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Low-Pressure Gas Effects on the Potency of an Electron Beam Against Ceramic Cloth

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LOW-PRESSURE GAS EFFECTS ON THE POTENCY OF AN ELECTRON BEAM AGAINST CERAMIC CLOTH

1. INTRODUCTION

The need for pressure hull repairs that will not leak in the environment of space even after being subjected to multiple cycles of thermal stress would alone make the development of space welding techniques desirable. Just as on Earth, in space there are many cutting, joining, and other tasks that can be dealt with expeditiously using welding equipment.

A Ukrainian-designed electron beam welder, the Universal Hand Tool (UHT), has already seen trials in space. In anticipation of electron beam welding in space, the question has arisen as to the extent of the hazard that is presented by the impingement of the electron beam upon fabric that might be used as a protective garment for astronaut welders.

Nextel AF–62 ceramic cloth designed to withstand temperatures up to 1,427 °C emerged from preliminary fabric screening tests as a potentially beam-resistent fabric. This report comprises an account of the effects of impingement of the UHT electron beam upon Nextel AF–62 ceramic cloth with an interpretation of the impingement effects. Only a limited number of observations were made; but these observations, while varied and complex in themselves, become qualitatively intelligible when interpreted as a result of low-pressure gas effects.

If the effect of gas pressure is ignored, the electron beam should rapidly lay down a surface charge on the cloth, and that surface charge should repel further incursions of the beam before any substantial heating of the cloth takes place. However, although beam deflections due to apparent charging were occasionally observed, it generally took no more than a few seconds for the beam to penetrate the cloth.

The power available in the beam is ample for welding thin sheet metal. The UHT delivers a current in the neighborhood of 75–80 mA at a setting of mode 6 and 100–105 mA at mode 8 at ≈8 kV, for powers ranging from 600–840 W. This level of power is estimated to be sufficient to melt the 2.4-mm-diameter disc of ceramic cloth that intercepts the beam in a fraction of a second. However, delays to burnthrough on the order of seconds were observed in tests[1] carried out at Marshall Space Flight Center in December 1995, as shown in table 1.

Table 1. Nextel burnthrough delay times.

UHT Standoff/ Beam Length (in.)	Burnthrough Delay Time (sec)		
	Single Layer	Double Layer	Triple Layer
2	–	27	30
6	–	8	8
12	18	7	8
24	–	8	6
48	>60	–	–

The beam setting was mode 7 for the double and triple layer and mode 6 for the single layer. The cloth sample size was ≈10 × 12 in. for the double and triple layer and 4 × 12 in. for the single layer. The cloth mounting frame was grounded.

A burnthrough delay time on the order of 6–8 sec was observed for the double and triple layer tests at intermediate standoff distances of 6–24 in. The anomalous 18-sec delay for the single layer fabric at 12 in. may be due to slightly reduced power (mode 6 instead of mode 7) and perhaps to some loss of heat from backside outgassing.

Substantially longer delays are observed at very short (2 in.) standoffs and also at very long standoffs if the evidence of a single measurement is sufficient to draw a conclusion. Occasional observations of UHT arc cutoff at short standoffs suggest that this could be a factor in lengthening delay times at short standoffs, but the explanation to be proposed does not require this.

2. INTERPRETATION OF RESULTS

The initial expectation was that the electron beam would lay down a negative charge on the insulating fabric that would repel further interaction and that the beam would not penetrate an insulating fabric. When it was found that the beam did indeed burn through insulating fabric, even thermally resistant ceramic fabric, an explanation was needed.

With an imperfect vacuum it is possible to see a faintly glowing parabolic sheath of excited atoms around the electron beam.[2] If some electronic collisions in the beam produce positive ions, these ions will be attracted to the negatively charged fabric and they will contribute their kinetic energy toward heating the fabric. Once positive ions are formed they are attracted to the negatively charged cloth so swiftly as to remain in a tightly packed group, essentially a beam (app. A). If heat is contributed faster than it can be conducted away through the fabric, the fabric temperature will increase until vapor emissions create conditions favorable for arcing and the full power of the beam impinges on the fabric. The full power of the beam is capable of causing immediate burnthrough.

A very rough preliminary analysis of this burnthrough process (app. B), while hardly conclusive, does appear to lend credence to an explanation in terms of power transmission by positive ions.

$$t_b \approx \frac{r_b^2}{4\alpha} e^{\frac{4\pi k w (T_b - T_o)}{P_+} + \gamma} \quad (1)$$

where

T_b = burnthrough temperature
T_o = ambient temperature
P_+ = positive ion beam power
t_b = burnthrough time
α = thermal diffusivity = $k/\rho C$ (0.025 cm^2/sec)
k = thermal conductivity of fabric (0.02 W/cm K estimated)
ρ = density of fabric (0.82 gm/cm^3)[3]
C = specific heat of fabric (1 W sec/gm K)[3]
r_b = radius of electron beam
w = thickness of fabric (0.12 cm)[3]
γ = Euler's constant = 0.5772

and

$$P_{+} \approx I_o V_o \left(\frac{q_i}{q}\right)\left(\frac{\sigma_i}{\sigma_s}\right)\left\{2\sqrt{\frac{L}{\lambda}}\left[D\left(\sqrt{\frac{L}{\lambda}}\right) - e^{-\frac{L'}{\lambda}} D\left(\sqrt{\frac{L-L'}{\lambda}}\right)\right]\left[\frac{1}{3\pi}\left(\frac{q_i V_o}{2kT}\right)^{\frac{3}{2}}\left(\frac{r_b}{L}\right)^{3}\right]\right.$$

$$\left. + \frac{\lambda}{L} e^{-\frac{L}{\lambda}}\left[1 - \left(1 - \frac{L-L'}{\lambda}\right) e^{\frac{L-L'}{\lambda}}\right]\right\}, \tag{2}$$

where

$$L' = \left[1 - \left(\frac{1}{3\pi}\right)^{\frac{2}{3}}\left(\frac{r_b}{L}\right)^{2}\left(\frac{q_i V_o}{2kT}\right)\right] L \ , \tag{3}$$

and

I_o = initial electron current produced by UHT
V_o = accelerating voltage of electron beam current (beam power = $I_o V_o$)
q_i = ionic charge
q = electronic charge
σ_i = ionization cross section
σ_s = scattering cross section
L = UHT to fabric standoff
λ = collision mean free path

$D(u) \equiv e^{-x^2}\int_0^x e^{u^2}\,du$ = Dawson's Integral

r_b = electron beam radius
k = Boltzmann's constant
T = temperature of contaminant gas,

provided that

$$L > r_b \sqrt{\left(\frac{1}{3\pi}\right)^{\frac{2}{3}}\left(\frac{q_i V_o}{2kT}\right)} \ . \tag{4}$$

If, on the other hand,

$$L \leq r_b \sqrt{\left(\frac{1}{3\pi}\right)^{\frac{2}{3}} \left(\frac{q_i V_o}{2kT}\right)} , \tag{5}$$

then

$$P_+ \approx I_o V_o \left(\frac{q_i}{q}\right)\left(\frac{\sigma_i}{\sigma_s}\right)\left\{\frac{\lambda}{L} e^{-\frac{L}{\lambda}}\left[1 - \left(1 - \frac{L}{\lambda}\right) e^{\frac{L}{\lambda}}\right]\right\} . \tag{6}$$

This explanation leads to the expectation that at low standoffs due to the creation of fewer positive ions in the shorter beam the burnthrough times become longer as observed. At long standoffs, more and more of the power carried by positive ion beam impinges outside the target disc of the electron beam so that the power density decreases and the burnthrough delay time increases. Hence, as observed, the burnthrough times rise at both short and long standoff distances and dip to a minimum at intermediate distances.

The material constitution is thought to have its effect on burnthrough, but the precise nature of the effect is not clear from the present observations. In order to make the results of the computations agree with the observed data, there needs to be assumed either (1) a low burnthrough temperature on the order of only 100 °C above ambient or (2) a beam target thickness on the order of the fibers in the fabric and not the fabric itself.

A low burnthrough temperature suggests arcing induced by the emergence of adsorbed gas from the fabric. Rigorous outgassing of the fabric before exposure to the beam could make it more difficult for an electron beam burnthrough to occur—so could thicker fibers or a dense nonfibrous structure, which would reduce the area for gas adsorption.

Component parts of composite structures, for example the fibers in cloth, may be heated much hotter than the average temperature of the structure. A cylindrical fiber of unit length on the surface of the cloth has an area exposed to the beam proportional to its diameter. The area through which excess heat can be conducted away is proportional to the square of its diameter. Temperatures to maintain equilibrium should therefore be inversely proportional to the fiber diameter. Heavier fibers or fully dense solids may make it more difficult for electron beam burnthrough to occur. But data are needed before any conclusions can be drawn.

3. CONCLUSIONS AND RECOMMENDATIONS

An 8-kV electron beam from the UHT welder operating with a current in the neighborhood of 100 mA at ambient pressures near or below 10^{-4} torr burns holes in Nextel AF–62 ceramic cloth designed to withstand temperatures up to 1,427 °C. This was a surprise to those who expected the cloth to be unaffected by the electron beam due to a rapidly acquired static charge, which would repel further effects of the beam. The following are conclusions drawn from the experimental data:

- Burnthrough times of the order of 8 sec for the UHT to work standoff distances ranging from 6–24 in. are much slower than would be the case if the full power of the electron beam were brought to bear.
- Burnthrough times increase rapidly at longer standoff distances (>60 sec for 48 in.).
- Burnthrough times increase rapidly at shorter standoff distances (in the neighborhood of 30 sec for 2 in.).

The following explanations for the above observations are proposed:

- Burnthrough is a result of a positive ion beam generated by collisions between 8-kV electrons and contaminant gas in the "vacuum" chamber.
- Burnthrough times are long because the positive ion beam carries only a fraction of the power of the electron beam.
- Burnthrough times increase rapidly at longer standoff distances because the positive ion beam expands with distance and its power density is thereby reduced.
- Burnthrough times increase rapidly at shorter standoff distances because of less contaminant gas available for electronic collision in the shorter standoff gap.

Based on the above explanatory model, a rough quantitative theory was synthesized (app. B). With plausible parameters incorporated, the quantitative model yields a minimum burnthrough time on the order of the observations and within the standoff range observed. Otherwise, the agreement is not particularly good, the minimal burnthrough time range of the computation being narrower than the observed range. Considering the crudeness of the computations, the result is considered adequate to establish the plausibility of the explanation. Refinement and validation of the theory are left for future work.

Finally, it must be emphasized that the data upon which the above conclusions are based is very meager; hence these conclusions should be regarded as tentative only. Further experimental work is required to form a basis for a secure theory of the potency of an electron beam against ceramic cloth.

APPENDIX A—SURFACE CAPTURE TIME FOR IONS GENERATED IN BEAM

If the ion is located at distance x along the beam axis from the fabric,

$$m\frac{d^2x}{dt^2} = -Ee = -\frac{\sigma e}{2\varepsilon}\left[1 - \frac{1}{\sqrt{1+\frac{R^2}{x^2}}}\right] . \tag{7}$$

Hence,

$$d\left(\frac{1}{2}\left(\frac{dx}{dt}\right)^2\right) = -\frac{\sigma e}{2m\varepsilon}\left[1 - \frac{1}{\sqrt{1+\frac{R^2}{x^2}}}\right]dx \ , \tag{8}$$

and carrying out the integration from collision site at x_o where the velocity is taken to be zero,

$$\frac{dx}{dt} = -\sqrt{\frac{\sigma e}{m\varepsilon}\left[\left(x_o - \sqrt{x_o^2 + R^2}\right) - \left(x - \sqrt{x^2 + R^2}\right)\right]} \tag{9}$$

and the time for collision of ion with fabric is

$$t = \int_{x=0}^{x=x_o} \frac{dx}{\sqrt{\frac{\sigma e}{m\varepsilon}\left[\left(x_o - \sqrt{x_o^2 + R^2}\right) - \left(x - \sqrt{x^2 + R^2}\right)\right]}} \ . \tag{10}$$

If the standoff distance of the UHT is $L \gg R$ and $x_o = L$, then

$$t \approx \int_{x=0}^{x=x_o} \frac{dx}{\sqrt{\frac{2VeR^2}{mLx}}} = \left[\sqrt{\frac{2mLx_o^3}{9VeR^2}}\right]_{x_o=L} = \sqrt{\frac{2mL^4}{9VeR^2}} \ , \tag{11}$$

and, for nitrogen molecules ionized 2 ft away from a 12-in.-diameter swatch of fabric

$$t \approx \sqrt{\frac{2\left[\left(28\ \mathrm{AMU}[\mathrm{N}_2]\right)\left(1.660\times10^{-27}\,\mathrm{N\,sec}^2/\,\mathrm{mAMU}\right)\right][24\ \mathrm{in.}\times0.254\ \mathrm{m/in.}]^4}{9[8{,}000\ \mathrm{N{\cdot}m/C}]\left[1.608\times10^{-19}\mathrm{C}\right][6\times0.254\ \mathrm{m/in.}]^2}} \approx 6.9\times10^{-6}\,\mathrm{sec}\ . \quad (12)$$

If the ionization takes place at x_o close to the fabric such that $x_o << R$, then

$$t \approx \sqrt{\frac{mLx_o}{2Ve}}\ . \quad (13)$$

If x_o = 1 in.,

$$t \approx \sqrt{\frac{\left[\left(28\ \mathrm{AMU}[\mathrm{N}_2]\right)\left(1.660\times10^{-27}\,\mathrm{N\,sec}^2/\,\mathrm{mAMU}\right)\right][24\ \mathrm{in.}\times0.254\,\mathrm{m/in.}][1\ \mathrm{in.}\times0.254\,\mathrm{m/in.}]}{2[8{,}000\ \mathrm{N{\cdot}m/C}]\left[1.608\times10^{-19}\mathrm{C}\right]}}$$
$$\approx 5.3\times10^{-6}\,\mathrm{sec}\ . \quad (14)$$

Sound speed in the chamber at room temperature is approximately

$$v = \sqrt{\frac{3kT}{m}} = \sqrt{\frac{3\left[1.3803\times10^{-23}\mathrm{N{\cdot}m\ /K}\right][300\,\mathrm{K}]}{\left[\left(28\ \mathrm{AMU}[\mathrm{N}_2]\right)\left(1.660\times10^{-27}\,\mathrm{N\,sec}^2/\,\mathrm{mAMU}\right)\right]}} = 516\,\mathrm{m/sec} = 1{,}693\mathrm{ft/sec}\ . \quad (15)$$

So the time for a positive ion to reach the fabric from a distance of 2 ft under its own thermal motion is about 0.0012 sec, while the time for electrostatically attracted motion takes place in 0.000007 sec. The ratio of ion thermal energy to electron energy is

$$\frac{\frac{3}{2}kT}{eV} = \frac{[1.5]\left[1.3803\times10^{-23}\mathrm{J/K}\right][300\,\mathrm{K}]}{\left[1.608\times10^{-19}\mathrm{C}\right][8{,}000\,\mathrm{J/C}]} = 0.483\times10^{-4}\ . \quad (16)$$

Thus the electrons in the beam have ≈20,700 times the thermal energy of the ions; however, in an elastic collision between widely disparate masses m_e [= 0.000055 AMU] and m [= 28 AMU] of electron and ion, respectively, only

$$\frac{4\frac{m_e}{m}}{\left(1+\frac{m_e}{m}\right)^2} = \frac{4\left[1.96\times10^{-5}\right]}{\left[1+1.96\times10^{-5}\right]^2} = 0.784\times10^{-4} \tag{17}$$

of the electron's energy can transfer to the ion. Given a coefficient of restitution α [$0 \le \alpha \le 1$] equal to the ratio of velocity of separation of the bodies after collision to the initial velocity of approach, the energy transfer becomes

$$\frac{\frac{m_e}{m}}{\left(1+\frac{m_e}{m}\right)^2} \le \frac{(1+\alpha)^2\frac{m_e}{m}}{\left(1+\frac{m_e}{m}\right)^2} \le \frac{4\frac{m_e}{m}}{\left(1+\frac{m_e}{m}\right)^2} \ . \tag{18}$$

Thus an electronic collision on the average would not be expected to as much as triple the ion/initial neutral molecule thermal velocity. Hence, while an ion produced by a beam impact 2 ft in front of the fabric moves to the fabric, thermal motions can displace it laterally by

$$(6.9 \times 10^{-6}\ \text{sec})\ (1{,}693\ \text{ft/sec})\ (12\ \text{in./ft}) = 0.14\ \text{in.} = 3.6\ \text{mm} \ . \tag{19}$$

This displacement takes it outside the beam radius. The UHT electron beam is defocussed for hand-held space welding to avoid the vapor cavity and the sensitivity to focus typical of commercial electron beam welders. Surface heat balance estimates for aluminum would require a beam radius larger than 0.3 mm to avoid a surface cavity at 800 W beam power but for iron, 1.9 mm.

The energy imparted to an ion by the attraction of the electrostatic charge from a piece of fabric substantially smaller than the standoff length is

$$\frac{1}{2}m\left(\frac{dx}{dt}\right)^2_{x=0} = \frac{\sigma e}{2\varepsilon}\left[\left(x_o - \sqrt{x_o^2 + R^2}\right) + R\right] \approx \frac{\sigma e R}{2\varepsilon}\left[1 - \frac{1}{2}\frac{R}{x_o}\right] \approx eV\left[1 - \frac{1}{2}\frac{R}{x_o}\right] \approx eV \ . \tag{20}$$

For a collision close to the surface where $R >> x_o$:

$$\frac{1}{2}m\left(\frac{dx}{dt}\right)^2_{x=0} = \frac{\sigma e}{2\varepsilon}\left[\left(x_o - \sqrt{x_o^2 + R^2}\right) + R\right] \approx \frac{\sigma e x_o}{2\varepsilon}\left[1 - \frac{1}{2}\frac{x_o}{R}\right] \approx eV\frac{x_o}{L}\left[1 - \frac{1}{2}\frac{x_o}{R}\right] \approx eV\frac{x_o}{L} \ . \tag{21}$$

APPENDIX B—BURNTHROUGH TIME ESTIMATE

B.1 Electron Power Transfer

In a perfect vacuum, an electron beam impinging on an insulator rapidly lays down a layer of negative surface charge (see app. C) until the charge deflects the beam and prevents the deposit of further charge.

Electric charges q of the same sign repel one another according to an inverse square law:

$$F = \frac{q^2}{4\pi\varepsilon r^2} \; , \tag{22}$$

where r is the distance between them and ε is the permittivity of free space, $8.85 \times -10^{-12}\ C^2/N{\cdot}m^2$. The electric field E of a single charge q is F/q, and the electric field E along the axis of a circular patch of charge of radius R with uniform density σ coulombs per unit area is:

$$E = \int_{r=0}^{r=R} \frac{\sigma 2\pi r dr}{4\pi\varepsilon\left(r^2 + x^2\right)} \left[\frac{x}{\sqrt{r^2 + x^2}}\right] = \frac{\sigma}{2\varepsilon}\left[1 - \frac{1}{\sqrt{1 + \frac{R^2}{x^2}}}\right] \; , \tag{23}$$

where x is the distance from the center of the patch outward from the charged surface. When x is much smaller than R, the well known field $\frac{\sigma}{2\varepsilon}$ at the surface of a charged insulator is obtained. When x is much larger than R, the field E approaches a value $\frac{\sigma R^2}{4\varepsilon x^2}$, which could also have been obtained by treating the patch as a charge $\sigma\pi R^2$ at a distance x from the point of measurement and invoking the inverse square law directly.

The potential drop of the electrons that can be transformed to heat upon striking a target at position x is given by:

$$\Delta V_- = V_o - \int_0^x E dx = V_o \left\{1 - \frac{x + \sqrt{R^2 + L^2 - 2Lx + x^2} - \sqrt{R^2 + L^2}}{R + L - \sqrt{R^2 + L^2}}\right\} \; , \tag{24}$$

where V_o = potential of electrons as they emerge from the UHT (typically 8 kV). The expression for ΔV_-

has been set to yield V_o when $x = 0$, and 0 when $x = L$ at the fabric interface. That is, electrons emitted from the UHT possess the full kinetic energy imparted to them by the tool, while the static charge on the fabric builds up so as to just reduce the velocity to zero at the fabric surface. Thus the surface charge is

$$\sigma = \frac{2\varepsilon V_o}{R + L - \sqrt{R^2 + L^2}} \quad . \tag{25}$$

If L is much larger than R,

$$\sigma \approx \frac{2\varepsilon V_o}{R} \quad , \tag{26}$$

and if L is much smaller than R,

$$\sigma \approx \frac{2\varepsilon V_o}{L} \quad . \tag{27}$$

The voltage contributing to the heat delivered to the surface of the fabric is

$$\Delta V_-(L) = 0 \quad , \tag{28}$$

and the power P_- delivered by the electrons to the fabric is zero.

B.2 Positive Ion Power Transfer

The potential drop that contributes to the heat delivered at the surface of the fabric by a positive ion created at x is

$$\Delta V_+(L) = \int_x^L E dx = V_o \left\{ \frac{R + L - \sqrt{R^2 + L^2 - 2Lx + x^2} - x}{R + L - \sqrt{R^2 + L^2}} \right\} \quad , \tag{29}$$

or, for very large fabric dimensions (R>>L):

$$\Delta V_+(L) \approx V_o \left\{ 1 - \frac{x}{L} \right\} \quad . \tag{30}$$

This is the same as the voltage representing the kinetic energy of the electrons:

$$\Delta V_-(L) \approx V_o \left\{ 1 - \frac{x}{L} \right\} \quad . \tag{31}$$

V_o (8,000 V) is much higher than a typical ionization energy ($\approx$15 V for nitrogen), so that $\Delta V_-(L)$ remains above the ionization potential until $x = 0.998L$, essentially the entire standoff distance. The ionization cross section σ_i for electron-contaminant gas collisions is expected to decrease somewhat[4] as potential $\Delta V_-(L)$ increases, but for the present rough approximation it will be taken to be constant.

As the velocity of electrons decreases, their density increases, and it will be assumed that the potential change does not impact the electron current which is proportional to the product of density and velocity. Hence, the number of ions produced per incremental length along the path to the fabric is approximated by

$$\frac{d\dot{N}_+^p}{dx} = \frac{1}{\lambda}\frac{I_o}{q}e^{-\frac{x}{\lambda}}\left(\frac{\sigma_i}{\sigma_s}\right) , \tag{32}$$

where

$\dot{N}_+^p$ = positive ion production rate
I_o = initial electron current produced by UHT
q = electronic charge
x = distance from UHT
λ = collision mean free path
σ_i = ionization cross section
σ_s = scattering cross section.

But not all the ions created in the beam path will strike the fabric within the beam target area. At greater distances from the fabric, more ions will spill outside the beam target area.

Suppose the ion has a radial velocity $v\sin\psi$ as well as a velocity $v\cos\psi$ along the beam. The ions under the attraction of the electric field E of the fabric charge accelerate and pick up a velocity increment $\frac{Ee}{m}\frac{t^2}{2}$, where q_i = ionic charge, m = ionic mass, and t is the time after the ion is generated. The radial deflection, ρ, of the ion is:

$$\rho = (v\sin\psi)t \ , \tag{33}$$

while

$$\xi = (v\cos\psi)t + \left(\frac{q_i E}{m}\right)\frac{t^2}{2} \ , \tag{34}$$

so that

$$\rho = \frac{2mv^2}{q_i E}\left[\sqrt{\cos^2\psi + \frac{2q_i E}{mv^2}\xi} - \cos\psi\right]\sin\psi \ . \tag{35}$$

If the mean translational kinetic energy, $\frac{1}{2}mv^2$, of a molecule is equated to the thermal energy, $\frac{3}{2}kT$, where k is Boltzmann's constant; and if $E = \frac{V_o}{L}$, then,

$$\rho = \frac{6kT}{q_i V_o}\left[\sqrt{L^2\cos^2\psi + \frac{2q_i V}{3kT}L\xi} - L\cos\psi\right]\sin\psi \quad . \tag{36}$$

Since

$$\frac{kT}{q_i V_o} \approx \frac{\left[1.3803\times10^{-23}\,\mathrm{J/K}\right]\left[300\ \mathrm{K}\right]}{\left[1.608\times10^{-19}\,\mathrm{C}\right]\left[8{,}000\ \mathrm{J/C}\right]} = 0.322\times10^{-5} \quad , \tag{37}$$

$$\rho \approx \sqrt{\frac{8kT}{q_i V_o}L\xi}\,\sin\psi = \rho_{\max}\sin\psi \quad , \tag{38}$$

where

$$\rho_{\max}^2 = \frac{8LkT}{q_i V_o}\xi = \frac{8L^2kT}{q_i V_o}\left(1-\frac{x}{L}\right) \quad . \tag{39}$$

For a standoff L of 2 in. (50.8 mm), the distribution scattered from a point x has a maximum radius on the fabric of $\sqrt{0.0665\left(1-\frac{x}{L}\right)}$ mm, which ranges from zero at the fabric surface ($x = L$) to 0.258 mm at the UHT ($x = 0$) in. The beam radius r_b is 1.2 mm. For standoff distances up to 9.29 in., $r_b \geq \rho_{\max}$.

The ions generated at each point on the beam cross section impinge upon the beam footprint until the generation point comes within $2\rho_{\max}$ of the cross section edge. A lower bound to the positive ion spread power correction $\frac{\dot{N}_b}{\dot{N}}$ can be obtained by computing the power loss, assuming all the ions to be lost from this outer rim of the beam cross section where the ion spread disc encounters the edge of the cross section.

$$\frac{\dot{N}_b}{\dot{N}} \geq \left(\frac{r_b - 2\rho_{\max}}{r_b}\right)^2 = \left(1-\frac{2\rho_{\max}}{r_b}\right)^2 \quad , \tag{40}$$

but if $\rho_{\max} \geq \frac{r_b}{2}$, the lower bound becomes zero and tells nothing. If the dropoff in ions striking the beam footprint were linear in the spillover region, then

$$\frac{\dot{N}_b}{\dot{N}} = 1-\left(\frac{2\rho_{\max}}{r_b}\right)+\frac{1}{3}\left(\frac{2\rho_{\max}}{r_b}\right)^2 \quad . \tag{41}$$

a power correction of 0.25 is obtained. This is a small enough correction that it will be ignored. But for $\rho > \rho_{max}$, the spillover can reduce the positive ion power substantially and must be accounted for.

For a given collision at distance ξ from the fabric, the fraction $df(\psi)$ of impacts at initial angle ψ from the beam direction is $\left[\frac{2\pi \sin\psi d\psi}{4\pi}\right]$ and the fractional probability $df(\rho)$ of an impact at radius ρ is

$$df(\rho) = \frac{2\pi \sin\psi d\psi}{4\pi} = \frac{\rho}{\rho_{max}} \frac{d\left(\frac{\rho}{\rho_{max}}\right)}{\sqrt{1-\left(\frac{\rho}{\rho_{max}}\right)^2}} \quad \text{for} \quad \rho \le \rho_{max} \ . \tag{42}$$

and

$$df(\rho) = 0 \quad \text{for} \quad \rho > \rho_{max} \ . \tag{43}$$

The absence of a factor of $\frac{1}{2}$ in the second term is explained by the double values of $\sin\psi$ as it varies from zero to π while $\frac{\rho}{\rho_{max}}$ varies from zero to 1. Integrals carried out within these limits go to 1 for each term.

Hence, for $\rho_{max} \ge \frac{r_b}{2}$,

$$\frac{d\dot{N}_+}{d\dot{N}_+^P} \approx \frac{\displaystyle\int_{\rho=0}^{\rho=r_b} \frac{\frac{\rho}{\rho_{max}}}{\sqrt{1-\left(\frac{\rho}{\rho_{max}}\right)^2}} 2\pi \frac{\rho}{\rho_{max}} d\left(\frac{\rho}{\rho_{max}}\right)}{\displaystyle\int_{\rho=0}^{\rho=\rho_{max}} \frac{\frac{\rho}{\rho_{max}}}{\sqrt{1-\left(\frac{\rho}{\rho_{max}}\right)^2}} 2\pi \frac{\rho}{\rho_{max}} d\left(\frac{\rho}{\rho_{max}}\right)} = \frac{2}{\pi}\left\{\sin^{-1}\left(\frac{r_b}{\rho_{max}}\right) - \frac{r_b}{\rho_{max}}\sqrt{1-\left(\frac{r_b}{\rho_{max}}\right)^2}\right\}$$

$$\approx \frac{8}{3\pi}\left(\frac{r_b}{\rho_{max}}\right)^3 \ . \tag{44}$$

Hence,

$$\frac{d\dot{N}_+}{d\dot{N}_+^P} \approx \frac{1}{3\pi}\left(\frac{q_i V_o}{2kT}\right)^{\frac{3}{2}}\left(\frac{r_b}{L}\right)^3 \frac{1}{\left(1-\frac{x}{L}\right)^{\frac{3}{2}}} . \tag{45}$$

The above approximation is good for $x \approx 0$, but breaks down close to the fabric when $x \approx L$. By no means does the expression $\frac{d\dot{N}_+}{d\dot{N}_+^P}$ go to infinity. It cannot be greater than 1, for which

$$\frac{x}{L} = 1 - \left(\frac{1}{3\pi}\right)^{\frac{2}{3}}\left(\frac{r_b}{L}\right)^2\left(\frac{q_i V_o}{2kT}\right) \approx 1 - \frac{\left[76.88 \text{ in.}^2\right]}{L^2} , \tag{46}$$

or as seen in table 2.

Table 2. Beam length at which ion spillover ceases.

UHT Standoff/ Beam Length (in.)	**for** $\frac{d\dot{N}_+}{d\dot{N}_+^P} = 1$
2	all x
6	all x
12	x>5.59 in.
24	x>20.80 in.
48	x>46.40 in.

The power P_+ that the positive ions transmit to the beam target area is then

$$P_+ \approx \int_{x=0}^{x=L} q_i \Delta V_-(L)\left(\frac{d\dot{N}_+^P}{dx}\right)\left(\frac{d\dot{N}_+}{d\dot{N}_+^P}\right)dx , \tag{47}$$

or

$$P_+ \approx \int_{x=0}^{x=L'} q_i\left(V_o\left\{1-\frac{x}{L}\right\}\right)\left(\frac{1}{\lambda}\frac{I_o}{q}e^{-\frac{x}{\lambda}}\left(\frac{\sigma_i}{\sigma_s}\right)\right)\left(\frac{1}{3\pi}\left(\frac{q_i V_o}{2kT}\right)^{\frac{3}{2}}\left(\frac{r_b}{L}\right)^3\left(1-\frac{x}{L}\right)^{-\frac{3}{2}}\right)dx$$

$$+ \int_{x=L'}^{x=L} q_i\left(V_o\left\{1-\frac{x}{L}\right\}\right)\left(\frac{1}{\lambda}\frac{I_o}{q}e^{-\frac{x}{\lambda}}\left(\frac{\sigma_i}{\sigma_s}\right)\right)dx , \tag{48}$$

where L' is the value of x for which $\frac{d\dot{N}_+}{d\dot{N}_+^P} = 1$. Hence,

$$P_+ \approx I_o V_o \left(\frac{q_i}{q}\right)\left(\frac{\sigma_i}{\sigma_s}\right)\left\{\left[\frac{1}{3\pi}\left(\frac{q_i V_o}{2kT}\right)^{\frac{3}{2}}\left(\frac{r_b}{L}\right)^3\right]\int_{x=0}^{x=L'} \frac{e^{-\frac{x}{\lambda}}}{\sqrt{\left(1-\frac{\lambda}{L}\frac{x}{\lambda}\right)}} d\frac{x}{\lambda} + \int_{x=L'}^{x=L}\left(1-\frac{\lambda}{L}\frac{x}{\lambda}\right)e^{-\frac{x}{\lambda}} d\frac{x}{\lambda}\right\} . \quad (49)$$

Evaluating the integrals:

$$\int_{x=0}^{x=L'} \frac{e^{-\frac{x}{\lambda}}}{\sqrt{\left(1-\frac{\lambda}{L}\frac{x}{\lambda}\right)}} d\frac{x}{\lambda} = -\sqrt{\frac{L}{\lambda}}e^{-\frac{L}{\lambda}} \int_{x=0}^{x=L'} \frac{e^{\frac{L}{\lambda}-\frac{x}{\lambda}}}{\sqrt{\left(\frac{L}{\lambda}-\frac{x}{\lambda}\right)}} d\left(\frac{L}{\lambda}-\frac{x}{\lambda}\right) = -\sqrt{\frac{L}{\lambda}}e^{-\frac{L}{\lambda}} \int_{u=\sqrt{\frac{L}{\lambda}}}^{u=\sqrt{\frac{L-L'}{\lambda}}} \frac{e^{u^2}}{u} du^2$$

$$= 2\sqrt{\frac{L}{\lambda}}e^{-\frac{L}{\lambda}} \int_{u=\sqrt{\frac{L-L'}{\lambda}}}^{u=\sqrt{\frac{L}{\lambda}}} e^{u^2} du = 2\sqrt{\frac{L}{\lambda}}e^{-\frac{L}{\lambda}}\left\{e^{\frac{L}{\lambda}} D\left(\sqrt{\frac{L}{\lambda}}\right) - e^{\frac{L-L'}{\lambda}} D\left(\sqrt{\frac{L-L'}{\lambda}}\right)\right\}$$

$$= 2\sqrt{\frac{L}{\lambda}}\left\{D\left(\sqrt{\frac{L}{\lambda}}\right) - e^{-\frac{L'}{\lambda}} D\left(\sqrt{\frac{L-L'}{\lambda}}\right)\right\} . \quad (50)$$

where $D(u)$ is Dawson's Integral[5] defined as

$$D(u) \equiv e^{-x^2}\int_0^x e^{u^2} du \quad , \quad (51)$$

and

$$\int_{x=L'}^{x=L}\left(1-\frac{\lambda}{L}\frac{x}{\lambda}\right)e^{-\frac{x}{\lambda}} d\frac{x}{\lambda} = -\frac{\lambda}{L}e^{-\frac{L}{\lambda}} \int_{x=L'}^{x=L}\left(\frac{L}{\lambda}-\frac{x}{\lambda}\right)e^{\left(\frac{L}{\lambda}-\frac{x}{\lambda}\right)} d\left(\frac{L}{\lambda}-\frac{x}{\lambda}\right) = \frac{\lambda}{L}e^{-\frac{L}{\lambda}} \int_{u=0}^{u=\frac{L-L'}{\lambda}} ue^u du$$

$$= \frac{\lambda}{L}e^{-\frac{L}{\lambda}}\left[1-\left(1-\frac{L-L'}{\lambda}\right)e^{\frac{L-L'}{\lambda}}\right] . \quad (52)$$

Hence,

$$P_{+} \approx I_o V_o \left(\frac{q_i}{q}\right)\left(\frac{\sigma_i}{\sigma_s}\right)\left\{2\sqrt{\frac{L}{\lambda}}\left[D\left(\sqrt{\frac{L}{\lambda}}\right) - e^{-\frac{L'}{\lambda}} D\left(\sqrt{\frac{L-L'}{\lambda}}\right)\right]\left[\frac{1}{3\pi}\left(\frac{q_i V_o}{2kT}\right)^{\frac{3}{2}}\left(\frac{r_b}{L}\right)^{3}\right]\right.$$

$$\left. + \frac{\lambda}{L} e^{-\frac{L}{\lambda}}\left[1 - \left(1 - \frac{L-L'}{\lambda}\right) e^{\frac{L-L'}{\lambda}}\right]\right\}, \tag{53}$$

where

$$L' = \left[1 - \left(\frac{1}{3\pi}\right)^{\frac{2}{3}}\left(\frac{r_b}{L}\right)^{2}\left(\frac{q_i V_o}{2kT}\right)\right]L . \tag{54}$$

Given a chamber pressure of 10^{-4} torr, the molecular density n of the chamber gas can be estimated from the perfect gas law:

$$n = \frac{P}{kT} \approx \frac{\left[10^{-4}\,\text{torr}\right]\left[1.333\times 10^{-4}\,\text{J}/\text{cm}^3\,\text{torr}\right]}{\left[1.38\times 10^{-23}\,\text{J}/\text{K}\right]\left[300\ \text{K}\right]} = 3.22\times 10^{12}\,\text{cm}^{-3} . \tag{55}$$

The collision cross section σ of the gas molecules is on the order of πr^2, where r is an atomic radius. If r is on the order of 10^{-8} cm, then σ_s, is on the order of 3×10^{-16} cm^2, and the mean free path λ of an electron in the gas is on the order of

$$\lambda \approx \frac{1}{n\sigma_s} = \frac{1}{\left[3.22\times 10^{12}\,\text{cm}^{-3}\right]\left[3\times 10^{-16}\,\text{cm}^{2}\right]} \approx 1{,}040\ \text{cm} = 408\ \text{in.} \tag{56}$$

Further, let $\frac{q_i}{q} \approx 1$, $\frac{\sigma_i}{\sigma_s} \approx 0.2$, $\frac{1}{3\pi}\left(\frac{q_i V_o}{2kT}\right)^{\frac{3}{2}} \approx 2.05\times 10^5$, and $r_b \approx 1.2$ mm $= 0.047$ in. Then the fraction of UHT power transmitted to the fabric by positive ions can be estimated (see table 3).

If $L > r_b\sqrt{\left(\frac{1}{3\pi}\right)^{\frac{2}{3}}\left(\frac{q_i V_o}{2kT}\right)} \approx 8.768$ in.

$$\frac{P_+}{I_o V_o} \approx [1][0.2]\left\{2\sqrt{\frac{L}{\lambda}}\left[D\left(\sqrt{\frac{L}{\lambda}}\right) - e^{-\frac{L'}{\lambda}} D\left(\sqrt{\frac{L-L'}{\lambda}}\right)\right]\left[\frac{674}{L^3}\right]\right.$$

$$\left. + \frac{\lambda}{L} e^{-\frac{L}{\lambda}}\left[1 - \left(1 - \frac{L-L'}{\lambda}\right) e^{\frac{L-L'}{\lambda}}\right]\right\}$$

$$\approx 0.2\left\{\frac{1{,}348 \text{ in.}^3}{L^3}\sqrt{\frac{L}{\lambda}}\left[D\left(\sqrt{\frac{L}{\lambda}}\right) - e^{-\frac{L'}{\lambda}} D\left(\sqrt{\frac{L-L'}{\lambda}}\right)\right]\right.$$

$$\left. + \frac{\lambda}{L} e^{-\frac{L}{\lambda}}\left[1 - \left(1 - \frac{L-L'}{\lambda}\right) e^{\frac{L-L'}{\lambda}}\right]\right\} . \tag{57}$$

where

$$L' \approx \left[1 - \frac{76.88 \text{ in.}^2}{L^2}\right] L . \tag{58}$$

If $L > r_b\sqrt{\left(\frac{1}{3\pi}\right)^{\frac{2}{3}}\left(\frac{q_i V_o}{2kT}\right)} \approx 8.768$ in., then

$$\frac{P_+}{I_o V_o} \approx 0.2\frac{\lambda}{L} e^{-\frac{L}{\lambda}}\left[1 - \left(1 - \frac{L}{\lambda}\right) e^{\frac{L}{\lambda}}\right] = 0.2\left[1 - \frac{\lambda}{L}\left(1 - e^{-\frac{L}{\lambda}}\right)\right] . \tag{59}$$

Table 3. Fraction of beam power transmitted by positive ions to electron beam footprint.

UHT Standoff/ Beam Length (in.)	P_+/I_0V_0		
	λ = 40.8 in. (10^{-3} torr)	λ = 408 in. (10^{-4} torr)	λ = 4,080 in. (10^{-5} torr)
2	0.00482	0.000489	0.0000490
6	0.01401	0.001463	0.0001470
12	0.08091	0.002050	0.0005283
24	0.00548	0.000806	0.0000830
48	0.00128	0.000230	0.0000247

B.3 Burnthrough Time Estimate

Suppose it is assumed that burnthrough occurs when the beam raises the temperature of a cylindrical disc with radius r_b, approximately the radius of the electron beam, and thickness w, the thickness of the fabric, to a critical temperature T_b. The rise in temperature may be estimated from a line source delivering power $\frac{P}{w}$ at $r = 0$, the temperature at radius r is approximately given by:[6]

$$T_b - T_o \approx \frac{P\left[\ln \frac{4\alpha t_b}{r_b^2} - \gamma\right]}{4\pi k w} \quad , \tag{60}$$

where

T_b = burnthrough temperature
T_o = ambient temperature
P = beam power
t_b = burnthrough time
α = thermal diffusivity = $k/\rho C$ (0.025 cm^2/sec)
k = thermal conductivity of fabric (0.02 W/cm K estimated)
ρ = density of fabric (0.82 gm/cm^3)[3]
C = specific heat of fabric (1 Wsec/gm K)[3]
r_b = radius of electron beam
w = thickness of fabric (0.12 cm)[3]
γ = Euler's constant = 0.5772,

provided that $\frac{r_b^2}{4\alpha t} \ll 1$. Note that at $t_b = 8$ sec,

$$\frac{r_b^2}{4\alpha t_b} \approx \frac{[0.12\ \mathrm{cm}]^2}{4\left[0.025\ \mathrm{cm}^2/\mathrm{sec}\right][8\ \mathrm{sec}]} = 0.018 \ . \tag{61}$$

If the power comes from a stream of positive ions

$$T_b - T_o \approx \frac{P_+\left[\ln \frac{4\alpha t_b}{r_b^2} - \gamma\right]}{4\pi k w} \quad , \tag{62}$$

or

$$t_b \approx \frac{r_b^2}{4\alpha} e^{\frac{4\pi k w (T_b - T_o)}{P_+} + \gamma} \approx [0.256 \sec] e^{\frac{[0.0302 W/K][T_b - T_o]}{P_+}} \quad . \tag{63}$$

$I_o V_o$ is on the order of 800 W and that at midrange distances when delays on the order of 8 sec are observed. The lowest vacuum level credible for the chamber 10^{-4} torr. A higher pressure would presumably cause the beam to cut off due to arcing within the UHT. Observations of beam cutoff were indeed occasionally noted at a standoff of 2 in. Hence the chamber vacuum level cannot be too far removed from 10^{-4} torr. At that vacuum level, it is estimated that the positive ions transmit 0.001 times the power imparted to the beam by the UHT, or ≈0.8 W. For theory to yield similar results;

$$T_b - T_o \approx 130 \text{ K} \ , \tag{64}$$

which, given T_o of ≈30 °C, would make

$$T_b \approx 160 \text{ °C} \ . \tag{65}$$

This value for T_b is far below the 1,427 °C that the cloth is intended to withstand. It would not, however, necessarily be out of line with a temperature sufficient to promote enough outgassing to induce arcing. Once arcing occurs and the full power of the UHT beam is brought to bear at the beam footprint, the cloth is immediately penetrated. So, accepting the value of 160 °C for T_b:

$$t_b \approx [0.256 \sec] e^{\frac{[3.93 W]}{P_+}} \quad . \tag{66}$$

An alternative interpretation consonant with a much higher burnthrough temperature is possible. Instead of using the value of the cloth thickness for w, the thickness of the disc subject to burnthrough, it might make sense to use the cloth fiber thickness, about an order of magnitude smaller than the cloth thickness. In this interpretation, the fibers on the surface of the disc catch the heat of the ion beam without transferring much of it to the depths of the fabric. When the surface fibers begin to emit adequate quantities of vapor, then the electron beam begins to deliver a substantial portion of its power to the fabric through arcing and burnthrough occurs.

The above expression yields the following tabulation (table 4) of delay times versus standoff.

Table 4. Theoretical estimation of Nextel burnthrough delay times.

UHT Standoff/ Beam Length (in.)	t_b = Estimated Burnthrough Delay Time (sec)		
	λ = 40.8 in. (10^{-3} torr)	λ = 408 in. (10^{-4} torr)	λ =4 ,080 in. (10^{-5} torr)
2	0.709	5,900	3.5×10^{43}
6	0.363	7.4	8.3×10^{13}
12	0.272	2.8	2,796
24	0.627	114	1.3×10^{25}
48	11.89	4.8×10^{8}	6.1×10^{85}

APPENDIX C—SURFACE CHARGING

A conservative estimate of the time Δt to lay down a beam repelling charge at $I = 75$ mA and $V = 8$ kV is:

$$\Delta t \approx \frac{\sigma \pi R^2}{I} \approx \frac{2\varepsilon V}{R}\frac{\pi R^2}{I} = \frac{2\pi\varepsilon RV}{I} = \frac{2\pi\left[8.85\times 10^{-12}\,\mathrm{C}^2 / \mathrm{N\cdot m}^2\right]\left[6\text{ in.}\times 0.0254\text{ m / in.}\right]\left[8{,}000\text{ N}\cdot\text{m / C}\right]}{\left[0.075\text{ C / sec}\right]}$$

$$= 0.904\times 10^{-6}\,\mathrm{sec}\ . \tag{67}$$

The mean electronic separation is $\approx 0.4\ \mu$, on the order of 1,000 atomic diameters.

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An 8-kv electron beam with a current in the neighborhood of 100 mA from the Ukrainian space welding "Universal Hand Tool" (UHT) burned holes in Nextel AF–62 ceramic cloth designed to withstand temperatures up to 1,427 °C. The burnthrough time was on the order of 8 sec at standoff distances between UHT and cloth ranging from 6–24 in. At both closer (2 in.) and farther (48 in.) standoff distances the potency of the beam against the cloth declined and the burnthrough time went up significantly.

Prior to the test it had been expected that the beam would lay down a static charge on the cloth and be deflected without damaging the cloth. The burnthrough is thought to be an effect of partial transmission of beam power by a stream of positive ions generated by the high-voltage electron beam from contaminant gas in the "vacuum" chamber. A rough quantitative theoretical computation appears to substantiate this possibility.

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