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Wear Mechanisms in Electron Sources for Ion Propulsion, 1: Neutralizer Hollow Cathode

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Upon the completion of two long-duration life tests of a 30-cm ion engine, the orifice channel of the neutralizer hollow cathode was eroded away to as much as twice its original diameter. Whereas the neutralizer cathode orifice opened significantly, no noticeable erosion of the discharge cathode orifice was observed. No quantitative explanation of these erosion trends has been established since the completion of the two life tests. A two-dimensional model of the partially ionized gas inside these devices has been developed and applied to the neutralizer hollow cathode. The numerical simulations show that the main mechanism responsible for the channel erosion is sputtering by Xe^+. These ions are accelerated by the sheath along the channel and bombard the surface with kinetic energy/charge of about 17 V at the beginning of cathode life. The density of the ions inside the neutralizer orifice is computed to be as high as 2.1×10^{22} m^{-3}. Because of the 3.5-times larger diameter of the discharge cathode orifice, the ion density inside the orifice is more than 40 times lower and the sheath drop 7 V lower compared with the values in the neutralizer. At these conditions, Xe^+ can cause no significant sputtering of the surface.

Nomenclature

AW	=	atomic weight
$c_{1,2,3,4}$	=	emitter temperature coefficients
$\mathbf{E}$	=	electric field, V/m
e	=	electron charge, C
$\mathbf{j}$	=	current density, A/m^2
$j_{e,\mathrm{th}}$	=	electron thermal current density, A/m^2
k_B	=	Boltzmann's constant, J/K
L_{ins}	=	length of the emitter insert, m
M	=	mass of xenon ion or atom, kg
m_e	=	mass of electron, kg
N_{AV}	=	Avogadro's number, mol^{-1}
n	=	particle density, particles/m^3
$\hat{\mathbf{n}}$	=	normal unit vector
$\dot{n}$	=	ionization rate, particles/m^3/s
p	=	pressure, Pa
Q^R	=	frictional heating, W/m^3
Q^T	=	thermal heating, W/m^3
r	=	radial coordinate, m
r_o	=	cathode orifice radius, m
T	=	temperature of ionized gas species, K
T_w	=	emitter temperature, K
$T_{w,\max}$	=	peak emitter temperature, K
t	=	time, s
$\mathbf{u}$	=	velocity of ionized gas species, m/s
V_C	=	cathode voltage, V
Y	=	sputtering yield, atoms/ion
z	=	axial coordinate, m
Δh	=	erosion depth or height, m
Δt	=	time increment, h
ε	=	species energy, J
$\varepsilon_{\mathrm{ip}}$	=	ionization potential, V
η	=	electrical resistivity, Ω-m
κ	=	thermal conductivity, W/m/K
λ	=	collision mean free path, m
ν	=	collision frequency, s^{-1}
ρ	=	material mass density, kg/m^3
σ	=	collision cross section, m^2
ϕ	=	plasma potential, V

Subscripts

e	=	electron
e, z	=	electron in z direction
h	=	heavy species (ion or neutral)
i	=	ion
i, z	=	ion in z direction
$i, \perp$	=	ion in direction perpendicular to surface
n	=	neutral
n, z	=	neutral in z direction
p	=	scalar quantity in grid cell center adjacent to boundary

I. Introduction

CATHODE erosion is a major failure mode that is not yet well understood in conventional ring-cusp ion engines. Two long-duration life tests of a 30-cm ion engine were performed by NASA between 1997 and 2004, in part to characterize known failure modes and in part to identify new failure modes. The Life Demonstration Test (LDT) of an engineering model thruster was terminated after 8192 h of operation [1]. During the test, the thruster was operated at the maximum-power (2.3 kW) throttle level, which will be called TH15 in this paper. The Extended-Life Test (ELT) of the Deep Space 1 flight spare ion thruster was conducted from 1998 to 2004 and accumulated 30,352 h [2]. During this test, the engine operated at five different throttle levels that included TH15.

Ring-cusp ion engines such as the 30-cm ion thruster mentioned previously usually operate with two thermionic orificed hollow cathodes: a discharge hollow cathode (DHC) that provides electrons for ionization of the propellant (usually Xe), and a neutralizer hollow cathode (NHC) that provides electrons for the neutralization of the ion beam. The cathode assembly consists mainly of the insert (emitter), cathode tube and orifice plate, heater and radiation shield, keeper tube and plate, cathode insulator, low-voltage propellant

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