Long Life Hollow Cathodes for High Power NEP Missions

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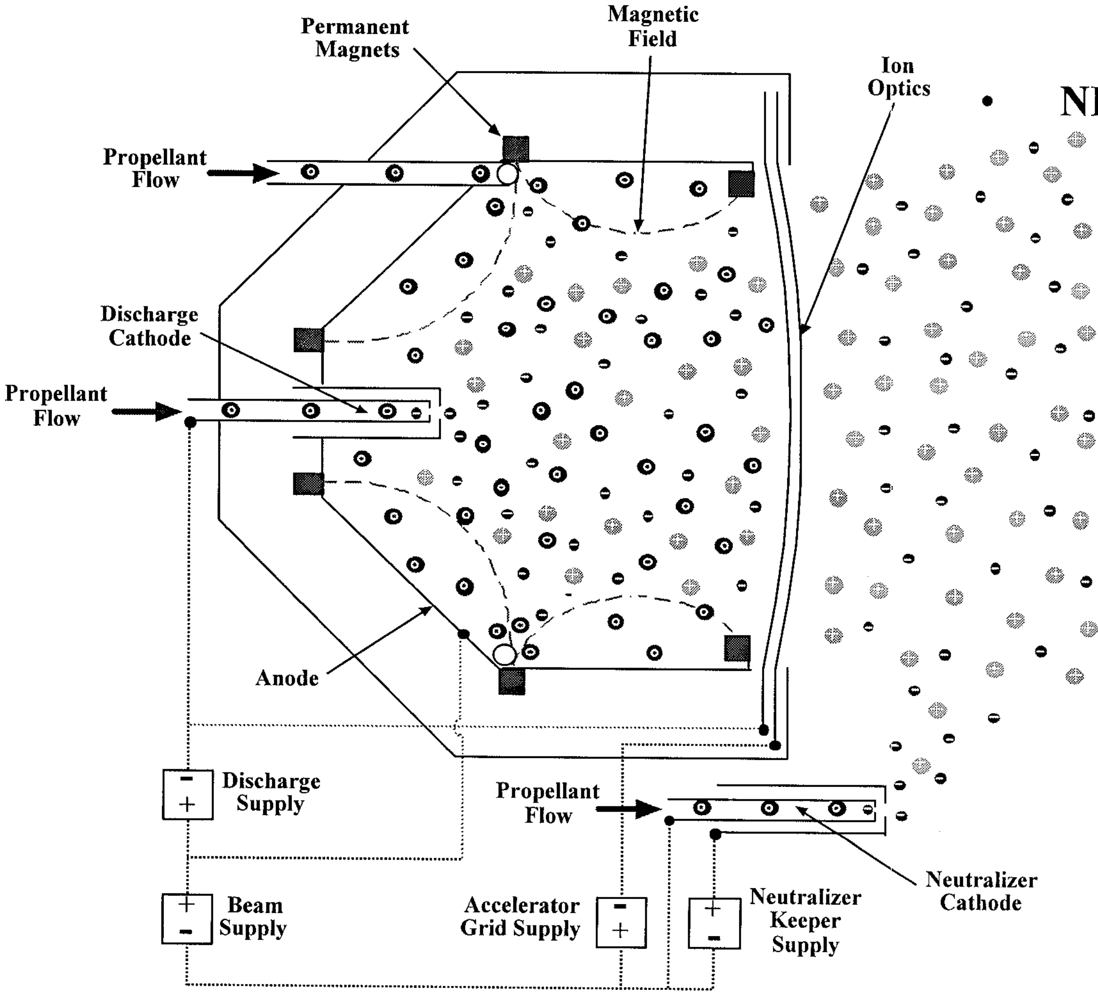
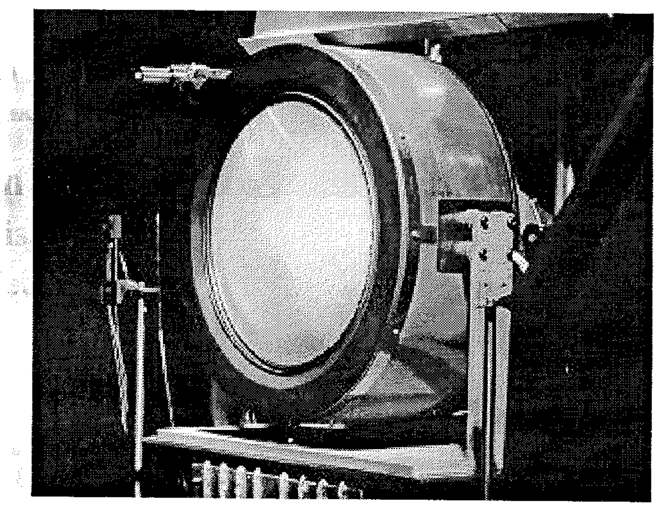
Long Life Hollow Cathodes for High Power NEP Missions

- Existing Hollow Cathode Life Inadequate for NEP Missions
  - NEP engines need to operate for 10 years
  - Longest duration hollow cathode failed after 3 years
- Approach
  - 10 year life tests not practical
  - Life requirements must verified by short tests & analysis
- High Fidelity Models Are Needed
  - Detailed, predictive physics
  - Must include all failure & performance degradation mechanisms
- JPL Hollow Cathode Model Development
  - Insert chemistry – new results including plasma effects
  - Insert region plasma
    - 2-D model
    - Limiting results compared with published data
  - Orifice physics including erosion – 1-D model results
  - Thermal model and Keeper & beyond – coming soon!

Hollow Cathodes are a Critical Technology for NEP



- **Most ion thruster have two hollow cathodes**
  1. **Discharge cathode**
  2. **Neutralizer**
- **NEP Ion thrusters will probably use HC's**
  - **Flight experience is primarily with HC based ion thrusters**
  - **Present ion thrusters that use RF to ionize the propellant are much less efficient than ones using hollow cathodes**
  - **Propellant utilization efficiency is critical for NEP missions**



Engineering model ion thruster built by NASA GRC during 8200 hour endurance test at JPL.

NASA/GRC Hollow Cathode Life Test

- Space Station Plasma Contactor Life Test
  - Longest test
  - Tim Sarver-Verhey, George Soulas, Mike Patterson, Scott Kovaleski
  - NSTAR like hollow cathode
  - Constant 13A emission current
- Hollow cathode failed to start after 3 years of operation
  - 23,776 hours - Starting voltage jumped from 50V to 725V
  - 28,000 hours – Failed to start
- Failure analysis
  - Free BaO and Ba depleted
  - Tungsten deposits on orifice plate
- Conclusion:

<u>Failure Mechanism-Insert Depletion</u>

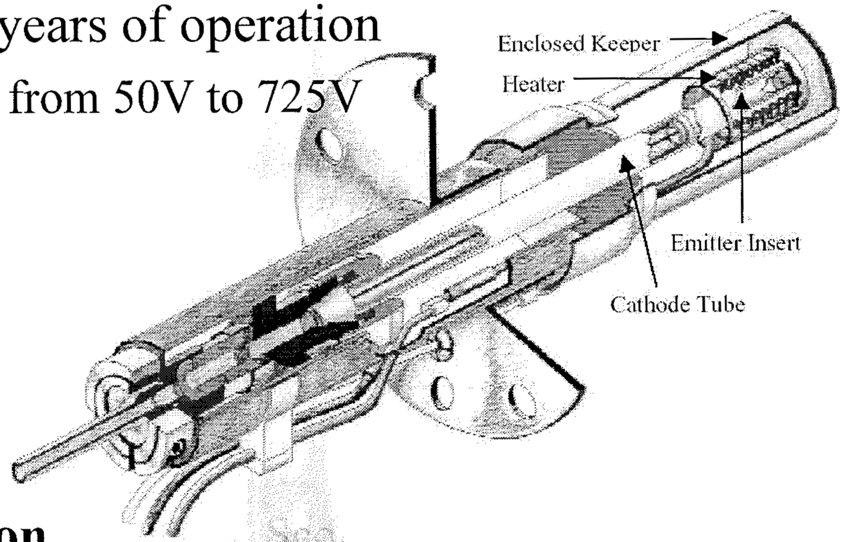


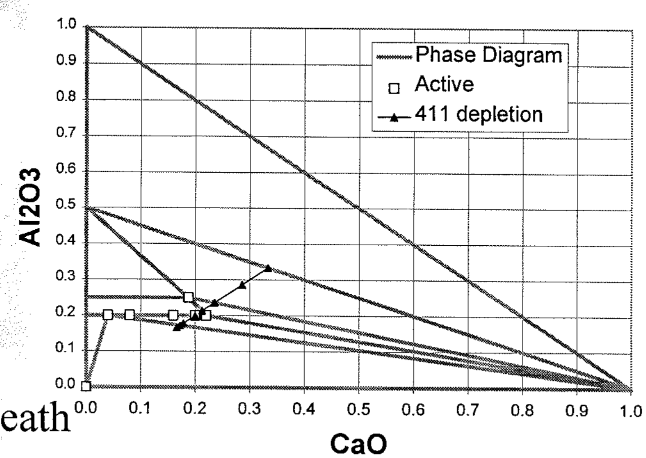
Figure 1. Drawing of a flight HCA (drawing not to scale).

Figure from "A Review of Testing of Hollow Cathodes for The International Space Station Plasma Contactor"S. D. Kovaleski, M. J. Patterson, G. C. Soulas, T. R. Sarver-Verhey, NASA Glenn Research Center, IEPC-01-271

Barium Ionization Reduces Insert Life

- Previous models of insert life based on equilibrium chemistry
  - Lipeles & Kan, Kovaleski
  - Observed Barium loss in EP hollow cathodes not much slower than vacuum cathodes.
- New model includes barium ionization
  - $Ba_{\alpha}Ca_{\beta}O_{\chi}(s) \quad BaO(g) + Ba_{\alpha-1}Ca_{\beta}O_{\chi-1}(s)$
  - $2BaO(g)+1/3\ W \quad 1/3Ba_3WO_6 + Ba(g)$
  - $Ba(g) \quad Ba^+ + e^-$ ⟵ **Not Included Previously**
- Ionization mean free path the order of a millimeter
  - Ba ionization potential 5.2eV T insert ~0.1 eV
  - Insert plasma $n_e \sim 10^{21}\ m^{-3}$ $T_e \sim 1$ eV
  - $\tau_{ionization} \sim 3x10^{-6}$ sec
  - Barium ions hit wall with ~10eV kinetic energy because of sheath
- Results
  - Very low barium neutral partial pressure in insert region
  - Barium loss rates greater than models assuming pressure equilibrium
- JPL lead team pursuing new hollow cathode designs that use proven traveling tube cathode techniques to increase insert life

BaO-CaO-Al2O3 Phase Diagram



New Approaches For Hollow Cathode Inserts

Iridium-Tungsten Insert

BaO Dispenser

Hollow Cathode Insert Plasma Model

- New physical model – Ion transport dominated by charge exchange with neutrals

$$\sigma_{CEX} \approx 10^{-18}\ \mathrm{m}^2$$
$$T \approx 1300\ \mathrm{K}$$
$$P \approx 10\ \mathrm{Torr}$$
$$n_0 \approx 7.5 \times 10^{22}\ \mathrm{m}^{-3}$$
$$\ell_{CEX} = \frac{1}{n_0\, \sigma_{CEX}} \approx 10^{-5}\ \mathrm{m} \quad << r_{insert}$$

- Reduces to ambipolar diffusion equation

$$-\nabla \bullet \left[D_a \nabla n\right] = \dot{n}$$

- Neglecting axial variation, Bessel function zero sets upper bound on the electron temperature

$$\frac{\partial^2 n}{\partial r^2} + \frac{1}{r}\frac{\partial n}{\partial r} + C^2 n = 0$$
$$C^2 = \frac{n_0 \sigma(T_e)\sqrt{\frac{8eT_e}{\pi m_e}}}{D_a}$$

- Comparison with data
  Malik, Montarde, and Haines, J. Phys D **33**, pp. 2307-2048, 2000

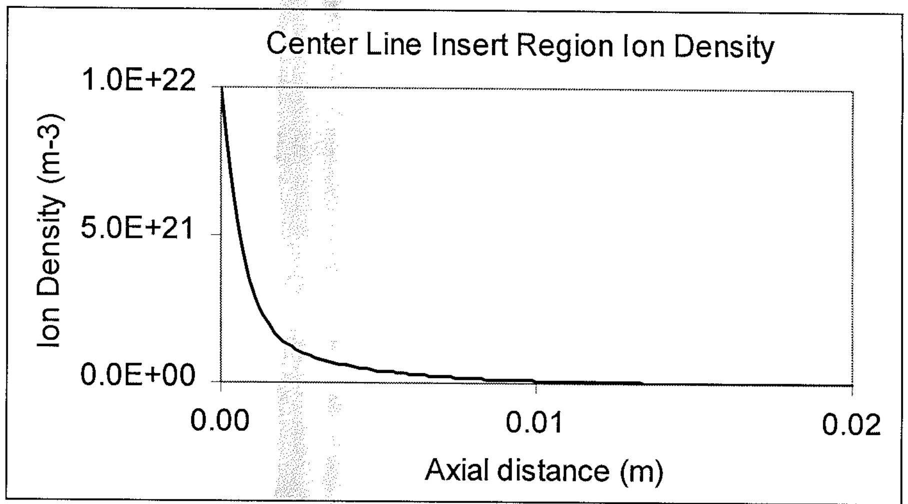
$$T_e^{data} = 1.1\, eV$$
$$T_e^{theory} \approx 1.075\, eV$$

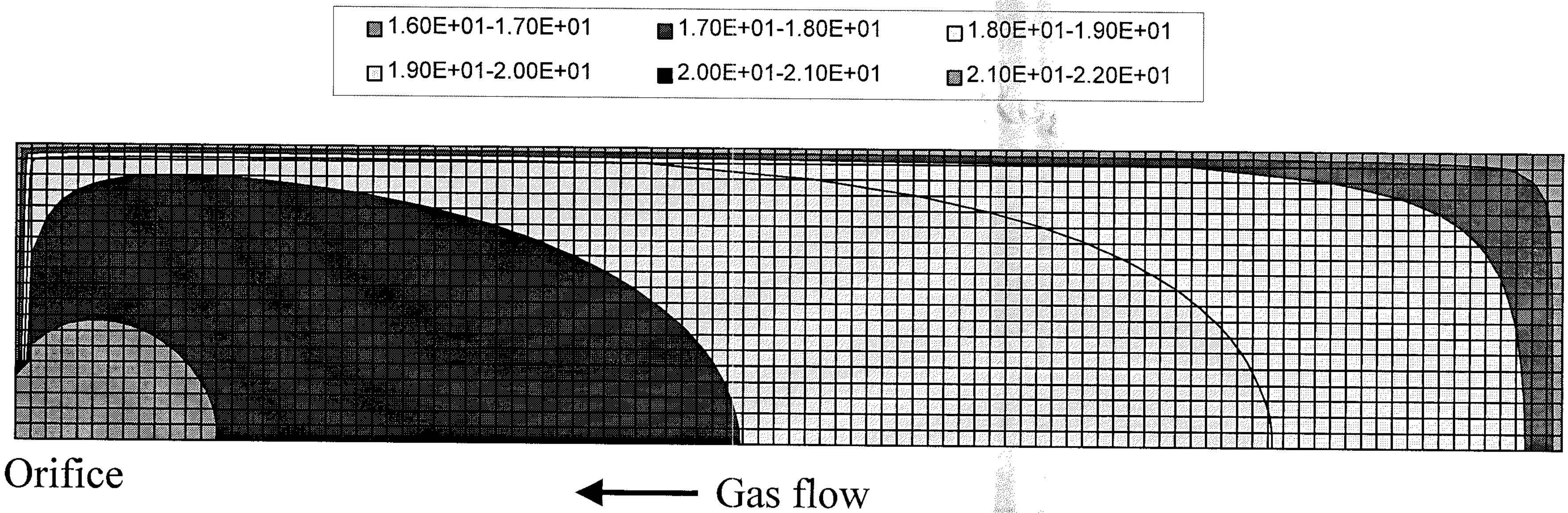
Comparison probably fortuitously good!

Model predicts low ion current density to insert – average ion velocity << Bohm velocity

First 2-D Calculations of Insert Region Ion Density

- Solution of ambipolar diffusion equation
- R-Z geometry
- Assumes constant T_e
- Ion density drops exponentially from orifice





1-D Model of Orifice Plasma

- The volume modeled includes the orifice and the chamfered region
- Extension of previous 0-D model
- Assumes quasi neutrality $n = n_i \approx n_e$
- Continuity equations

$$\pi R^2 \left(-\dot{n} + \frac{\partial u_0 n_0}{\partial z} \right) + 2\pi R u_{wall} n = 0$$

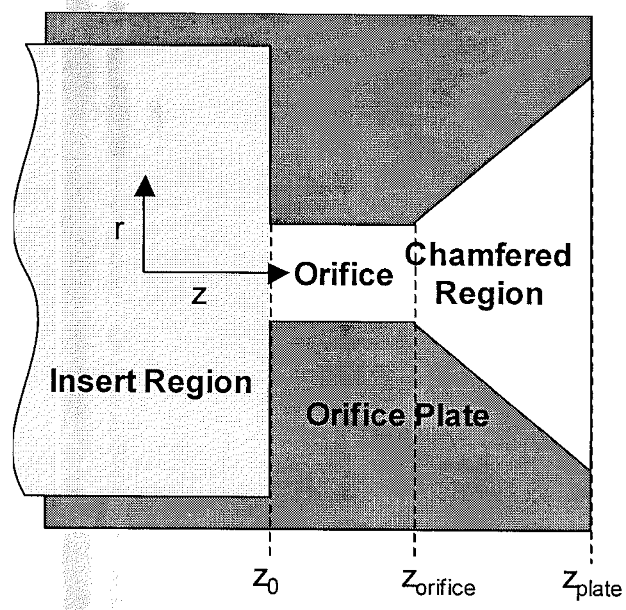
$$\pi R^2 \left(\dot{n} + \frac{\partial u_i n}{\partial z} \right) - 2\pi R u_{wall} n = 0$$

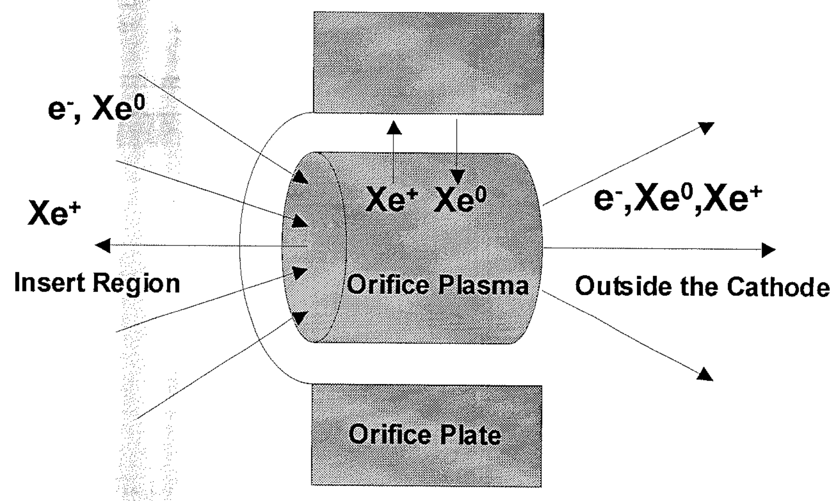
$$\pi R^2 \left(e\dot{n} + \frac{\partial j_e}{\partial z} \right) = 0$$

- Ion and electron momentum equations

$$n(u_i - u_0) = -D_i \frac{\partial n}{\partial z} + n \mu_i \mathbf{E}$$

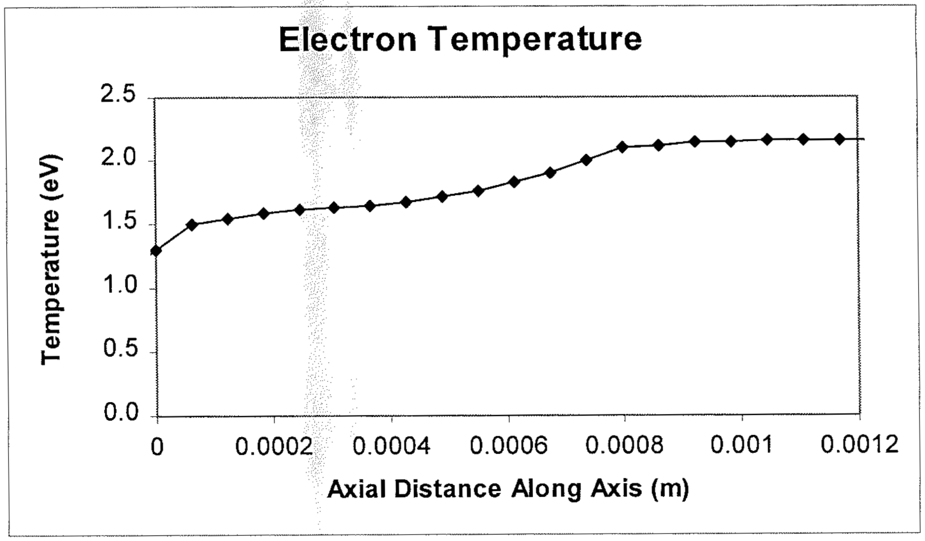
$$j_e = e D_e \frac{\partial n}{\partial z} + e n \mu_e \mathbf{E}$$

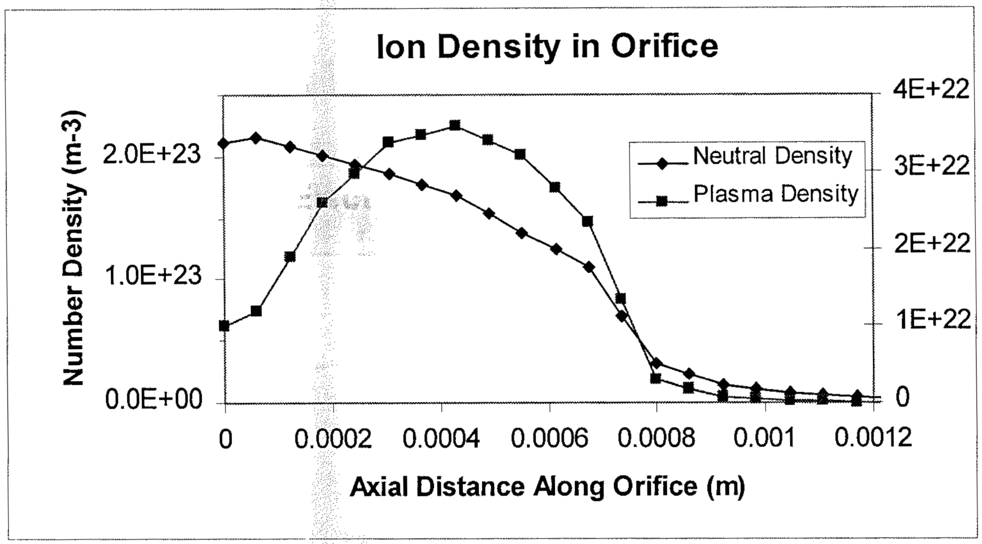




First Results From 1-D Orifice Model

- Electron temperature rises monotonically in orifice from insert region to chamfered region
- Ion density peaks in orifice
  - Ions flow back into insert region
  - Ions flow out toward keeper
- Ion diffusion approximation breaks down in chamfer region
  - Drop in neutral gas density
  - Region include for boundary conditions at orifice exit
- Ionization fraction ~ 10%

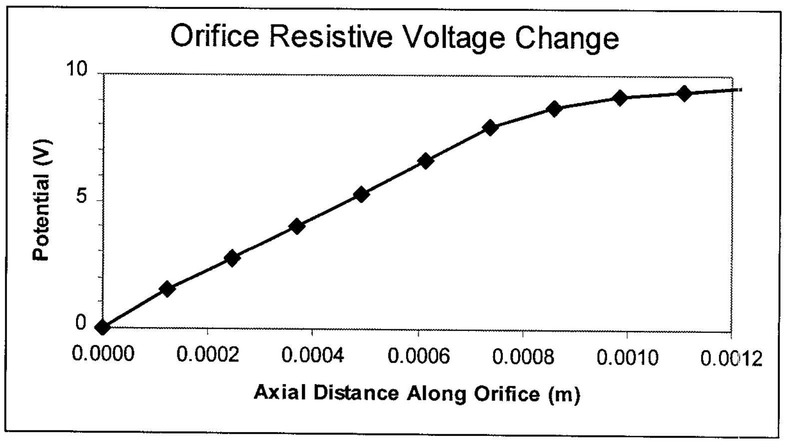


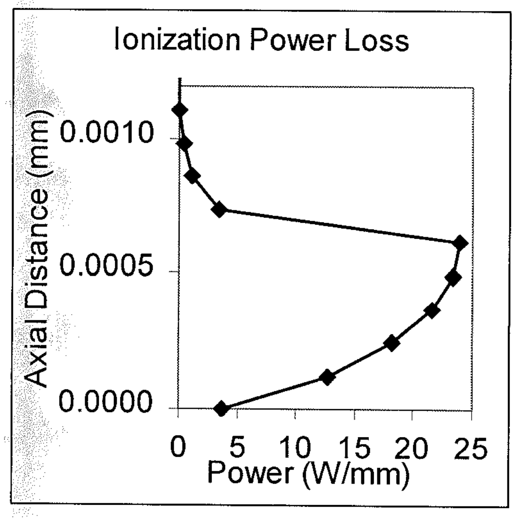


Model Shows Ionization Contribution to Current

- Ionization contributes electrons to the current and ions to the wall
- Ionization contributes about an ampere to the current
- Ions impact to the walls probable orifice erosion mechanism
- Power to the wall sum of ionization energy and ion kinetic energy including sheath

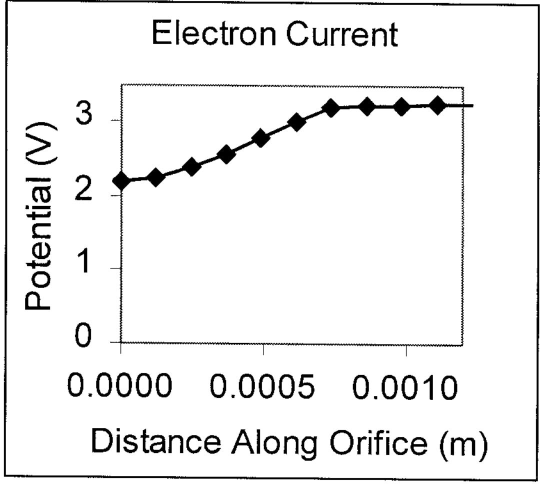
Ionization loss profile similar to observed orifice erosion data



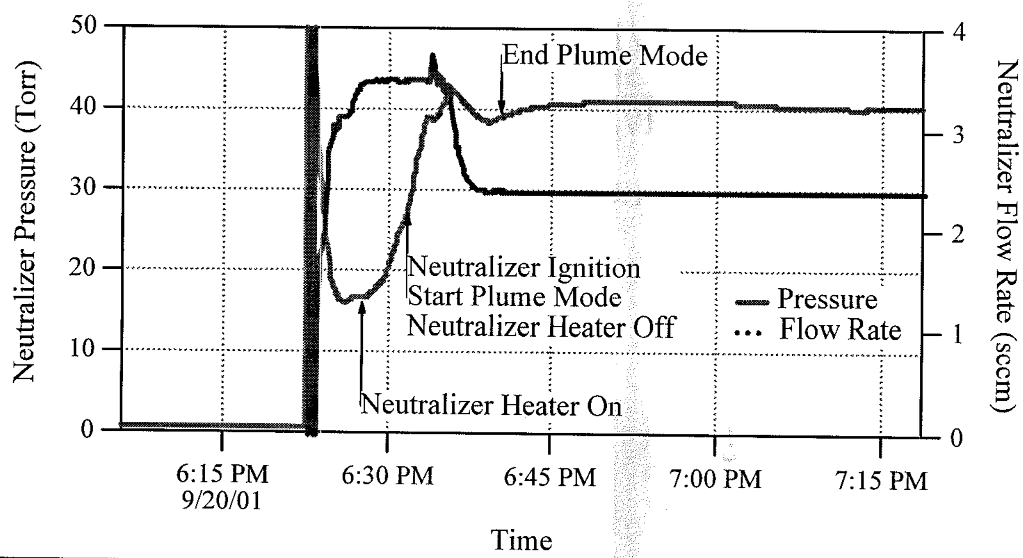


Model Results May Explain HC Pressure Rise

- Observation: Hollow cathode pressure rises when discharge is ignited
- Neutral flow between Poisseuille and Knudsen
  (Dan Goebel private communication)
- Inlet flow ~ 3.5 sccm
- Ionization currents to the walls ~ 1 Amp
- Ions that hit the walls come off as neutrals
- Neutral flow from walls at > 14 sccm
- Increased collisions with the wall acts as increased viscosity resulting in increased pressure drop



Pressure increase after discharge initiation in NSTAR neutralizer hollow cathode



Long Life Hollow Cathodes for High Power NEP Missions

- Models being developed to describe hollow cathode operation and wear mechanisms
  1. Insert chemistry
  2. Insert region plasma (1 & 2-D)
  3. Orifice and chamfer region plasma (1-D variable area)
- Early results encouraging
  - Barium ionization increases loss rate
  - Insert region electron temperature set by ambipolar diffusion
  - Ionization profile in orifice region consistent with orifice erosion shape
- Planned Electric Propulsion Model Development
  - Hollow cathode models
    - Xe^{++} generation
    - Combined insert & orifice 2-D model
    - Thermal model including plasma effects
  - 2-D discharge chamber model
    - Hollow cathode keeper region
    - Magnetic field effects on transport
    - Xe^{++} generation