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From Order to Flight in Eighteen Months: The MECA/Electrometer Case Study

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ABSTRACT

The rapid development of space instrumentation is increasingly important in this faster, cheaper, better era. This paper discusses the development of the MECA/Electrometer. It used a number of innovations including (a) rapid design of three prototypes, (b) fabrication of a 20 units, (c) testing by three institutions, and (d) testing over a wide range of temperature, pressures, atmospheres, and vibration conditions in an eighteen month period.

A. INTRODUCTION: The development of space instruments requires instruments perform over a wide set of environmental conditions that usually exceed Earth operating conditions. In addition the development must be accomplished quickly which usually mean within an 18 month period. This paper highlights, in italics, the development principles used in the design, fabrication and test of the MECA/Electrometer.

The MECA/Electrometer was designed to facilitate the characterization of electrostatic properties of materials on the surface of Mars in preparation for human exploration. The strategy is to develop an instrument whose results can be compare to laboratory measurements. If the comparison is favorable then future laboratory measurements can be performed with confidence in characterizing new materials intended for use on Mars. *To facilitate the electrometer development, a total of twenty units were fabricated.*

B. MECA/ELECTROMETER: MECA (Mars Environmental Compatibility Assessment) project is scheduled for launch December 2001. The purpose of the MECA/Electrometer, seen in Fig. 1, is to

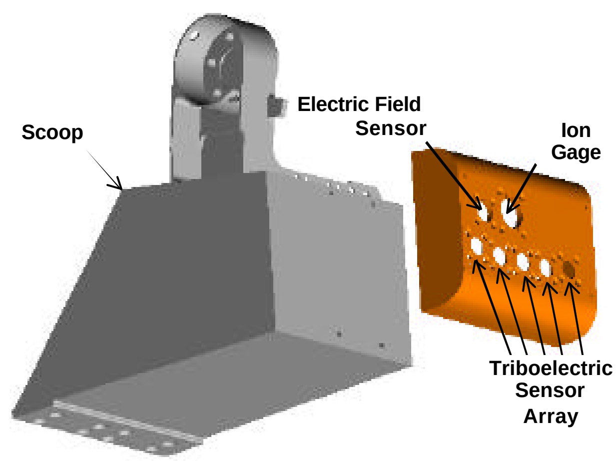

Figure 1. MECA/Electrometer and Mars ’01 scoop.

determine the nature of the electrostatic properties of the Martian atmosphere and regolith. The electrometer is used to measure (a) the triboelectrically-induced charge after the **Triboelectric Sensor Array** is rubbed through the Martian soil and pulled away from the surface, (b) the electric field strength above the Martian soil using the **Electric-Field Sensor,** and (c) atmosphere ion currents using the **Ion Gage**.

C. REQUIREMENTS: The mission environmental conditions are listed in Table 1. These conditions generally exceed Earth-bound conditions especially for commercially available electronic components. *Thus, the instrument components must be tested to assure operation and survival during the mission.*

Table 1. Mission Environment

Location	Parameter	Value	Units
Earth	Planetary Protect. (H_2O_2)	55	°C
Launch	Launch Acceleration	3000	g
Cruse	Radiation Dose	1500	Rad(Si)/yr
Mars	Radiation Dose	10	Rad(Si)/yr
Mars	Temp Operate	-40 to 30	°C
Mars	Temp Survival	-107 to 65	°C
Mars	Temp Var.	60	°C/day
Mars	Pressure	5-10 [1]	mb
Mars	Atmosphere	CO_2 95% [1]	NA
Mars	Humidity	<0.1 [1]	%

The parameters for the triboelectric and electric field sensors and ion gage are listed in Table 2. In order to meet these requirements, the electrometer must be designed to have very low leakage. *The high impedances needed for the electrometer and ion gage were achieved by using high resistance printed wiring boards, guard rings, one op amp per sensor, and rigorous board cleaning.*

Table 2. Instrument Performance Parameters

Parameter	Value	Units
Tribo Voltage Sensitivity	1.8	kV/V
Tribo Voltage Range	±7.2	kV
Tribo Voltage Resolution	3.5	V
Ion Curent Sensitivity	30	pA/V
Ion Current Range	±120	pA
Ion Current Resolution	60	fA

D. ELECTROMETER DESIGN: The design approach included developing three different prototypes. The first prototype, shown in Fig. 2, was designed to verify the performance of the electronics [2] over the mission temperature range and likely high voltages. The electrometer requires the maintenance of very high resistance…of the order of 10E15 ohms. *Maintaining such impedances is layout and materials dependent and was evaluated by constructing physical prototypes.*

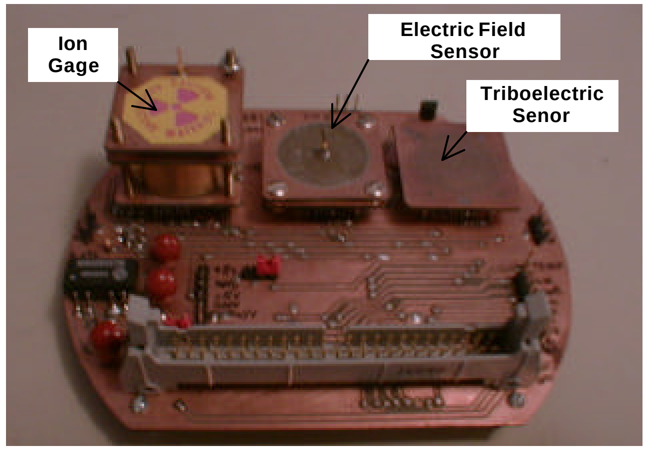

Figure 2. Initial 11.7-cm diameter prototype, ELE1, ELE2, ELE3, and ELE4, designed to verify the allowed verification of the basic design concept functionality of the electronic circuitry in the Mars chamber shown in Fig. 6.

The second prototype, shown in Fig. 3, was more flight like in that it demonstrated the approach for arraying the triboelectric sensors. It also allowed for rubbing experiments that established the sensitivity or amplifier gain of the circuitry.

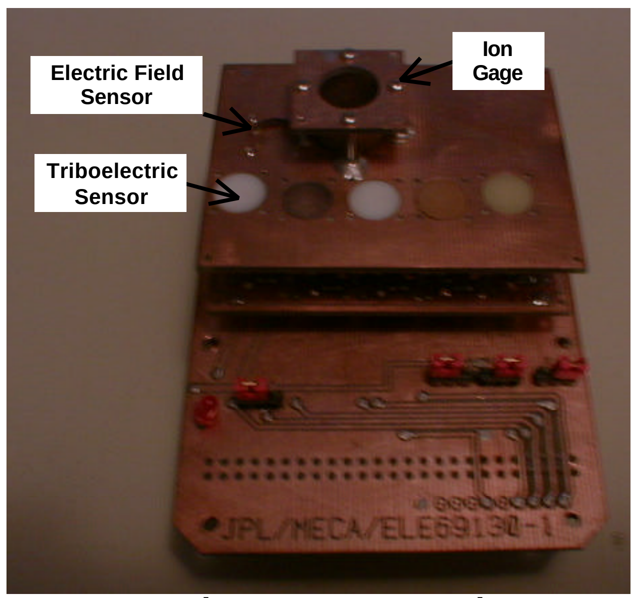

Figure 3. Second prototype, ELE5 and ELE6 7-cm wide, designed to verify triboelectric sensor array response to rubbing.

Finally, the flight article, shown in Fig. 4, illustrates the final compaction of the unit that was fitted into a titanium housing and attached to the scoop of the robotic arm. The assignment of the dielectrics for the sensors is given in Table 3 along with their dielectric constant and bulk resistivity. The dielectrics were chosen from the positive and negative portions of the triboelectric series [3].

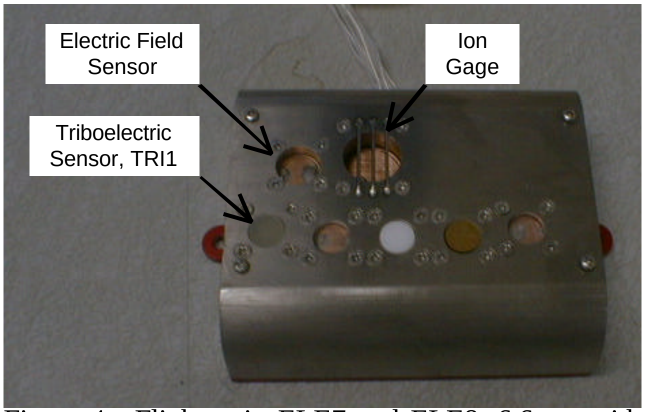

Figure 4. Flight unit, ELE7 and ELE8, 6.6-cm wide and 66 gm. The dielectrics are listed in Table 3.

Table 3. Triboelectric Sensor Dielectrics

No.	Material Name	Formal Name	Dielec. Constant 1 MHz	Bulk Resistivity (ohm-cm)
TRI1	G10, FR4	Fiberglass/ Epoxy	4.7 [4]	7.8E15 [4]
TRI2	Lexan™	Poly-carbonate	2.96 [6]	2E16 [6]
TRI3	Teflon™, PTFE	Polytetra-flouro-ethylene	2.1 [7]	1E18 [5]
TRI4	Rulon J™	--	2.4 [8]	8.2E18 [8]
TRI5	Lucite™, PMMA	Polymethly-mathacrylate	2.63 [7]	>5E16 [6] >1E14 [9]

The prototypes are listed in Table 4 along with the location of the units. The design approach included the fabrication of nine flight-like units. This number was determined by having three units for the flight team, three units for experimenters outside JPL, and two units for JPL experimentation. *Having multiple experimenters making a variety of measurements helped to identify problem early.*

The project was started in March 1998 and, as seen in Table 4, the first prototypes were started in June 1998. The flight and flight spare were delivered in mid September and October 1999.

E. FABRICATION: The electric field and triboelectric sensors and ion gage electrodes, as seen in Fig. 5, were supported above the electronics board by wires connected directly to the input of guarded operational amplifiers. Dielectrics, mentioned in Table 3, were mounted on top of the triboelectric sensors. This assembly was mounted in the titanium housing seen in Fig. 4.

Table 4. MECA/Electrometer Development Events.

PrototypeNo.	**Start**	**Comments**
ELE1 JPL	14Jun98	Switch leakage too high
ELE2 JPL	1Nov98	Ion gage evaluation
ELE3 JPL	22Nov98	Breakdown ~45 kV
ELE41 KSC ELE42 JPL	1Dec98	More breakdown studies Ion current studies
ELE5 JPL	27Dec98	Soil-dust studies
ELE61 JPL ELE62 KSC	31Jan99	First insulators installed First triboelectric rubbing First serial interface
ELE71 JPL ELE72 KSC	17Apr99	First titantium housing First automatic rubbing
ELE81 ELE82 Flight ELE83 ELE84 Model ELE85 Spare#1 ELE86 KSC ELE87 ELE88 KSC ELE89 Spare#2	2May99	Flight equipment Material selection Martian soil response

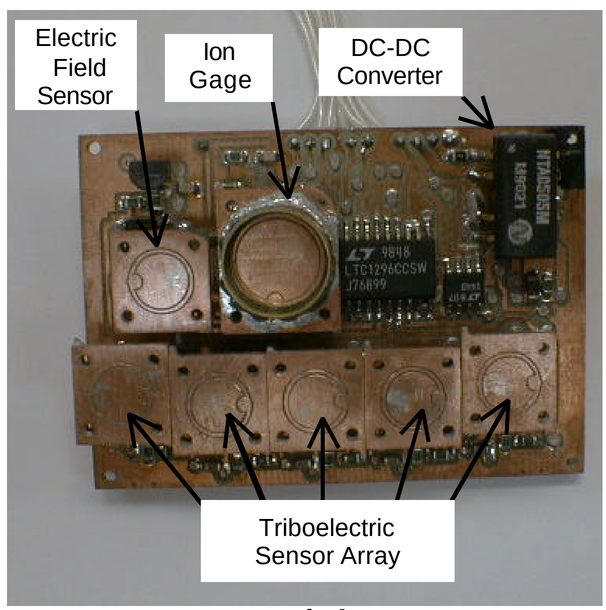

Figure 5. Top view of the 4.5 cm x 6.4 cm MECA/Electrometer printed wiring board showing the sensor electrodes.

The electrometer was fabricated in 35.5-μm double-sided copper-clad 1.52-mm FR-4 printed wiring board. The traces were cut using a milling machine with a minimum pitch of 0.5 mm. The components were hand soldered using flux-laden solder paste. The flux was removed at room temperature using an ultrasonic trichloroethylene bath followed by an acetone rinse, alcohol rinse and air dry. *This procedure insures fabrication of low-leakage electrodes required for electrometer measurements.*

Eight units were fabricated as represented by the four units pictured in Fig. 6. This facilitates the objective of having additional units for use in laboratory tests that can be used to compare with results from Mars.

Figure 6. Four Meca/Electrometers for use in laboratory measurements.

The flight units were given a planetary protection procedure intended to sterilize using an H_2O_2 plasma. The procedure was carried out in a chamber heated to 55°C. The chamber was evacuated five times and an H_2O_2 plasma created for 5 minutes.

F. TEST APPARATUS: The characterization of the electrometer involved testing the units over a variety of: (a) temperatures, (b) pressures, (c) atmospheres, (d) humidity, (d) rubbing and (e) vibration conditions. Three apparatuses were used to perform the characterization. The Mars chamber, shown in Fig. 7, can produce environments with temperatures between –100 to 200°C, pressures between 0.01 to 1013 mb, and atmospheres of air and CO_2.

The chamber, shown in Fig. 8, is housed in an oven that is used to control the temperature by cooling with LN_2 and resistive heating. The brass chamber has a 12.5-cm diameter and 12.5 height. A rough pump creates pressure in the chamber where the desired atmosphere is introduced through a controlled leak.

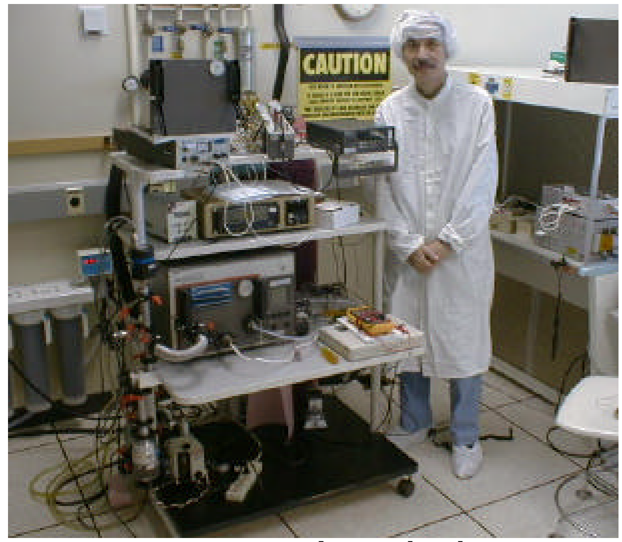

Figure. 7. JPL Mars simulation chamber apparatus in MECA Lab contained on a movable cart.

The temperature of the gas inside the chamber is at the temperature of the chamber wall. Knowing the gas temperature and pressure is important in characterizing electrostatic charging and breakdown phenomena.

Figure 8. Mars chamber brass jar, 12.5-cm diameter and 12.5 height, shown next to the oven used to control the chamber temperature.

The chamber was used to characterize the basic functionality of the electrometer over the temperature range from –100 to 40°C. Of concern was the dc-dc converter, seen in Fig. 5, which was successfully operated after a cold start at –100°C.

The chamber was also used to characterize the triboelectric response to rubbing the sensors with wool felt. Two rubbing apparatuses were developed. In the apparatus, shown in Fig. 9, the electrometer is stationary and the rubbing media is moved across the sensor head by a motor-driven linear actuator. Head pressure is determined by the weight of the electrometer.

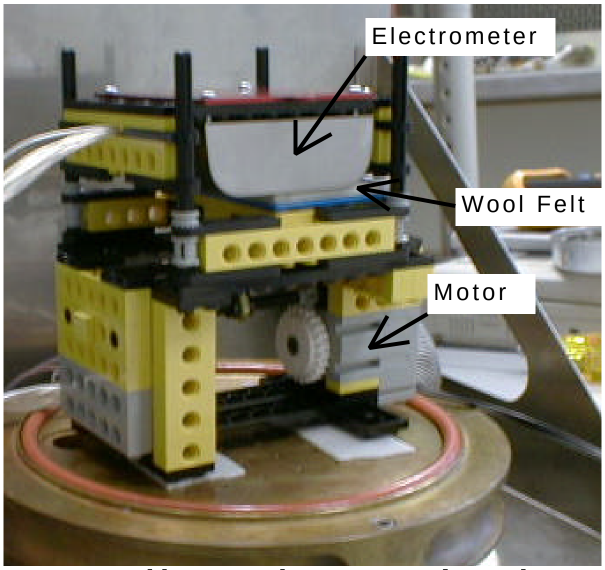

Figure 9. Rubbing machine mounted on the Mars chamber plate.

In the rubbing machine, shown in Fig. 10, the electrometer moves via a motor-driven linear actuator across the rubbed media attached to a platform. Pressure to the sensor head is applied by a weight and pulley system attached to the sample platform guided by a slider. This apparatus is housed in a temperature and pressure controlled chamber. Results from this apparatus are comparable to the machine shown in Fig. 9. However, the stroke and rubbing speed are higher and better controlled in this machine than the one shown in Fig. 9.

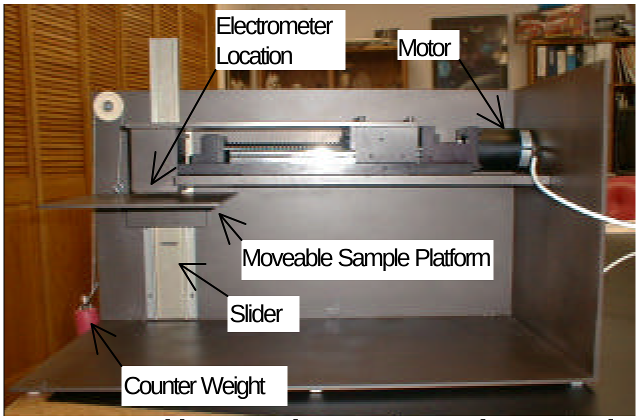

Figure 10. Rubbing machine 61-cm wide use in the Materials Science Laboratory at KSC.

The vibration of the electrometer was accomplished using the configuration shown in Fig. 11. Of concern was 28 0-80 flathead fasteners that secure the sensors to the electrometer housing. To eliminate problems, the ends of the fasteners were secured using solithane. Tests were performed before and after vibration to verify functionality.

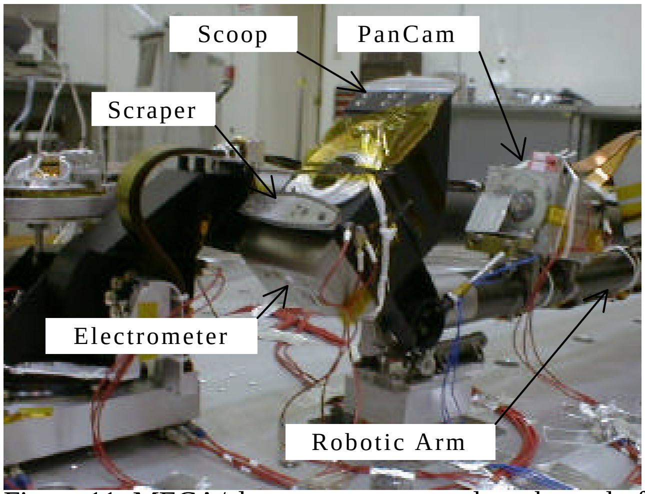

Figure 11. MECA/electrometer mounted on the end of the Mars ’01 robotic arm arranged for vibration tests.

G. TEST RESULTS: The response of the electric field and triboelectric sensors is shown in Fig. 12. In this test, teflon is charged negatively by rubbing with wool felt. The charged teflon is placed before the sensors for about 20 seconds.

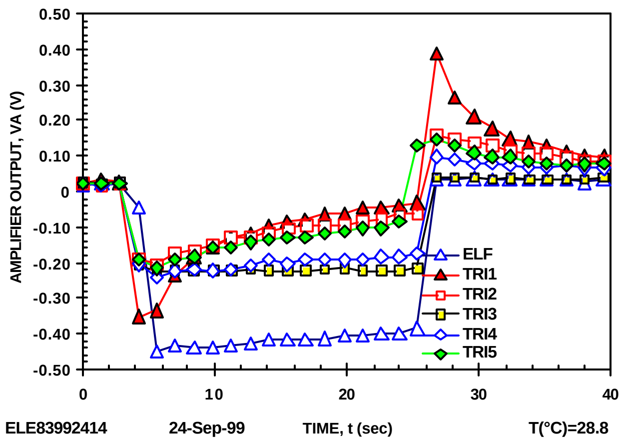

Figure 12. Response of ELE83 to white-wool felt charged teflon (charged negatively) between 5 and 26 s after start of test.

The response shows that three sensors, ELF, TRI3, and TRI4, have only a negative response. The other three, TRI1, TRI2, and TRI5 have both a negative and positive response. This is indicative of the resistivity of the dielectrics. That is, during the time the negatively charged teflon is present, positive charge leaks into the lower resistivity dielectrics to neutralize the negative charge on the teflon. Upon removal of the teflon, the positive charge leaks away producing the positive response.

The electrometer's long-term response, shown in Fig. 13, indicates that the sensors have low-leakage currents. That is, a 0.6 V drift after 10 hours, corresponds to an op amp input current of 5 fA given an input capacitance of 10 nF and amplifier gain of 4. The variability between sensors is due in part to differences in op amp input currents. As shown elsewhere [2], the leakage currents decrease dramatically at low temperatures. Thus, the electrometer leakage current is satisfactory for making measurements on Mars that will be less than 100 seconds in duration. Figure 13 also shows the ion gage response which has a sensitivity of 30 pA/V. The full scale ion gage capability is 120 pA and the resolution is 60 fA.

The voltage response of the electric field and triboelectric sensors, shown in Fig. 14, is due to the dielectric between the sensing electrode, seen in Fig. 5, and the test plate used in these measurements. On average, the triboelectric-sensor sensitivity is 1.8 kV/V and full-scale detection capability and resolution is 7.3 kV ± 3.5 V. The full scale charge detection capability and resolution is 1800 ± 0.9 pC. The charge particle resolution is 5.5 million charges.

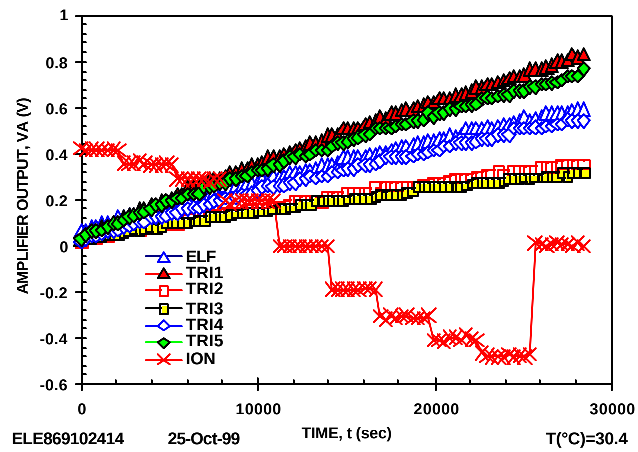

Figure 13. Electrometer, ELE86, ten-hour characterization test at room ambient at 30 % RH with a 1-µC Am-241 source exciting the ion gage biased in one volt steps between – and +4 V.

The design approach was biased in favor of a wide dynamic range rather than high sensitivity. It is important that the measurements on Mars not exceed full scale.

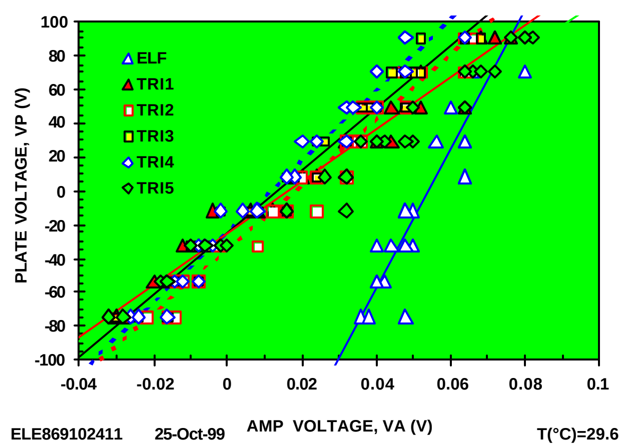

Figure 14. ELE86 test where the sensitivity of the electric field sensor is 4.1 kV/V and triboelectric sensors are ~1.8 kV/V.

Rubbing measurements, shown in Figs. 15 and 16, illustrate the response that can be expected on Mars. The results, shown in Fig. 15, were taken near ambient conditions. Using the average triboelectric sensor response, the 1 V response corresponds to 1.8 kV generated on TRI3 and TRI4.

The response shown in Fig. 16, was measured at 450 mb, which is approximately half an atmosphere. As seen in the figure, a voltage close to 1 V was generated while the rubbing media is in contact with the TRI3 and TRI4 but this voltage can not be sustained once the sensors separate from the sensing media. Thereafter, the response of TRI3 and TRI4 drops to a value dictated by the Gauss breakdown voltage limit [Cross]. The charging of TRI1, TRI2, and TRI5 are unaffected at this pressure. This behavior provides a glimpse into the response at lower pressures.

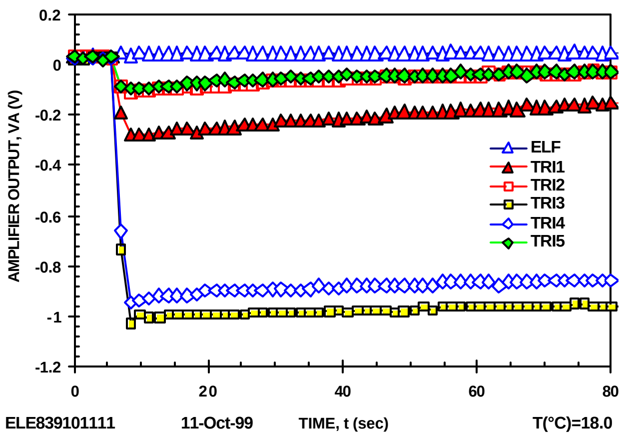

Figure 15. ELE83 rubbed in air on white-wool felt at 890 mb and 18.0°C.

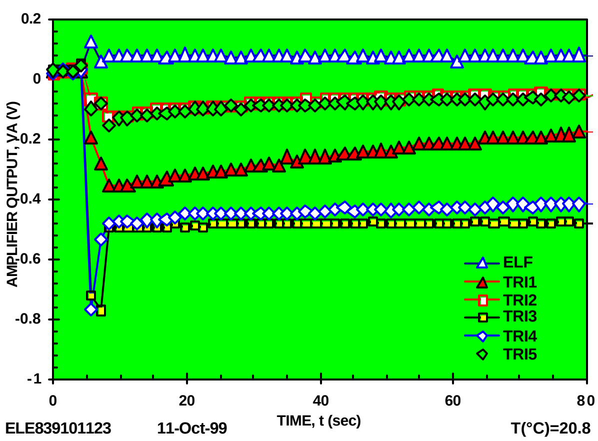

Figure 16. ELE83 rubbed in air on white-wool felt at 445 mb and 20.8°C.

H. DEVELOPMENT PRINCIPLES: The fabrication of this electrometer used the following principles in its development:

1. Design Principles:

a. Use conservative minimum layout design rules; in this case 0.5 mm pitch was used.
b. Keep the operation simple by not using autoscaling but be prepared to sacrifice sensitivity for a wide dynamic range.
c. Use off-the-shelf components to speed development but see 3a.
d. Preserve electrometer and ion gage high impedances using guard rings and a one op amp per sensor approach. Do not attempt to multiplex high impedance circuits.
e. Design for cleanliness so that high impedances are maintained and planetary protection sterilization procedures are simple.

2. Fabrication Principles:
a. Use rigorous cleaning procedures to maintain high impedances.
b. Use H_2O_2 sterilization at 55°C to keep temperatures lower than heat sterilization procedures.

3. Test Principles:
a. Test components early to ensure operability over the Martian temperature range.
b. Make many prototypes to (a) facilitate problem solving by having several units under test at one time and (b) gather statistics to determine operating conditions which are difficult with novel high impedance circuitry.
c. Test under realistic conditions by developing simple test apparatus such as the rubbing machines shown in Figs. 9 and 10.

I CONCLUSION: The development of this novel instrument occurred within an 18 month period because of the design simplicity which allowed production of twenty units, attention to detail in the fabrication cycle including rigorous cleaning, and parallel testing that identified problems early. Attention was focussed on maintaining high impedance circuitry in the design (guard rings and one op amp per sensor) and fabrication (chemical cleaning).

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