Results

The modified equations derived here were programmed and used in conjunction with the transient heat equation with source term. The radiant heat to each node was input in the source term after each conduction time step. This quasi-linearization of the combined transient conduction and radiation problems gave credible results.

In a problem with constant emissivities, only one symmetric matrix inversion was required for all of these equations. However, in a problem where emissivities varied with temperature, this inversion was required after each conduction time step. Even a symmetric matrix inversion proved too time consuming. The equations derived here were solved by a less accurate relaxation technique for this case.

The largest problem solved contained 300 enclosure surfaces. The core saving was $300^2 - (300/2)(300 + 1) = 44{,}850_{10}$ words. The time saved by a symmetric vs a nonsymmetric system of equations is difficult to estimate precisely. However, considering that the solution is performed thousands of times per computer run when emissivity varies with temperature, the savings can be quite significant.

Reference

[1] Sparrow, E. M. and Cess, R. D., *Radiation Heat Transfer*, Brooks Cole Publishing Co., Belmont Calif., 1966.

Propellant Condensation on Surfaces near an Electric Rocket Exhaust

W. C. Lyon*
Hittman Associates, Inc., Columbia, Md.

In a recent paper,[1] Reynolds and Richley considered propellant condensation near the exhaust of ion thrusters. In part, they stated, "Charge exchange ions formed in the exhaust beam are not collimated and their scattering and impaction on surrounding surfaces could be a problem. However, both the quantity and energy levels are considerably less than those of the primary ions.[2] Because of the magnitude of neutral efflux and the lack of collimation, neutral particle effluxes present a potentially more serious problem." This conclusion is identical to that of Staggs, et al.[2] Recently, we completed an investigation in which the charge exchange mechanism could cause condensation or erosion problems where the primary beam and neutral fluxes constituted no problem. The data reinforce the first part of the Reynolds and Richley conclusion and point out the potential danger in neglecting small contributors.

The application investigated[3] is illustrated in Fig. 1. It consists of a cylindrical spacecraft with a cesium ion thruster thrusting at 45° to the spacecraft axis. Located in the same plane is a radiator with a cold patch designed to operate at 100°K. The geometry prohibits direct impacting of the neutral atoms (or Group 2 ions) upon the cold patch, but Group 4 ions have a direct entry to the patch.

Neutral Atom Distribution

The neutral atom distribution for $r > a$, is approximately[4]

$$\Gamma(r,\theta) = \Gamma_0 \frac{a^2}{r^2} \cos\theta \bigg/ \left[1 + \frac{2a^2}{r^2}\cos\theta + \frac{a^4}{r^4}\right]^{1/2} \quad (1)$$

Received April 13, 1970; revision received July 16, 1970. This work was performed under NASA-GSFC Contract NAS5-9479, Modification 14.

* Staff Consultant. Member AIAA.

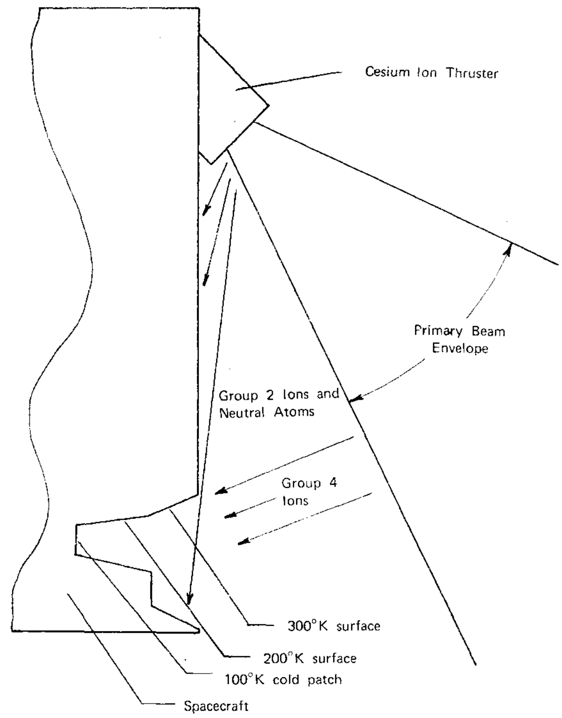

Fig. 1 Approximate spacecraft-thruster configuration showing low temperature radiator.

where Γ is the particle current density in the direction of the radius vector; r is the distance from the center of the ion engine exhaust plane to the position of interest; θ is the angle between r and the normal to the engine exhaust plane; Γ_0 is the particle current density at the ion engine exhaust plane; and a is the radius of the ion engine exhaust opening.

The assumed thruster† has an atomic (un-ionized) flow rate of 10^{-7} lb/sec of cesium. For the geometry considered, the direct neutral flux arriving on the lower 300°K surface is about 2.3×10^{12} atoms/cm^2-sec. This temperature is high enough that the atoms do not accumulate, but immediately evaporate.‡ The approximate distribution of atoms which results is given in Table 1. The cold patch does not "see" a 300°K surface and consequently no cesium arrives at the cold patch from such surfaces.

The evaporation rate for a surface at 200°K is 7.1×10^7 atoms/cm^2-sec. Hence, for practical purposes, the cesium accumulation rate on this surface is equal to the rate at which cesium atoms arrive if one assumes a sticking coefficient of

Table 1 Approximate distribution of atoms to surfaces and space

Destination	Percentage of atoms hitting lower 300°K surface	Arrival flux, atoms/cm^2-sec
Upper surface at 300°K	12.2	1.1×10^{11}
Upper surface at 200°K	7.5	1.3×10^{11}
Radiator side walls at 300°K (not shown in Fig. 1)	20.2	...
Space	60.1	...

† The calculations are based upon behavior assumed by the author and R. Hunter (NASA-GSFC). See Ref. 5 for a description of a typical cesium thruster.

‡ Evaporation rate is calculated from[3] $N = P/(2\pi mkT)^{1/2}$, where P is the vapor pressure, m the mass of the atom, k the Boltzmann constant, and T the absolute temperature.

one. The time required to accumulate a monolayer on the upper 200°K surface is a little less than one hr. The rate on the other 200°K surfaces is about one monolayer each five hr. In a few days a 200°K surface will behave as though it were composed of cesium.

Since the cold patch "sees" only space and the 200°K surfaces, the evaporation rate from these surfaces determines the rate at which cesium arrives at the cold patch. For practical purposes, no atoms evaporate at 100°K. Treating the arrival rate as equal to the condensation rate yields a buildup rate of about 5×10^7 atom/cm²-sec or one monolayer each 2400 hr. This is not a serious problem for radiator lifetimes of a few thousand hours.§

Group 4 Ions

The charge exchange ion production rate is

$$N = Q\Delta L A n n_0 \tag{2}$$

where N is the number of charge exchange ions produced per unit time in the volume $(A\Delta L)$; Q is the charge exchange cross section; ΔL is an increment of length; A is the cross-sectional area; n is the number of ions arriving at the volume per unit time per unit area; and n_0 is the neutral atom density. The cross-sectional area of the exhaust plume at the engine is $\pi D^2/4$ where D is the engine exhaust diameter. Taking ΔL in Eq. (2) to be unity and considering only the central portion of the beam [$\theta = 0$ in Eq. (1)] gives the number of charge exchange ions produced per unit length

$$N(r) = \pi Q D^2 n n_0'/(4[16\, r^4/D^4 + 8\, r^2/D^2 + 1]^{1/2}) \tag{3}$$

where n_0' is the neutral atom density at the exhaust plane;

$$n_0' = \mu_0'(\pi m/8kT)^{1/2} \tag{4}$$

and μ_0' is the rate per unit area at which neutral atoms leave the engine exhaust plane. Experiments[6] have shown the electric field in ion exhaust beams to be primarily radial. Therefore, the charge exchange ions will move radially. The arrival rate per unit area at a distance x perpendicular to the exhaust plume centerline is

$$N(r,x) = N(r)/2\pi x \tag{5}$$

Hence

$$N(r,x) = QD^2 n\mu_0'(\pi m/8kT)^{1/2}/8x\,[16\,(r/D)^4 + 8\,(r/D)^2 + 1]^{1/2} \tag{6}$$

The behavior of this equation is shown in Fig. 2. For the spacecraft, $r \approx 65$ cm and $x \approx 81$ cm. The Group 4 flux is $\sim 2.2 \times 10^{10}$ ions/cm²-sec. If a sticking coefficient of one is assumed, the time to accumulate a one monolayer thickness is about 5 hr. One hundred monolayers will build up in about 20 days. This concentration is fatal to the radiator because it effectively destroys the high emissivity coating on the cold patch.

Group 2 Ion Behavior

Group 2 ion behavior, for a preliminary estimate, can be obtained by considering deviations from an equivalent thruster. For this study, the mercury thruster characteristics presented by Staggs, Gula, and Kerslake[2] were used as a base. (The errors in ratioing to this thruster were not evaluated and may be large. The results must be interpreted accordingly.) From Eq. (2)

$$N_{Cs}/N_{Hg} = (QAn'n_0')_{Cs}/(QAn'n_0')_{Hg} \tag{7}$$

§ Accumulation of cesium on the 200°K walls, on a first look, is not serious. The relative emissivity and absorptivity of cesium and the aluminum walls are similar. We did not investigate the specular behavior, and this could cause trouble. A better approach would be to eliminate the cesium entirely.

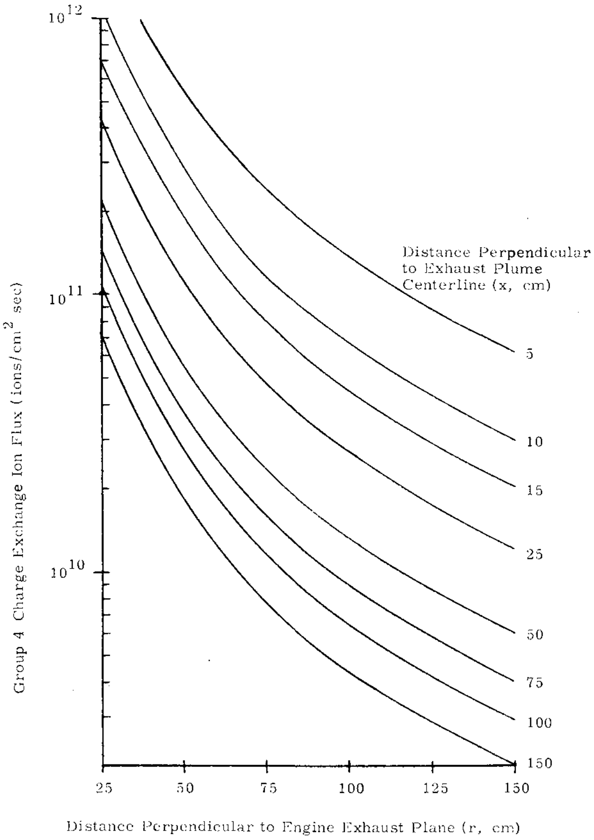

Fig. 2 Group 4 ion flux.

where the ΔL's are taken as the same for each thruster. The efficiency is given by

$$\eta = n'/(n' + \mu_0') \tag{8}$$

Next, note that the current is

$$J = n'A \tag{9}$$

Combining Eqs. (4 and 7–9) yields

$$\frac{N_{Cs}}{N_{Hg}} = \frac{\eta_{Hg}(1-\eta)_{Cs}(m_{Cs}T_{Hg})^{1/2}(J_{Cs})^2 A_{Hg} Q_{Cs}}{\eta_{Cs}(1-\eta)_{Hg}(m_{Hg}T_{Cs})^{1/2}(J_{Hg})^2 A_{Cs} Q_{Hg}} \tag{10}$$

The data in Table 2 were applied. Equation (10) immediately gives

$$N_{Cs} = 3.5\, N_{Hg} \tag{11}$$

The Group 2 ions entering the radiator make an angle of about 52° with the exhaust plume centerline. The mercury thruster Group 2 ion flux is about 1.3×10^{13} ions/steradian sec for this angle. The corresponding cesium engine flux is 4.6×10^{13} ions/steradian sec. The flux at the radiator is 2.9×10^{10} ions/cm². The neutral atom flux at this same position is 2.3×10^{12} atoms/cm²-sec. The Group 2 ion flux is small in comparison.

The point where the engine is closest to the spacecraft represents a separation distance of 13.3 cm at a 90° angle with the exhaust plume. Reference 2 shows the same Group 2 flux as at a 52° angle. Taking this value (the real value will ap-

Table 2 Inputs assumed for Eq. (10)

Item	Hg	Cs
η	0.80	0.80
T, °K	500	533
J, ions/sec	1.54×10^{18}	8.28×10^{17}
Q, cm²	6×10^{-15}	2.43×10^{-14}
Molecular weight	201	132.9
Exhaust diameter, cm	15	7.62

proach zero at 90°), we obtain a Group 2 cesium ion flux of about 10^{12} ions/cm²-sec.

Hall[4] presents the following equation for target erosion rate, which he states to hold after an initial period during which the target is becoming saturated with propellant atoms

$$dx/dt = \Gamma S/n \quad (12)$$

where dx/dt is the rate of change of target thickness with respect to time (cm/sec); B is the bombarding ion flux density (ions/cm²-sec); S is the sputtering yield (target atoms/ion); and n is the target number density (atoms/cm³). Daley[7] presents data that show that the sputtering yield is about one atom per incident ion for an energy of 600 ev. The primary flux at the cesium thruster exhaust is 1.8×10^{16} ions/cm²-sec. The corresponding erosion rate is 3×10^{-7} cm/sec or about 1 cm/1000 hr. As an approximation, erosion rates at other positions may be determined as a direct ratio with the flux.

If we apply the approximation to Group 2 ions, it will be conservative since the average ion energy is lower than the Group 1 ions. This means that, on the average, fewer atoms are sputtered per ion impacting on the surface. The Group 2 ion flux of 10^{12} therefore erodes about 4×10^{-5} cm/1000 hr. This is a very small amount and should not be a problem for a solid surface. However, it may be significant for a surface such as aluminized Mylar. A more detailed investigation would be indicated if such a surface were located close to the thruster.

Conclusions

Conditions exist in some spacecraft where it is incorrect to neglect the charge exchange ions in evaluating the effect of ion thruster exhaust. Low temperature surfaces that are recessed into the spacecraft may be particulary sensitive because of directional effects. A very gross analysis also indicates that sputtering due to Group 2 ions might be a problem for thin films. Further work is indicated in this area.

The problems could be eliminated in the analyzed spacecraft by two changes: 1) recess the thruster into the spacecraft so that the exhaust opening cannot be seen from the spacecraft, and 2) charge the thruster neutralizer to about 50 or 100 v to prevent Group 4 ions from reaching the spacecraft. The former eliminates direct impingement of neutral atoms and Group 2 ions upon the spacecraft. The latter provides sufficient potential difference that the low energy Group 4 ions cannot penetrate to the spacecraft.¶

References

[1] Reynolds, T. and Richley, E. A., "Propellant Condensation on Surfaces near an Electric Rocket Exhaust," *Journal of Spacecraft and Rockets*, Vol. 6, No. 10, Oct. 1969, pp. 1155–1161.

[2] Staggs, J. F., Gula, W. P., and Kerslake, W. R., "Distribution of Neutral Atoms and Charge-Exchange Ions Downstream of an Ion Thruster," *Journal of Spacecraft and Rockets*, Vol. 5, No. 2, Feb. 1968, pp. 159–164.

[3] "A Study of Cesium Exhaust from an Ion Engine and Its Effect upon Several Spacecraft Components," HIT-399, June 1969, Hittman Associates, Inc., Columbia, Md.

[4] Hall, D. F., Newnam, B. E., and Womack, J. R., "Electrostatic Rocket Exhaust Effects on Solar-Electric Spacecraft Subsystems," *Journal of Spacecraft and Rockets*, Vol. 7, No. 3, March 1970, pp. 305-312.

[5] Sohl, G., Reid, G. C., and Speiser, R. C., "Cesium Electron Bombardment Ion Engine," *Journal of Spacecraft and Rockets*, Vol. 3, No. 7, July 1966, pp. 1093–1098.

[6] Sellen, J. M., Jr., Kemp, R. F., and Hieler, R. H., "Observations of Neutralized Ion Thrust Beams in the 25-Meter NASA Testing Chamber," CR-53634, 1964, TRW, NASA.

[7] Daley, H. L. and Perel, J., "Cesium Ion Sputtering of Aluminum, Copper, and Titanium, AIAA Paper 66-203, San Diego, Calif., 1966.

¶ Staggs[2] believes the energy of these charge exchange ions is less than about 50 v. Sellen[6] gives a 7 or 8 v potential across a beam. Beam potentials of less than 10 v relative to the ion source are reported.

Total Emittance Measurements of Thin Metallic Films at Cryogenic Temperatures

G. R. Cunnington* and G. A. Bell†
Lockheed Palo Alto Laboratory, Palo Alto, Calif.

AND

B. F. Armaly‡ and C. L. Tien§
University of California, Berkeley, Calif.

Nomenclature

A	=	sample frontal area = absorber
a_b	=	blackbody absorptance ≈ 0.98
a_s	=	sample absorptance for blackbody radiation at T_b and sample at T_s; a'_s, same, but sample at T_c
F	=	sample to blackbody view factor = blackbody to sample view factor
T_b	=	blackbody absorber temperature
T_c	=	sample temperature during calibration ≈ 20 or 77°K
T_s	=	sample temperature
Q_c	=	calibration power input
Q_l	=	heat flux to blackbody thermal link
Y_c, Y_s	=	blackbody radiation exchanges with wall during calibration and during sample run
ϵ_b	=	blackbody emittance at T_b ≈ 0.98
ϵ_s, ϵ_s'	=	sample emittances at T_s and at T_c, respectively
σ	=	Stefan-Boltzmann's constant

Introduction

THE most efficient multilayer insulation reflective shield concept uses vacuum-deposited gold or aluminum (~500 Å) on a very thin plastic sheet (0.15 to 0.25 mils thick) such as Mylar or Kapton which greatly reduces system weight[1] and thermal anisotropy[2] of the insulation over one using metal foils. The first theoretical work on the radiation properties of thin metallic films[3] was based upon the Drude single (or free) electron (DSE) theory of optical constants. However, it later became apparent that the anomalous skin effect (ASE) theory[4] should be used rather than the DSE theory for the cryogenic temperature range. The recent work of Domoto et al.[5] showed that the predicted values of total hemispherical emittance ϵ based upon the ASE theory could be an order of magnitude greater than those predicted by the DSE theory. It has been shown[6,7] for the condition when the film thickness becomes smaller than the electron mean free path that the electrical and thermal properties of the film will differ from those of the bulk metal. To incorporate the size effect (i.e., influence of film thickness) into the skin effect, Dingle[8] established the theoretical framework for evaluating the radiative properties of thin metallic films on the basis of the ASE theory. An extensive analysis of size and skin effect at cryogenic temperatures has recently been done by Armaly and Tien.[9]

This Note reports measurements of ϵ for vacuum-deposited, high-purity gold films on plastic and metal substrates over the temperature range of 60–300°K. Effect of film thickness on ϵ

Presented as Paper 70-63 at the AIAA 8th Aerospace Sciences Meeting, New York, January 19–21, 1970; submitted March 5, 1970; revision received September 4, 1970. The authors are grateful to M. McCargo and S. A. Greenberg, who provided the proton transmission measurements, and to D. A. Vance for preparation of gold on copper specimens. Work at the University of California conducted under NASA Grant NGR-05-003-295, Ames Research Center, Moffet Field, Calif.

* Staff Scientist. Member AIAA.
† Senior Scientist.
‡ Presently at Department of Mechanical and Aerospace Engineering, University of Missouri, Rolla, Mo. Member AIAA.
§ Professor of Mechanical Engineering. Associate Fellow AIAA.