additionally, an ozone test strip (Macherey-Nagel, Duren, Germany), showed no discoloration after the manufacturer-indicated 10 min of exposure ~30 cm from the generator: the calibration chart suggests this indicates a concentration of <90 μg/m³ (i.e. <0.045 ppm). However, the test strips are only rated for relative humidity of 30% (and anecdotal evidence from reviewers on the amazon.com site via which the strips were purchased...
suggests that they do not function below 30%), and that measured in the room (103) was only 12–14%. No ozone smell was noted: an olfactory signature of ozone can be detectable at concentrations of 0.007–0.02 ppm depending on individual (Cain et al., 2007).

Anecdotally, degradation of some polymer materials (e.g. a butyl rubber washer on a camera tripod) has been noted in proximity to sources like the MMRTG, but whether this is simply a coincidental occurrence, or caused by direct radiation effects on the polymer, or by intermediates such as nitrogen oxides or ozone, is unknown. Our observations are at least not inconsistent with ozone not being a factor, but further investigation of this question, with more sensitive techniques and in more controlled circumstances, may be justified.

3.4. Atmospheric electrical conductivity

The decay of Plutonium-238, the fundamental process with an 87.7-year half-life that enables current US RPS, results in alpha emission. These particles are contained within the fuel and the MMRTG housing. Other nuclear reactions in the fuel (e.g. alpha interaction with oxygen atoms and spontaneous fission, see e.g. Kelly et al., 2006), however, result in a flux of neutrons and gamma rays which do reach the outside. Although not as strongly ionizing as alpha and beta particles, these emissions cause the generation of some ion pairs in the atmosphere in the vicinity of the generator. We are not aware, however, of any previous measurements of this effect in the free atmosphere.

Our principal tool was an Alphalabs AIC handheld ion counter. This is essentially an instrument that measures the leakage current in a Gerdien condenser (i.e. a concentric cylindrical air-gap capacitor, aspirated by a fan). The current is converted into separate abundances of negative and positive charge carriers (ions) – the abundances are not equal, as negative ions tend to be preferentially absorbed on aerosols or surfaces – using known ion mobilities. Because the current is an instantaneous measurement, it is prone to rapid fluctuations (which may be real, owing to the stochastic ion production and possibly turbulent advection).

As a supplemental measurement, a low-voltage relaxation probe was constructed (see Appendix). This measured the decay of the voltage on a plate, and since it is an integrated-current measurement, avoids
distracting fluctuations (but measurements take several minutes). As an additional opportunistic measurement, a Monroe Ionizer Performance Analyzer (IPA 287) was available at the INL facility. This device is typically used in electronics clean rooms to monitor the effectiveness of air ionizers deployed to avoid the buildup of static charge around sensitive components. In effect it also functions as a relaxation probe, but it operates with an unshielded electrode, mitigating stray field effects by operating at a high voltage (1000 V). The high voltage may cause sensitivity to ions of different mobility from the other measurements.

The measurements are summarized in Table 1. In the laboratory environment, well away from the generator, the ion detector indicated a 200–1000 ions per cubic centimeter. Close to the generator, especially in the smaller room 117, the ion counts reached ~70,000/cm³, a ~200 fold increase: negative ion counts were typically a little lower than positive ones, and generally rather more variable.

The ‘natural’ ~30 min decay time for indicated by our relaxation probe (Fig. 5) may be accurate, or may be shorter than the ‘true’ (atmosphere-limited) value due to leakage currents in the op-amp, or caused by surface moisture or other instrumental imperfections. The ~30-fold drop in relaxation time to ~1 min (Fig. 5) near the generator may actually correspond, therefore, to more than a 30-fold increase in atmospheric conductivity in that the background conductivity was below the instrument floor. In principle the conductivity is proportional to the ion density (assuming constant ion mobility), thus the increase may actually have been as high as ~300x. In any case, the relaxation time $\tau$ can be related (Chalmers, 1967) directly to conductivity $\sigma$ simply as $\sigma = \varepsilon / \tau$, where $\varepsilon$ is the permittivity of air (~free space) and thus $\sigma = 1.1 \times 10^{-13}$ S/m.

Placing a plastic sheet between the generator and the instruments was expected to lead to an enhancement of conductivity, owing to the

| Location                                      | +ve Ion Count (1000/cc) | -ve Ion Count (1000/cc) | Relaxation Time (min) | Note                                      |
|-----------------------------------------------|-------------------------|-------------------------|-----------------------|-------------------------------------------|
| Outdoor Background                            | 0.2                     | 1.0                     |                       |                                           |
| Indoor Background                              | 0.3–0.6                 | 0.1–0.6                 | >—30                  |                                           |
| In Room 103 (typ ~2 m away from RTG)           | 5–42                    | 4.3–30                  | 3–4                   | IC 1–2 m high. Relaxation probe on floor. |
| 103 Adjacent to RTG (—30 cm from center)       | 15–33                   | 3–19                    |                       | On metal table                            |
| 103 Adjacent to RTG (thin PE sheet)            | 7–18                    | 5–18                    |                       | On metal table                            |
| 103 Adjacent to RTG (2 mm acrylic shield)      | 2–22                    | 2–12                    |                       | On metal table                            |
| 103 In plume (50 cm above RTG)                 | 14–69                   | 56–71                   |                       |                                           |
| In Room 117 (typ ~2 m away from RTG)           | 10–20                   | 3.5–35                  |                       |                                           |
| 117 Adjacent to RTG (—30 cm from center)       | 44–70                   | 36–59                   | 1–1.3                 | On metal table                            |
| 117 Adjacent to RTG (—60 cm from center)       | 17–50                   | 8–24                    | 2–2.7                 | On metal table                            |
| 117 Adjacent to RTG (—75 cm from center)       | 8–20                    | 3–42                    |                       | On metal table                            |

Fig. 4. Thermal images of the MMRTG on its handling fixture. The color scale runs roughly from 22 to 144 °C (295–417 K). The fins are 65 cm tip to tip. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 5. Time series of voltage on relaxation probe. Background measurements were taken in the anteroom. Next to the generator in room 103, the voltage falls with a time constant of about 1 min.
possible generation of more ionizing protons via neutron interaction with the hydrogen-rich plastic (plastic layers are sometimes used in neutron detectors for the same reason). However, we could not reliably detect such an effect. We suspect that the plastic blocked the turbulent transport of ions formed in immediate vicinity of the generator to the instrumentation, and that this was a larger effect than any increase in the ionization ability of the radiation near the instrument. It is possible that there may have been effects due to charge on the insulating plastic itself. Sustained experimentation was not pursued since proximity of the plastic to the hot fins would be a concern (in fact, a plastic connector cover had inadvertent contact with one of the Cassini RTGs in Florida in 1997, and removal of the small blob of melted material required assessment of the impact on thermal paint e.g. Lockheed, 1998).

The Monroe analyzer reports its plate voltage with time, unless the voltage decay is too slow and the measurement aborts. This was the case in the anteroom away from the generator (thus, as with the relaxation probe, the unperturbed terrestrial atmosphere is too insulating to reliably constraining, serve as an independent confirmation of the relaxation probe and ion counter results—with higher levels encountered in 117 vs 103, and with positive ions being more abundant, and with proximity to the generator increasing conductivity at least one order of magnitude above the indoor background. For reference, an ionizer is considered highly effective at static charge alleviation in electronics facilities if the Monroe relaxation time is 1 min or less.

4. Discussion

We now set the measurements in context with theoretical expectations for Earth, and what might be expected in other environments.

4.1. Thermal perturbation

The nominal thermal output of the MMRTG fuel is ~2 kW. In steady state, this heat must leave the generator via a combination of convection and radiation (plus a small amount of conduction through the mounting fixture).

We may approximate the radiating area A as a cylinder 0.7 m high and 0.7 m in diameter, just spanning the fin tips, thus A~1.4 m². The radiative heat flux, assuming unit emissivity, is approximately \( \sigma T^4 \), with \( \sigma \) the Stefan-Boltzmann constant 5.67 \(/C^2\) and \( T \) the Stefan-Boltzmann constant 5.67 \(/C^2\) the air density (the INL facility is at ~1.0 kg/m³ the air density (the INL facility is at 5.67 \(/C^2\) the Stefan-Boltzmann constant 5.67 \(/C^2\) the air density (the INL facility is at 105075

These basic considerations are in reasonable agreement with the measurements in section 3.1, noting that the plume is not uniform. Integrating the combined temperature and updraft velocity profiles of Fig. 3 suggests a sensible heat flux in the plume of ~300 W. Thus, the overall predictions of Lorenz (2016) on the local temperature and velocity perturbations are borne out by experiment.

4.2. Electrical environment

A similar exercise (simple algebraic model) can be applied to the atmospheric electricity measurements. Detailed modeling of the radiation spectrum is beyond the scope of this paper, but an order-of-magnitude calculation sets a context. Although the Plutonium-238 decay results in alpha emission, these particles are absorbed within the generator housing. However, interactions of the alpha particles with oxygen and other atoms in the fuel, and other nuclear reactions, result in an emission of gamma rays and neutrons to the external environment—details of the radiation emissions from RPS are discussed in, for example, Jun et al. (2013), Smith (2018) and Lee and Bairstow (2015). The neutron flux at a distance of ~50 cm from the centerline of the MMRTG, which is not quite a point source, is a few times \( 10^{10} \) neutrons/cm²/year (with the leading digit being somewhat dependent on direction.) There are therefore ~1000 neutrons/cm²/sec, with a characteristic energy of the order of 1 MeV, emerging from the generator just beyond the fin tips, and these may penetrate several meters to tens of meters in air.

Considering an ionization energy for air of 34 eV per ion pair, a 1 MeV neutron may generate ~30,000 ion pairs. If these are spread over a 3 m path length (over which the flux declines significantly by the inverse square law as well as absorption/scattering), then the nearby ion pair production rate is ~1000 * 30,000/300 = 100,000 per cm² per second. This may be compared with the typical generation rate due to cosmic rays and natural radioisotopes at the Earth’s surface of a few per cm²/s (see e.g. National Research Council, 1986; Harrison and Tammet, 2008; Aplin, 2013).

In steady state, ignoring the role of aerosols, the ion production rate q is balanced by recombination via a second order process (i.e. the recombination rate depends on the product of positive and negative ion densities \( n_+ \), \( n_- \)). Since these are approximately equal (~\( n \)), it follows that \( q = \alpha n^2 \), with the recombination coefficient \( \alpha \) suggested to be \~10⁻⁶ cm³/s (Harrison and Tammet, 2008). Thus, \( n = (q/\alpha)^{0.5} \) and we obtain for \( q = 4/cm²/s \) a value of \( n \) of 2000/cm³, a factor of just a few higher than we observed, an unsurprising difference since we have not included scavenging by aerosols (adding a term to \( n \), see e.g. Aplin, 2013) or shielding by the building, which could reduce the value of \( q \). We measured the particle density in room 103 using a Particle Scan Pro instrument (Part # 310 20 00 00) at only ~1 particle per cubic centimeter or less for particles of diameter 0.5 μm and above, or a mass concentration of \( <0.001 \) mg/m³. This is far too low to act as an appreciable sink for ions, e.g. (Harrison, 2006) shows an appreciable (20%) effect on conductivity by smoke only for concentrations over 0.02 mg/m³. Thus, substituting \( q = 100,000/cm²/s \) for the environment close to the MMRTG, we obtain \( n \approx 300,000/cm²² \), again about a factor of 4 larger than we observed, but again plausibly consistent given the simplicity of the model.

The Martian atmosphere has a cosmic ray ion production rate (e.g. ~2/cm²/s, Norman et al., 2014) near the surface that is similar to that on Earth. This is the product of a higher cosmic ray flux (since the much thinner atmospheric column offers little shielding) multiplied by the smaller lower local mass density. The slow ion recombination rate on Mars means that a given production rate yields a considerably higher ion density and thus a higher electrical conductivity than Earth, between \( 10^{-12} \) and \( 10^{-10} \) S/cm (Berthelier et al., 2000): photoelectron production by the ultraviolet flux that reaches the surface likely also plays a (diurnally-varying) role (Grard, 1995). The low atmospheric density (~50x smaller than Earth) would yield a near-MMRTG ionization perhaps only of the order of 1000/cm³/s. The low density also means the absorption

\[ \frac{\Delta T}{T} = -0.01 \text{ as here, and } x \sim 1 \text{ m, we find } V \sim 0.4 \text{ m/s}. \]
distance for neutrons and gamma rays from the MMRTG would be ~50x longer than on Earth, and thus somewhat weak ionization per unit volume would occur in a ‘bubble’ several tens of meters across, the variation in rate driven largely by the inverse square law. Martian winds are typically 5 m/s or more (Lorenz, 1996) so the conductivity enhancement may be swept into a long but faint ion plume: such a plume, a couple of km long, was observed in winds of 2 m/s downwind of a nuclear reactor in Greenland (Ruhnke, 1962).

On Titan, the situation is rather different. The column mass (~10x that of Earth) blocks much of the cosmic ray flux from reaching the surface, and the ambient ion production rate is only about 0.2/cm³/s (e.g. Borucki et al., 1987) so the proportional enhancement by the MMRTG is more significant. The ambient conductivity is predicted to be lower than Earth (i.e. < 10⁻¹⁴ S/m). The local mass density is 4x higher than Earth, and thus ionization due to MMRTG radiation will be localized to within a few meters or tens of cm. Even assuming no enhancement due to neutron-hydrogen interactions in the atmosphere, the local enhancement to conductivity may be substantial (up to ~10⁰). Since ambient winds near the surface are only of the order of 0.3 m/s (e.g. Lorenz, 2006), there is comparatively little dilution. This effect may largely defeat any attempt to measure ambient atmospheric electrical conductivity on Dragonfly (Lorenz, submitted). On the other hand, there is a positive (!) effect in that the enhanced conductivity may help alleviate (Lorenz, 2020) any charge buildup associated with charged dust on the surface (the so-called ‘triboelectric charging’ hazard on aircraft).

5. Conclusions

The measurements reported here for the Earth’s atmosphere cannot, of course, be applied directly to Mars or Titan, in that the environmental parameters are different (air temperature rise will be lower in a denser atmosphere, the buoyant acceleration of the plume will depend on gravity, ion densities depend on gas composition, ion recombination rate etc.) However, these results give some ‘ground truth’ to anchor predictions on RPS missions to these environments, and we have shown that simple algebraic models can yield results in good agreement with those observed here, with thermal plume perturbations of a few Kelvin and updraft velocities of a fraction of a meter per second.

We believe the results here are the first report of atmospheric electrical conductivity enhancement by RPS emissions, and suggest that sensitive, and perhaps even rather rudimentary, instrumentation can detect or be influenced by such enhancement. This influence is likely more significant, and more localized to close proximity of the generator, at Titan than at Mars. It would be valuable to model the ionization in these different environments, taking the full spectrum of gamma and neutron emissions into account.

CRediT authorship contribution statement

Ralph D. Lorenz: Formal analysis, Data curation. Eric S. Clarke: Writing - original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Relaxation Probe

To supplement the ion counter instrument, and to serve as a backup since the opportunity to make these measurements was unique and time-constrained, a relaxation probe (figure A1) was constructed at the first author’s laboratory. This device simply applies a voltage (3.2 V, from a lithium battery connected momentarily via a microswitch) to a flat-plate (4 x 3cm) brass electrode in a grounded steel can (Ashers Whisky Cake) with a wire mesh shield to block stray fields but to admit radiation and the diffusive entry of ambient air. The plate voltage is measured by an ultra-low-current (i.e. ‘electrometer’) operational amplifier – the Analog Devices 549 CE air-wired as a simple voltage follower (see figure A2). The slow decay of the voltage by charge leakage through the air (monitored with a digital voltmeter and stopwatch) indicates the atmospheric conductivity. We may recall that this principle (using a leaf electroscope) was used by the Curies to detect radioactivity in samples, and thereby discover radium and polonium (e.g. Grard et al., 2006) – in fact the Huygens RP used the same 549 CE device (e.g. Falkner, 2004) as its ~10 femtoAmp bias current is very attractive in this application. The circuit was designed for simplicity and robustness, and with small battery components (A23 12 V battery to drive the amplifier, which draws only a tiny current), to facilitate accommodation in hand luggage for commercial air transport.
Fig. A1. View of the relaxation probe – the rectangular brass plate is visible through the grounded steel mesh used to suppress interference. Slide switch atop 12V battery is at upper left; the microswitch lever to initiate a new measurement is at lower right: wires at bottom go to a digital voltmeter for readout. US quarter (24 mm diameter) for scale.

Fig. A2. Relaxation probe circuit. The power switch is a small slide switch, the plate charge switch is a momentary device (microswitch actuated by a lever through the case).

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