

## The Effects of Neutral Gas Release on Vehicle Charging: Experiment and Theory

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### ABSTRACT

This paper describes an experimental and theoretical research effort related to the mitigation of spacecraft charging by Neutral Gas Release (NGR). The Space Power Experiments Aboard Rockets programs (SPEAR I and III) [Mandel *et al.*, 1998; Berg *et al.*, 1995] and other earlier efforts have demonstrated that NGR is an effective method of controlling discharges in space. The laboratory experiments were conducted in the large volume Space Physics Simulation Chamber (SPSC) at the Naval Research Laboratory (NRL). A realistic near-earth space environment can be simulated in this device for which minimum scaling needs to be performed to relate the data to space plasma regimes. This environment is similar to that encountered by LEO spacecraft, e.g., the Space Station, Shuttle, and high inclination satellites.

The experimental arrangement consists of an aluminum cylinder which can be biased to high negative voltage ( $0.4 \text{ kV} < V < 10 \text{ kV}$ ) and diagnostics. The cylinder incorporates a neutral gas release valve designed for millisecond release times, a pressure-regulated neutral gas reservoir, and variable Mach number nozzles. After the cylinder is charged to high voltage, the neutral gas is released, inducing a breakdown of the gas in the strong electric field about the cylinder. Collection of ions from the newly created dense plasma, along with secondary electron emission from the cylinder surface, provide the return current necessary for grounding the body.

The theoretical treatment assumes a simple Townsend discharge along with the fundamental assumption of exponential electron growth in an

avalanche fashion as one proceeds from the cathode toward the anode during neutral gas breakdown in the presence of high potentials. In addition the nozzle release of neutral gas is modeled and a simple linear spatial dependence of the applied potential is assumed. This basic model produces quite good results when compared to the experiment.

### I. Experimental Description

The SPSC is a 1.8-m diameter by 5-m long cylindrical vacuum chamber shown in Figures 1 and 2 which can be evacuated to a background pressure near  $10^{-6}$  torr. The basic parameter regimes can be found in [Walker *et al.*, 1998 (a,b)]. A number of experiments have been performed in the chamber in addition to those described here [Amatucci *et al.*, 1996, 1998(a,b); Walker *et al.*, 1995, 1997, 1998(a,b)]

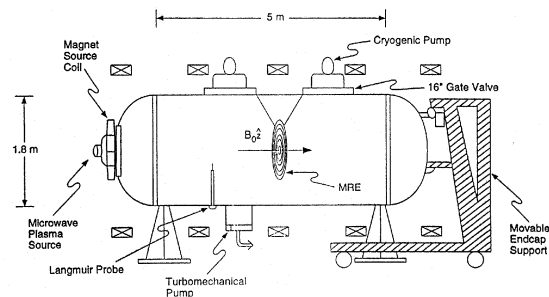


Figure 1

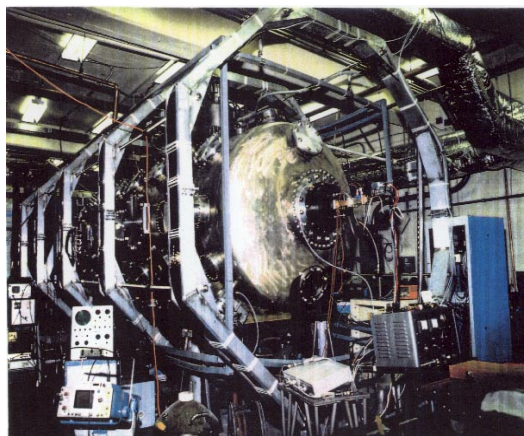


Figure 2

## II. Electronics: charging and discharging scenario

Figure 3 shows a schematic representation of a one cylinder experimental arrangement whereas Figure 4 is a photograph of a two cylinder configuration used to simulate the SPEAR III geometry. In the laboratory the small cylinder in Figure 4 was removed from the experiment and a neutral gas release valve was placed in the large cylinder. The single aluminum cylinder is 10 cm in diameter and 10 cm in length. Two separate nozzles, designated M3(Mach 3) and M9(Mach 9) were used to release the neutral gas after charging.

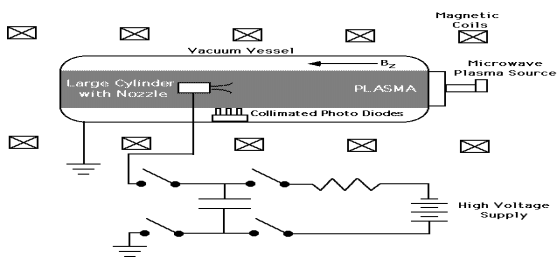


Figure 3

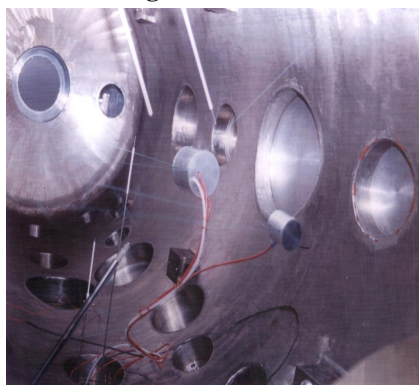


Figure 4

During the discharges, cylinder voltage and current collected by the cylinder were measured as functions of time. These parameters are shown for a typical run in Figure 5. For measurement purposes, several in-house-developed diagnostics were used including a high voltage sensor [Siefiring et al., 1995] which was developed and used in the laboratory testing in the determination of plasma potential.

## III. Experimental Results

In these studies we have done work related to the effects of NGR in discharges where the voltage applied to the cylinder is varied from about -600 V to -2400 V. Figure 6 is a plot of the minimum potential necessary to initiate breakdown versus plenum pressure for three

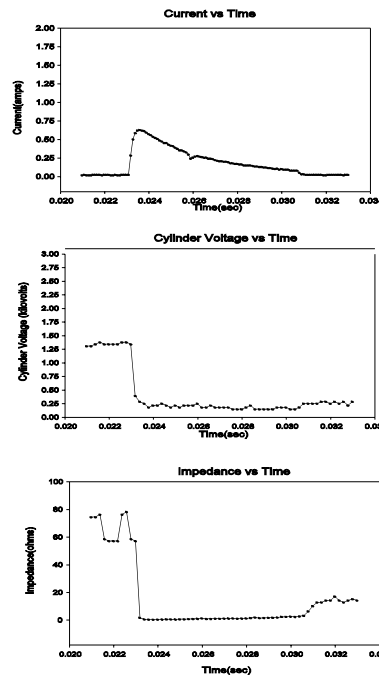


Figure 5

separate gas puff species using only the M9 nozzle. Each point in Figure 6 corresponds to an average of 10 separate experimental runs. From this plot one can conclude that krypton and argon initiate breakdown at a lower potential than neon for the same gas plenum pressure

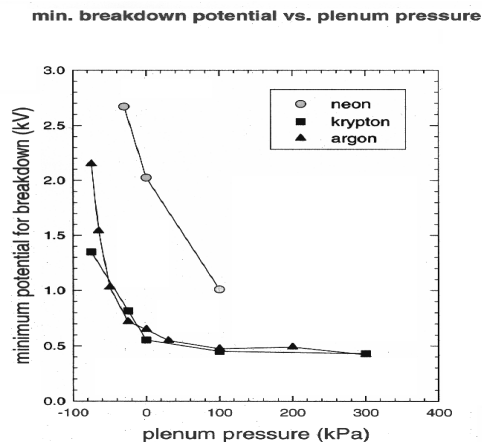


Figure 6

Figure 7 shows results of the discharge studies for argon only. Each data point is again an average of 10. The preliminary conclusion from this data is that the M9 nozzle discharges the cylinder at lower potentials than the M3.

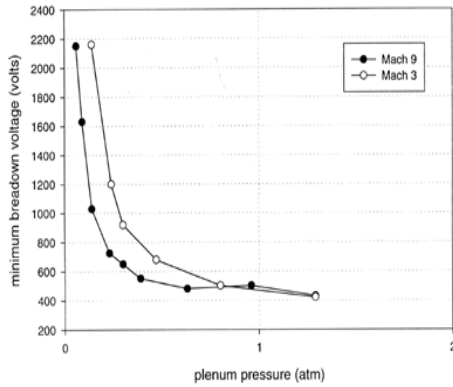


Figure 7

#### IV. Theory

##### The Discharge Model

The study of neutral gas breakdown in the presence of high potentials has been underway since the beginning of this century [Townsend, 1900, 1901; Loeb, 1939; Raizer, 1997]. The fundamental assumption is that the number of electrons grows exponentially in an avalanche fashion as one proceeds from cathode toward anode:

$$N(x) = N_0 \exp\left[\int_0^x \alpha(x) dx\right] \quad (1)$$

where  $N_0$  is the number of electrons released from the cathode and  $\alpha$  is the Townsend ionization coefficient and is defined as the number of ionization events performed along a 1 cm path in the electric field direction. An empirical formula for  $\alpha$  for inert gases [Raizer, 1997]

$$\alpha = B_1 N e^{-B_2 \left(\frac{N}{E}\right)^{1/2}} \quad (2)$$

is used in much of the theoretical and numerical analysis, where  $B_1$  and  $B_2$  are empirical “constants” determined from experimental plots of the electric field necessary for breakdown versus neutral pressure for various inert gases.

The condition for a self-sustaining discharge [Raizer, 1997] is,

$$I = \int_0^{\infty} dx \alpha(x) \geq \ln(1 + \gamma_i^{-1}) \quad (3)$$

where  $\gamma_i$  is the coefficient for electron emission from the cathode per incident ion. This condition essentially states that a discharge will be able to sustain itself if each electron generated from the cathode produces sufficient ionization (through collisions with the neutral gas) such that the resultant secondary emission (caused by this ionization) is sufficient to replace at least the original electron. For  $\gamma_i \sim 0.15$ , for example, the right hand side of this equation equals 2.

##### Expansion with nozzles

In a nozzle the flow is primarily one dimensional through an area which varies with distance. The area first constricts to a minimum at the throat where the flow speed becomes the local sound speed,  $V_t = (\gamma T_t / m)^{1/2}$  where  $T_t = (2/\gamma + 1)T_c$  is the gas temperature at the throat. . Using part of the analysis by Barrere [1960, Ch. 2], we can show that the nozzle area  $A$  and velocity  $V$  are related to the values at the throat by,

$$\frac{A_t}{A} = \frac{V}{V_t} \left[ \left( \frac{\gamma + 1}{2} \right) \left( 1 - \left( \frac{V}{V_t} \right)^2 \right) \right]^{\frac{1}{\gamma - 1}} \quad (4)$$

Nozzle mach numbers are typically quoted by using the ratio of  $V_e$  to the local sound speed,  $V_{st}$ , at nozzle exit or,

$$M \equiv \frac{V_e}{V_{st}} = \frac{V_e}{V_s} \sqrt{\frac{T_c}{T_e}} = \left( \frac{V_e}{V_s} \right)^{\frac{2\gamma - 1}{2(\gamma - 1)}} \left[ \frac{A_e}{\Gamma A_t} \right]^{\frac{1}{2(\gamma + 1)}} \quad (5)$$

Here  $A_e$  is the exit area,  $V_s$  is the speed of sound in the plenum and  $T_e$  is the exit temperature which we can find from,

$$\frac{T_e}{T_c} = \frac{2}{1+\gamma} \left[ \frac{A_t V_t}{A_e V_e} \right]^{\gamma-1} \quad (6)$$

**Expansion after leaving nozzle**

Because there is residual energy in the gas, the expansion accelerates longitudinally and transversely. The longitudinal acceleration is negligible, however, because the exit temperature is small compared with the plenum temperature,  $T_e \ll T_c$ . For example, for the M3 nozzle,  $T_e/T_c = 0.05$  according to Eq. (6); for the M9 nozzle this ratio is even smaller. Therefore, past the nozzle it is legitimate to approximate  $V(z) \sim V_e$ .

Transverse acceleration is generally small as well. To show this, we observe that the gas can be treated as a jet moving with a fixed longitudinal speed,  $V_e$ , outside the nozzle. Since the transverse velocity is presumed small,  $V_{\perp} \ll V_e$ , the jet can be treated as a freely expanding, long beam. In that case the area expands as [Fernsler et al., 1994],

$$A(z) = A_e + 2z\sqrt{\pi A_e} \tan\theta_0 + \pi z^2 \left[ \tan^2\theta_0 + \frac{2T_e}{mV_e^2} \right] \quad (7)$$

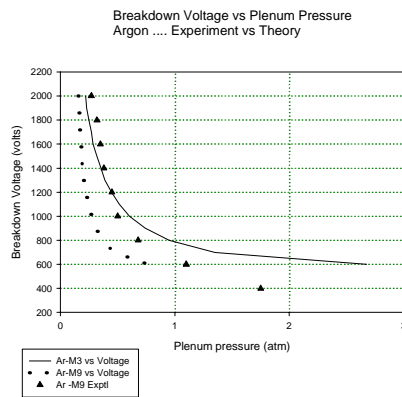
where  $\theta_0 = V_{\perp}/V_e$  (at  $z=0$ ) is the half-angle of the nozzle. This expansion produces a larger area at a given  $z$  than simple cylindrical expansions due to the presence of thermal energy.

**V. Comparisons of Theory and Experiment**

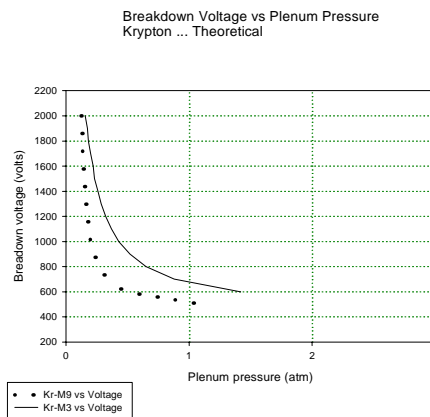
**Breakdown potentials versus gas flow**

Using the criterion outlined in Eq (3) above we plot in Figures 8 through 10 the predicted breakdown voltages for the three gases used in the experiment and for each of the two nozzles. The plot of Figure 8 also shows the argon data superimposed on the theoretical plots. From these plots, the lightest gas tested, neon (Figure 10), requires significantly higher levels of release gas to break down for a given cylinder charging voltage than either argon or krypton. This result is

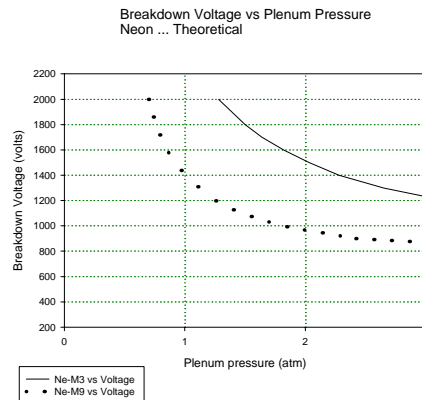
consistent with the data shown in Figure 6 and is indicative of the fact that krypton and argon are easier to ionize than neon.



**Figure 8**



**Figure 9**



**Figure 10**

If we examine the breakdown condition of Eq.(3) in somewhat more detail the integral appears as,

$$I = \int_{z_L}^{\infty} N(z,p) c_1 e^{\frac{-c_2}{\sqrt{\frac{E(z)}{N(z,p)}}}} dz \quad (8)$$

where  $N(z,p)$  is neutral density given by,

$$N(z,p) = \frac{F_0(p)}{A(z)V_e}, \quad (9)$$

and  $z_L$  is the lower integration limit.  $F_0(p)$  is the conserved neutral particle flux from the plenum,  $A(z)$  is as given in Eq. (7) and  $V_e$  is the exit velocity which is calculated from the area ratio of Eq. (4). This relation assumes that the velocity of the exit gas is constant as a function of distance from the release point. We note specifically that  $z_L$  corresponds to the surface of the charged object where spherical symmetry is assumed, *i.e.*,  $z = 0$  is taken as the origin of a charged sphere for definition of the spatial falloff of the potential. In this analysis then, the electric field and potential have the simple one-dimensional form,

$$\Phi(z) = -V_{ch} \left( \frac{z_L}{z} \right) \quad \therefore \quad E(z) = V_{ch} \left( \frac{z_L}{z^2} \right) \quad (10)$$

where  $V_{ch}$  is the charging potential. With the definition of  $z_L$  as above, we are assuming that the exit area of the nozzle is at the surface of the cylinder; therefore  $A(z_L)$  corresponds to  $A_e$  in Eq. (4) and  $N(z_L,p)$  is the gas density at the exit area face (note, not the throat).  $F_0(p)$  is dependent upon the pressure,  $p$ , and temperature,  $T$ , in the plenum, the release gas molecular mass,  $\mu$ , and the area of the nozzle throat,  $A_t$ , *i.e.*,

$$F_0(p) = \Gamma \frac{p A_t}{\sqrt{mRT}} \quad (11)$$

In this equation, the molecular mass,  $m$ , is in kg,  $p$  in pascals,  $A_t$  in  $m^2$ ,  $T$  in Kelvin,  $\Gamma$  is a function of the adiabatic constant [Walker, *et al.*, 1998(a,b)], and  $R$  is the universal gas constant.

### Breakdown dependence on release-gas Mach number

As demonstrated above the gas density at a fixed distance from the nozzle is independent of mass; however, not of exit velocity and therefore (local) Mach number as seen in Eq.(5). Since the variation of pressure in the plenum is essentially an isothermal process, only the gas density is affected and not the exit velocity as would be the case were the temperature allowed to vary. The density decreases going away from the cylinder as the area of the expanding cone widens. However, the gas exits the M9 nozzle faster but is colder than the M3, *i.e.*, its perpendicular temperature is less. Therefore, gas from M9 expands less than from M3 so that, at a fixed distance from the nozzle, the area of the gas front is smaller. This effect is much stronger than either the density dependence on speed or distance from the nozzle. The net result is that there is a higher relative density at a fixed distance from the cylinder for the higher Mach number nozzle and therefore breakdown is easier. Although not shown, the density continues to decrease as a function of exit velocity to the point that at the limit that the velocity ratio is 2, we produce an infinite area and hence a density decrease to zero. These theoretical arguments suggest that the higher mach number nozzles should produce breakdown with less gas pressure than lower mach number nozzles. These results are corroborated by the experimental plots.

### VI. Summary

We have conducted laboratory simulations and developed a basic theoretical model of the effects of neutral gas release on space vehicle charging in the LEO space environment. The experiments were performed in the NRL Space Physics Simulation Chamber.

The results presented here are the first stage of a more exhaustive investigation into the optimum choice of a release gas and release speed in order that spacecraft which acquire potentials either through natural or artificial means can discharge these voltages at the lowest level possible. The Townsend discharge model and breakdown criterion expressed through the integral of Eq (3) explain experimental results quite well. Because of the success of this model we are in the process of continuing work with it in order to guide certain phases of the experimental effort and to suggest nozzle and gas release designs for optimum performance.

We are able to conclude that argon and krypton tend to discharge the payload at lower potential than neon and that the M9 nozzle is better at discharging for a given plenum pressure than M3 nozzle. We are continuing this experiment with studies using different neutral gases and mixtures of neutral gases, with different cylinder surfaces and with varying electron and neutral gas environments. In addition we are investigating the effect of the orientation of the puff with respect to the local magnetic field and geometrical effects.

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