Journal of Spacecraft and Rockets

VOLUME 8 JULY 1971 NUMBER 7

Monopropellant Thruster Exhaust Effects upon Spacecraft

WARREN C. LYON
Hittman Associates Inc., Columbia, Md.

Nomenclature

a = ion engine exhaust opening radius
A = cross-sectional area
$A_{nn'}$ = Einstein coefficient
B = absorption coefficient
c = speed of light
D = thruster exhaust diameter at the thruster exhaust plane
e = electron charge
E = energy
f = absorption oscillator strength (Landenburg f value)
h = Planck constant
I = photon intensity
J = inner quantum number
k = Boltzmann constant
m = atom mass
n = ion arrival rate per unit area per unit time
n,n' = excitation level
n_o = neutral atom density
N' = charge exchange ion production rate
N = atom density
N'' = number of adsorbed atoms per unit area
$N(r,x)$ = charge exchange ion arrival rate per unit area
r = distance from thruster exhaust opening
P_a = absorption probability
P = pressure
P_v = vapor pressure
Q = charge exchange cross section
t = time
T = temperature
x = distance measured perpendicular to exhaust plume centerline
x',y',z' = dimension as in Fig. 5
α,β = angles (see Fig. 5)
Γ = evaporation rate
$\Gamma(r,\theta)$ = atom flow rate
Γ_a = atom arrival rate
Δ = line width
ΔL = incremental length
θ = angle from plume centerline
λ = wavelength
μ_o' = rate per unit area at which neutral atoms leave engine exhaust plane
ν = frequency
τ = mean life
$\bar{\omega}$ = statistical weight

Warren C. Lyon holds a B.S. (1954) from the University of New Hampshire and an M.S. (1955) from the University of Virginia in Chemical Engineering. He has completed most of the course work required for a Ph.D. in Nuclear Engineering (University of Tennessee, 1955–1956, and University of Maryland, 1964–1969). He is presently on the staff of Hittman Associates where he is responsible for investigations pertaining to thruster characteristics and the effects of outgassing upon spacecraft and onboard experiments. He also acts as a project engineer on selected programs in other technical areas and serves as a company consultant in technical areas such as heat transfer, thermodynamics, energy conversion, nuclear engineering, and computer applications. Earlier, Mr. Lyon was responsible for the supervision of several technical areas within the company, and has been both a technical supervisor and a technical specialist prior to joining Hittman Associates. In addition, for a number of years Mr. Lyon was on the staff of the Drexel Institute of Technology where he taught graduate courses in the evening program in Nuclear Engineering, Thermodynamics, and Heat Transfer. He has written 34 technical reports and 12 papers, has contributed major sections to a number of other reports, and has been the author or a major contributor to many proposal efforts. He is a member of the AIAA.

Presented as Paper 70-1143 at the AIAA 8th Electric Propulsion Conference, Stanford, Calif., August 31–September 2, 1970; submitted September 11, 1970; revision received April 1, 1971. Many of these studies were supported by the NASA Goddard Space Flight Center, under Contracts NAS5-9479 and NAS5-11826. The author gratefully acknowledges the assistance of R. Bartlett and R. Hunter of the Goddard Space Flight Center in the performance of the cesium and hydrazine studies, the many valuable suggestions furnished by the staff of the *Journal of Spacecraft and Rockets* in the revision and improvement of the manuscript, and the data volunteered by several people who provided additional information. Note that some of the conclusions presented in AIAA Paper 70-1143 have been changed.

Background

INTERACTIONS between rocket and thruster exhaust products, other contaminants, and spacecraft components have been reported in numerous references. Many of the observed effects were not anticipated. For example, deposits were formed on the outside of the astronaut's viewing windows during the first two Gemini flights.[1,2] Particulate contamination was first reported by astronauts Glenn and Carpenter and has been observed in many manned flights as well as being recorded by TV from the Pegasus 2 spacecraft.[3] The Nimbus II and III HRIR (High Resolution Infrared Radiometer) detector cell temperature control was unsatisfactory,[4,5] probably due to contaminant recondensation phenomena.[6] The Gemini S-010 and S-012 micrometerite experiments revealed a number of contaminants, including deposited material, surfaces pitted by thruster debris, corrosion from chemical reactions, and gouging by cohesive particles.[7] These, as well as many other examples, clearly show that space in the vicinity of a spacecraft provides an environment that is far from the vacuum many times assumed by the designer. Anything that contributes to the environment is of immediate concern.

Spacecraft are becoming more sophisticated. The Nimbus HRIR detector cell was to operate between -70 and $-80°C$ (design point was $-75°C$) (see Ref. 4). The initial values were close to the design point, but over a few hundred orbits, the temperature rose to greater than $-65°C$ (see Refs. 4, 8, and 9). This almost tripled instrument noise to signal ratios. Now we are considering temperatures of 100°K for an ATS experiment[10] and of 70°K on SMS (see Ref. 11). If we have difficulty at $-75°C$, the need to carefully investigate behavior at $-200°C$ is obvious. (A 30°C change in temperature at 100°K can change contaminant evaporation rate by 10^6 (see Ref. 12).

Onboard thrusters are a potential major source of spacecraft contamination. Their exhaust characteristics must be carefully investigated if problems are to be recognized prior to flight. Many studies of exhaust plume shapes, heating rates, and pressures have been reported, but most were intended for application to large motors. A number of Apollo oriented studies have covered exhaust behavior of intermediate range motors. The small thruster (<one pound thrust) literature provides, with a few exceptions, reports limited to thruster performance, design features, etc.

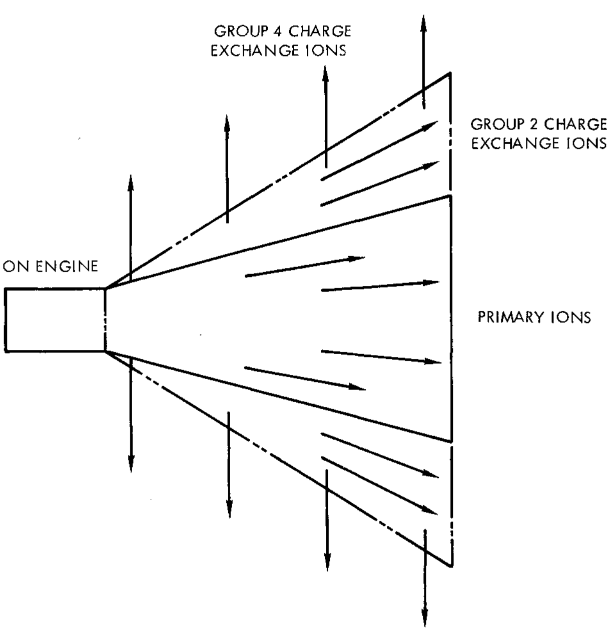

Fig. 1 Ion distribution schematic.

Consideration of small thruster exhaust effects is the topic of few investigations.

Most of the small thrusters under consideration for spacecraft utilize a single propellant. Further, many missions are being planned for the use of advanced thrusters as opposed to the cold gas thrusters that have been utilized on many spacecraft. This paper will be restricted to the area of monopropellant thrusters and in addition will exclude discussion of cold gas systems. It is not intended to completely cover the field, but through the evaluation of several thrusters of different types it should give an indication of the problems that can be expected. The types that will be covered include ion thrusters which use mercury and cesium and thrusters that use Teflon, hydrazine, and ammonia as the working medium.

Ion Thrusters

Exhaust Plume

Exhaust from an ion thruster consists of collimated ions and uncollimated ions and neutral atoms. The collimated ions, which constitute most of the exhaust, are high energy ions primarily contained within an envelope defined by a small semiangle. These ions, referred to as Group 1 ions, do not interact with a spacecraft unless something is placed directly in the beam. All other ions are secondary ions produced by charge exchange reactions between neutral atoms and the Group 1 ions. Those produced within the thruster accelerating structure which escape the thruster, referred to as Group 2 ions, travel in approximately straight lines with the origin at the thruster exhaust. Those which are generated in the primary beam external to the thruster, termed Group 4, travel roughly perpendicular to the beam. (Group 3 ions are those which are produced within the thruster with insufficient energy to escape. Since they do not escape, they are of no concern here.) The un-ionized portion of the exhaust drifts outward from the thruster at approximately thermal energy. This behavior is shown schematically in Fig. 1.

Neutral atom distribution

The neutral atom distribution, for $r > a$, is approximately[13]

$$\Gamma(r,\theta) = \Gamma_o(a/r)^2 \cos\theta/[1 + 2(a/r)^2 \cos\theta + (a/r)^4]^{1/2} \quad (1)$$

where Γ_o is the value of $\Gamma(r,\theta)$ at the ion engine exhaust plane.

Group 4 ions

The charge exchange ion production rate is

$$N' = Q\Delta LAnn_o \quad (2)$$

Lyon[14,15] has shown that the arrival rate per unit area at a distance x perpendicular to the exhaust plume centerline is

$$N(r,x) = \frac{QD^2n\mu_o'(\pi m/8kT)^{1/2}}{8x[16(r/D)^4 + 8(r/D)^2 + 1]^{1/2}} \quad (3)$$

This is an approximate equation. There has been no allowance for the depletion of atoms as the high velocity ions pass through them and the accuracy in the vicinity of the exhaust opening is poor, which is the location where the rate of change with r is the greatest.

Group 2 ions

Preliminary estimates can be based upon the behavior of an equivalent thruster. One approach has been used by Staggs[16] who presented a set of scaling relationships for electron bombardment thrusters.* Another approach, used by Lyon,[14,15] is based upon a ratioing of Eq. (2).† These two approaches use the available data in slightly different form and are both approximations which are subject to errors.

Typical characteristics

The Group 1 primary ion beam principally is contained within a 15–20° semiangle.[13,14,17,18] The propellant utilization efficiency is 80–90% for mercury E.B. thrusters,[13,15,19–23] about 99% for cesium contact engines,[13,24,25] and about 80–93% for cesium E.B. thrusters.[26] The neutral efflux normally is assumed to correspond to a thermal velocity of about 1400°K for the cesium contact thruster and in the vicinity of 500°K for the E.B. thrusters. Recent information indicates that neutral atom temperatures for the latter may be in the vicinity of 1000°K (see Ref. 27). If this preliminary information is correct, the neutral atom velocities are higher than commonly assumed, and neutral density therefore is lower. (Our calculations have been based on the older 500°K values.)

Typical primary velocities are about 30,000 m/sec and current densities of E.B. thrusters range from about 1–4 ma/cm². Short life Cs contact thruster densities are about 10–20 ma/cm² (at the exit plane).[13]

Contaminants

Most studies neglect the effect of material other than propellant in the exhaust plume. This assumption should not be made until it can be justified since contamination can be the major factor. The problem normally originates within the thruster. For example, Hall[13] points out that Hg E.B. engines typically produce a molybdenum flux of about 2×10^{14} atoms/cm² sec due to electrode sputtering. Similar results can be expected with the aluminum grids from cesium thrusters except that there will be less contaminant because the thruster operates at lower voltages and the sputtering problem will not be as great.[28] Such items as charge exchange effects also may be a consideration with the contaminant, although the problem probably will be small because the fluxes will be low and there is no reason to expect large charge exchange cross sections.

Plume Effects

Surface accumulation

A preliminary determination of propellant accumulation may be based upon a balance between condensation rate and evaporation rate, with the additional assumption that the surface behaves as though it were composed of pure propellant. Further, the condensation rate can be computed from the arrival rate multiplied by a condensation coefficient. The latter is the ratio between the rate at which the molecules condense on a surface and the rate at which they intersect the surface. Dushman[29] quotes two investigators who determined the coefficient as equal to one; one for metal atoms condensing on metal surfaces and the other for high boiling point organic liquids. Hall[13] also quotes an investigator[30,31] who states that metallic vapors have a unity sticking coefficient. This means the arrival rate may be treated as the condensation rate for cesium and mercury. Basic thermodynamic considerations relating the number of atoms which cross an area, pressure, and mean velocity lead immediately to a mathematical representation of the accumulation rate:

$$dN''/dt = \Gamma_a - P/(2\pi mkT)^{1/2} \qquad (4)$$

where Γ_a is the atom arrival rate. It is useful to assume the accumulation rate equal to zero so that the resulting equation represents equal accumulation and evaporation rates. Then the theoretical predictions may be compared to computed arrival rates to see if propellant buildup is possible. This information is presented in Fig. 2 to show the accumulation and nonaccumulation regions. The plots are terminated at a rate of 10^6 since anything which sticks to a surface at a temperature lower than the range of the graph will remain on the surface. Conversely, anything which arrives at a rate less than this will take so long to accumulate (roughly one mono-layer per 10,000 days) that it will not be of concern.

Reynolds[17,21,32] and Hall[13,18,33] have published the results of studies of mercury thrusters upon typical spacecraft surfaces. They found that impingement rates were high enough under some conditions that condensation could be a problem. Specifically, they found perturbations in solar-panel characteristics close to the spacecraft due to the change in optical behavior. Hall warned that such metals as gold and solder could cause trouble and that insulator resistivity and electrode gaps could be degraded. He also discusses a number of materials and reactions. Reynolds warned that even surfaces not in the line-of-sight of the initial propellant trajectories could still receive impingement through reflection or reevaporation from surfaces in the direct line-of-sight of the thruster exhaust. He also warned that material within the beam could be sputtered onto adjacent surfaces. Finally, he stated that surfaces within the 15° semiangle exhaust cone probably would not become coated because of ion-beam resputtering, but that surfaces outside the cone could receive a deposit.

We have studied the condensation problem specifically for a radiation cooler designed to operate at 100°K (see Refs. 10, 14, and 15). The cooler-spacecraft-thruster configuration

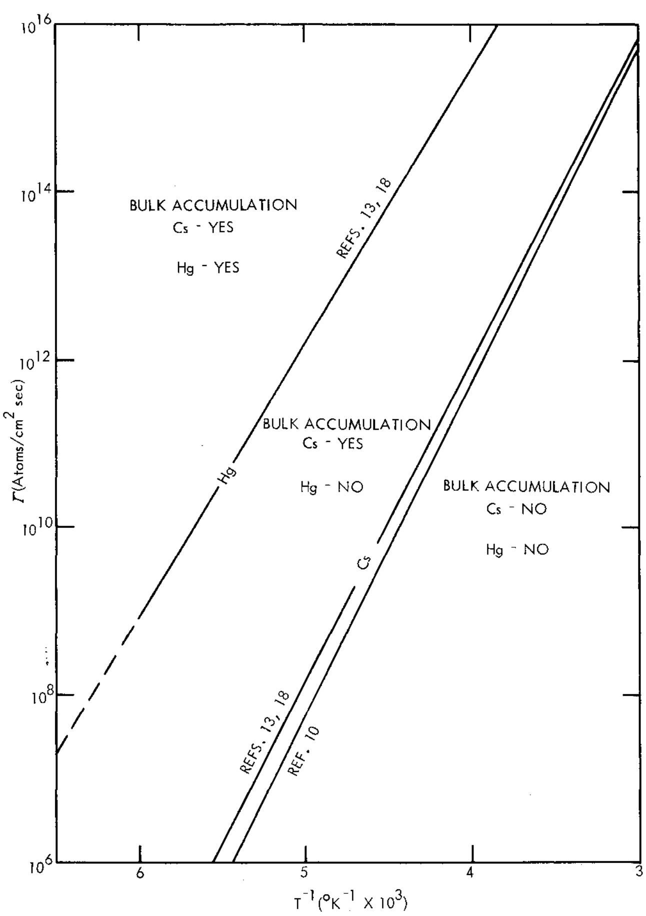

Fig. 2 Evaporation rate behavior.

* These relationships are derived in Refs. 10 and 14.

† Based upon a suggestion by an Associate Editor of the *Journal of Spacecraft and Rockets.*

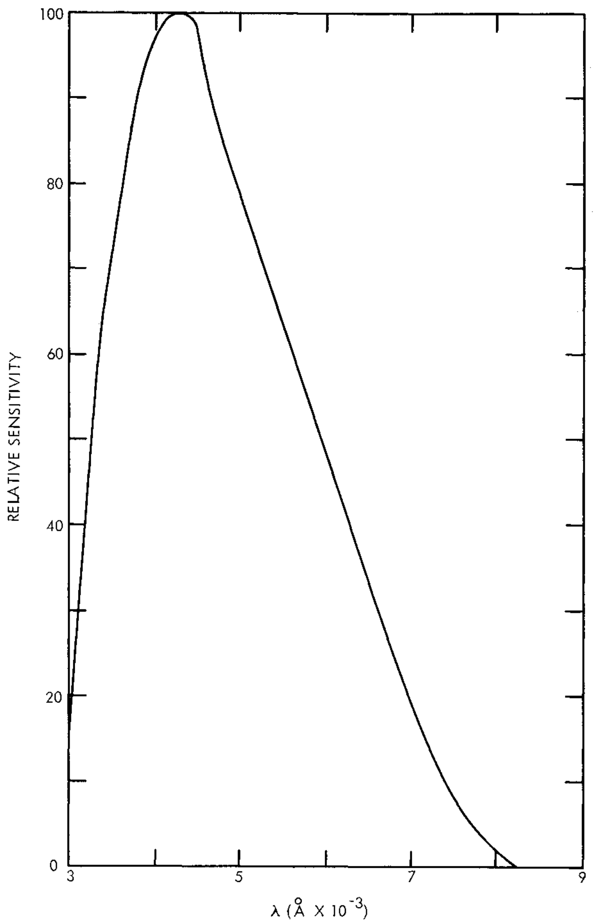

Fig. 3 Spectral response curve S-20.[36]

was such that the cold patch of the cooler could not "see" the thruster exhaust opening nor could it see any surfaces exposed to the exhaust beam. The cold patch did have a field of view to the thruster exhaust beam at about a 90° angle to the beam centerline. Evaluation of the behavior

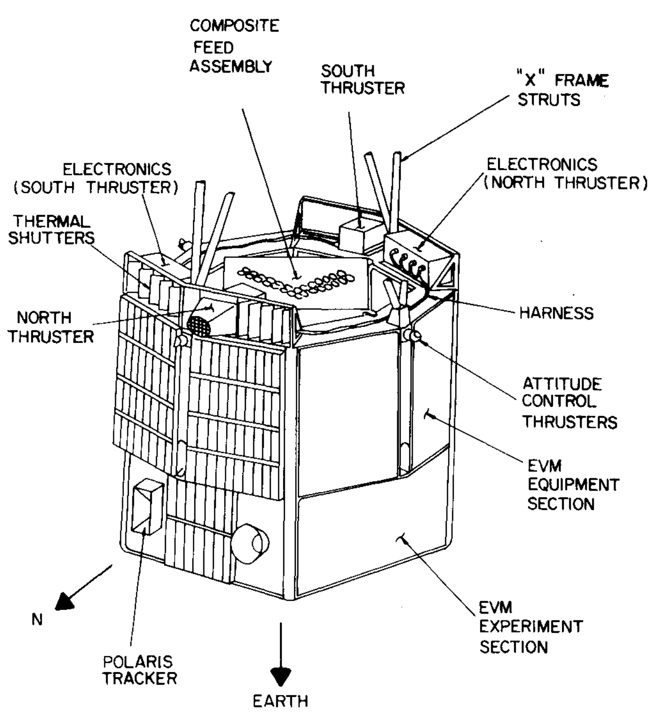

Fig. 4 Assumed ATS-F and -G configuration.

showed that the Group 1 and 2 ions were no problem, nor were the neutral atoms of immediate concern. However, the rate at which the Group 4 ions entered the radiator and condensed upon the cold patch would have been fatal in a few weeks. Although the neutral atoms did not appear to cause a direct problem, they did accumulate on some surfaces within the cooler. Since the specular behavior of the cooler walls is critical to its operation, accumulation should not be permitted. The problem was eliminated by recommending that the thruster be recessed into the spacecraft a short distance or that the exhaust opening be shielded so that the cooler opening did not have a view of the exhaust opening. The Group 4 ions could in theory be eliminated by operating the beam neutralizer at a slight negative potential relative to the spacecraft so that the low velocity Group 4 ions could not penetrate to the spacecraft.[34] This latter suggestion could introduce other problems via collection of a charge from space for a low altitude satellite, but probably would be of little concern with high altitude satellites such as the ATS-F.

Plume sunlight and absorption behavior

Since an ion thruster ejects mass in the vicinity of a spacecraft, there may be concern that observations of faint light sources could be seriously perturbed. We have investigated this effect in studying interaction of a cesium thruster with a Polaris star tracker.[14,35] Surprisingly (because of the tenuous nature of the thruster exhaust), there may be a problem. The preliminary analysis shows that sufficient sunlight may be scattered by the exhaust plume that the tracker would be affected. If this occurs with cesium, it also may occur with mercury (which we have not investigated).

For purposes of the study, the Polaris star tracker sensor was assumed to follow the spectral response curve shown in Fig. 3.[36] The principal series for cesium is shown in Table 1.[37] With the exception of the first two lines, there are a number of lines which correspond to the sensor response range. (This is only a summary table. The sharp, diffuse, and fundamental series also have lines within the sensor response range. Further, Moore[38] lists 73 transitions involving the ground state. For the time being, we will work only with the sharpest lines of the principal series.) The first line for cesium II (singly ionized cesium) occurs at 930 Å (Ref. 38). This indicates that cesium ions are transparent to photon energy in the range of interest. Therefore, the analysis may be limited to neutral cesium atoms.

The radiative decay coefficients indicate that excited state lifetimes are in the microsecond range.[39] Therefore, we assumed all atoms would be in the ground state and the analysis could be simplified since the various excited levels could be neglected (for the preliminary treatment). Consistent with this assumption is the assumption that if a ground state atom absorbs a photon and becomes excited, it will immediately decay, re-emitting one or more photons. We assumed it would decay to the ground state, thus re-emitting a photon of the same length that it absorbed. This assumption is open to considerable question and will introduce error into the analysis. Finally we assumed an optically thin gas. This means sunlight intensity within the plume is a constant and any photons emitted by excited atoms will not be absorbed. (The assumption is not good

Table 1 The principal series of Cs (Ref. 37)

λ, Å	*E*, ev	λ, Å	*E*, ev
8943.46	1.386	3617.41	3.427
8521.12	1.455	3611.52	3.433
4593.16	2.699	3480.13	3.562
4555.26	2.721	3476.88	3.566
3888.65	3.188	3184.2	3.893
3876.39	3.198		

adjacent to the exhaust opening; but becomes acceptable a meter or two away.)

Cole[40] has shown that cesium has a hyperfine structure with the first fine structure line actually consisting of six lines and the next consisting of four lines. The other lines also probably have such a structure and a careful examination of the behavior should therefore take this into account. Since the purpose of this study was to establish the magnitude of the problem, the hyperfine structure was ignored, which probably will result in an underprediction of the absorption phenomena.

If atoms of level n' are exposed to photons of frequency $\nu(nn')$ at an intensity $I_\nu(nn')$, the number of upward transitions per unit volume per unit time is[41]

$$N_\nu' = N_{n'} I_{\nu(nn')} B_{n'n} \tag{5}$$

and the absorption coefficient $B_{n'n}$ is related to the Einstein coefficient of spontaneous emission, $A_{nn'}$, by

$$A_{nn'}\tilde{\omega}_n/\tilde{\omega}_{n'} = B_{n'n}2h\nu^3/c^2 \tag{6}$$

If the inner quantum number is J,

$$\tilde{\omega}_n = 2J + 1 \tag{7}$$

One may show that the Einstein A value is related to the f value by

$$A_{nn'} = 8\pi^2 e^2 \nu^2 \tilde{\omega}_{n'} f_{nn'}/(mc^3\tilde{\omega}_n) \tag{8}$$

Combining this and noting the basic relation between frequency and wavelength, λ, gives

$$N_\nu' = N_{n'} I_{\nu(nn')} 4\pi^2 e^2 \lambda f_{nn'}/(hmc^2) \tag{9}$$

which, coupled with the geometric considerations, makes it possible to compute plume absorption effects since f values are available in the literature (see Refs. 42 and 43). Since we have assumed immediate decay from excited states, it also provides re-emission rates.

In actuality, Eq. (9) is a distribution function. To obtain true numbers we must consider wavelengths between λ and $\lambda + \Delta\lambda$. This is most easily done by introducing the line width, defined as the range of wavelengths over which a photon will interact in the vicinity of a line. This has been the topic of many investigators.[44-47] One of the simplest equations is Richtmyer's[45]

$$\Delta = \lambda^2/(2\pi c\tau) \tag{10}$$

where τ is the mean life of the level and the transition involves the ground state. Since $\tau = 1/A_{nn'}$, immediately

$$\Delta = 4\pi e^2(2J' + 1)f_{nn'}/[mc^2(2J + 1)] \tag{11}$$

To complete the treatment, we consider the geometry of the spacecraft shown in Fig. 4. The geometrical relationships for the spacecraft, the thruster exhaust plume, and the Polaris tracker are illustrated in Fig. 5. The neutral atom distribution is known from Eq. (1). Therefore, if we "look" outward from the center of the Polaris tracker opening we can, with the known geometry, compute the atom density along the line of sight. Immediately, the probability of photon absorption from the sun's light may be computed for any incremental volume along the line of sight. This absorption creates an excited state atom, which then (according to our assumption) immediately decays. If the re-emitted photon has an equal probability of being emitted in any direction, the number of photons scattered into the tracker instantaneous field of view may be calculated from the known scattering position and the instantaneous field of view geometry. There results for the intensity of the scattered photons which enter

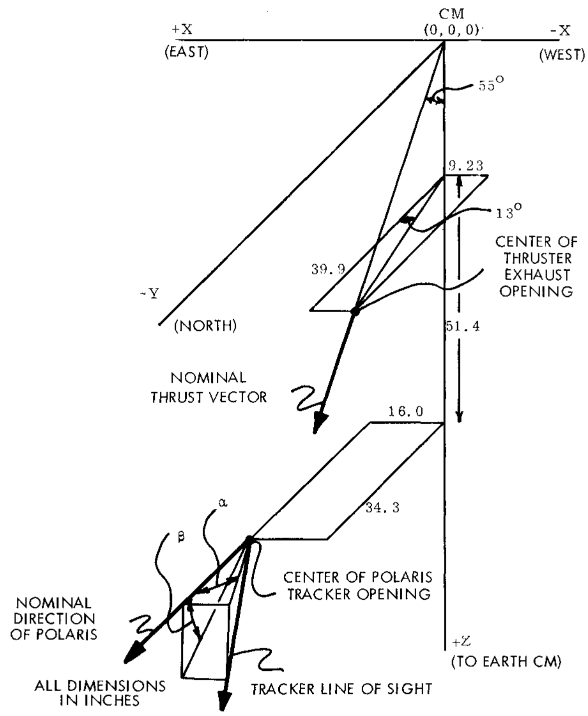

Fig. 5 Tracker—thruster geometry.

the tracker lens within the field of view

$$I = \int_{y'=0}^{\infty}\int_{x'=y'\tan\alpha_1'}^{y'\tan\alpha_2'}\int_{z'=y'\tan\beta_1'}^{y'\tan\beta_2'} \frac{A_l y' P_a I_o dx'dy'dz'}{4\pi(x'^2 + y'^2 + z'^2)^{3/2}} \tag{12}$$

The probability of absorption can be determined from Eqs. (9) and (11) with consideration to the geometry and resulting atom density. Using the solar flux data of Fig. 6[48] we can

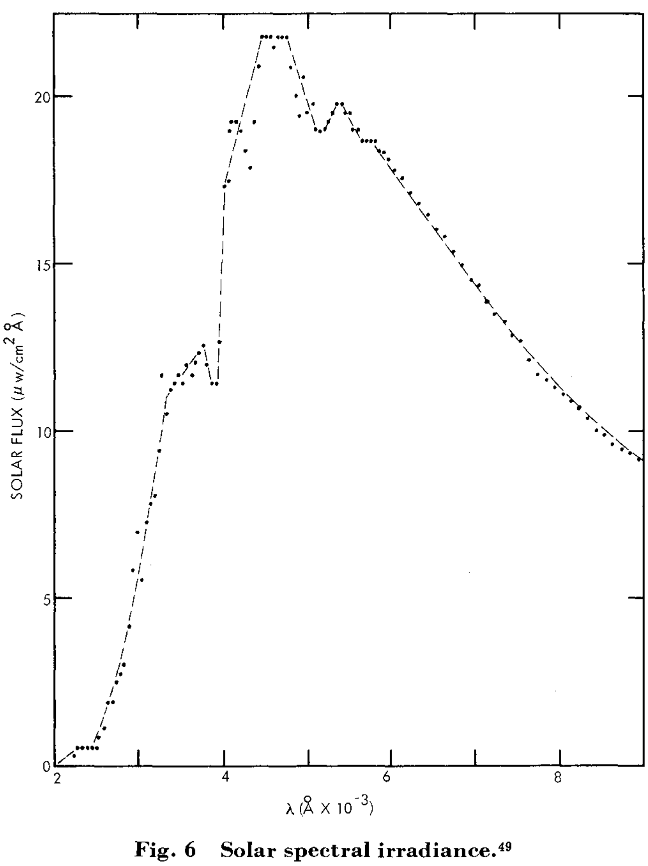

Fig. 6 Solar spectral irradiance.[49]

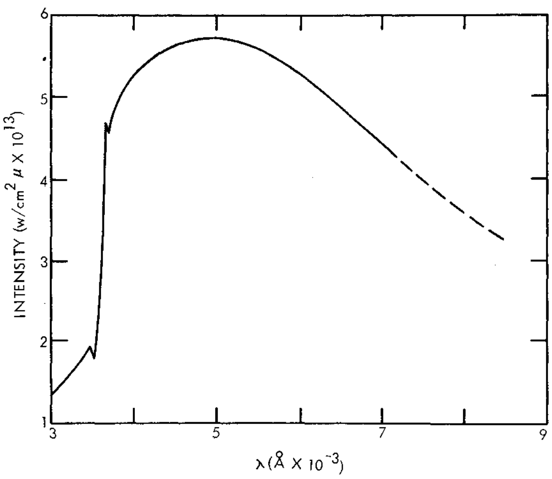

Fig. 7 Polaris spectral energy distribution.[49]

compute the energy entering the tracker for each of the principal series lines. Finally, taking into account the relative response of the sensor (Fig. 3) and adding the response for each of the lines, we obtain the total response of the sensor to the scattered sunlight. The same response curve can be combined with the Polaris spectral energy data presented in Fig. 7 (Ref. 49) to obtain the relative tracker response to Polaris. There results the behavior shown in Table 2. Immediately, we see the energy reflected from the plume to be larger than the energy received from Polaris. The preliminary analysis indicates that a problem may exist. Also note the line widths. These are so small that the amount of Polaris energy absorbed by the plume will be completely negligible in comparison to the total.

We conclude that plume absorption of starlight is no problem, but plume scattering of sunlight into the star tracker field of view may be a problem.

Contaminant effects

Propellants used in ion thrusters are relatively free from impurities. Unfortunately, a potential contamination problem arises from sputtering of the accelerator grid. Mercury thrusters typically eject molybdenum and cesium thrusters typically eject aluminum. Staskus[50] has reported that solar cell sensors located at a distance of about 30cm from the accelerator grid center and about 60° from the beam axis on the SERT II were degraded rapidly due to the operation of mercury ion thrusters. Sensors reached 50% opacity in 7.5–12 hr when maintained at −40°C and in 6.5–8.8 hr when held at +60°C. The author concluded from the results that no significant mercury contamination occurred and that the contamination of both sensors was due to the molybdenum. Reynolds[32] has reported the results of a laboratory investigation in which similar behavior was obtained. He attributed the difference in contamination levels on the SERT spacecraft to a possible difference in the localized grid sputtering rate in the neutralizer region. He also reported that the grid material appeared to be removed at a rate of about 210 monolayers/hr (averaged over the total thruster cross-sectional area) and that this material was distributed nearly randomly from the accelerator surface. An interesting aspect is the observation that when solar cells were located directly within the high intensity region of the beam, there was no accumulation of material due to resputtering effects; but when cells were located outside this region, a buildup was observed. (This is similar to behavior reported for Teflon thrusters, where a reason has, to our knowledge, not been postulated.) The radial distribution of contaminant ranged from near zero near the thruster axis to a maximum and back to near zero with increasing radial distance. A theoretical analysis also is contained in the report. (See also Hall[33] and Richley[51] where other analyses are given.)

Erosion effects

The erosion capabilities of the primary beam from an ion thruster have been mentioned. This effect has been recognized for some time, but the effect of the Group 2 ions usually is neglected. Although this normally is a good assumption, such is not always the case. A rough estimate of this effect was presented in Ref. 15 which showed that of the order of 10^{-5} cm/1000 hr could be eroded from materials located at a wide angle from the plume centerline. Although this is a very small amount, it could be significant for a material such as aluminized Mylar. If such a surface were located close to the ion thruster, then a more careful examination would be indicated.

Other effects

Hunter[52] reported no detectable EMI on the ATS-IV satellite. The SERT II carried a RFI experiment to study the frequency bands 300–700 MHz, 1680–1720 MHz, and 2090–2130 MHz.[53] Initial results from the experiment were that background radiation from earth based sources grossly reduced the resolution of the measurements. The ion beam data, when compared to the Earth background, did not appear to be a problem. However, the author points out that the range of interest to planners for communication systems for deep space is an order of magnitude below that of the Earth and for this reason firm conclusions are not drawn.[54]

A number of chemical and physical effects have been studied in depth by Hall.[13,18,33,55] Mercury appears to cause few problems with typical organic spacecraft material such as silicones, polyesters, epoxies, polyimides, polyacetals, and Teflon. There also is no effect with many of the typical thermal control coatings. It reacts slowly with silver, but the problem does not appear serious. The reaction rate with soft solder is rapid and the mechanical properties are seriously affected. Cesium reacts with Teflon FEP and Kapton H-Film (a polyimide), and reacts rapidly with soft solder. A number of thermal coatings have been exposed to 3 kev mercury ions. There was no effect upon the emittance of all samples and upon the absorptance of black samples. The absorptance of white paints and RTVs was markedly increased. Quartz and 0211 microsheet optical properties were unaffected. Hall warns, however, that optical coatings may be degraded by ion bombardment.

The ion thruster can have an effect upon the environmental plasma and the spacecraft potential. The SERT II behavior

Table 2 Polaris tracker—Cs thruster interaction results[a]

Cs atom level	λ,μm	f	Line width, cm	Sensor relative response[b]
$6P_{1/2}$	0.8943	0.394^{+0}	1.400^{-12}	0
$6P_{3/2}$	0.8521	0.811^{+0}	1.445^{-12}	0
$7P_{1/2}$	0.4593	0.284^{-2}	1.009^{-14}	2.75^{-6}
$7P_{3/2}$	0.4555	0.174^{-1}	3.09^{-14}	1.60^{-5}
$8P_{1/2}$	0.3888	0.317^{-3}	1.127^{-15}	1.09^{-7}
$8P_{3/2}$	0.3876	0.349^{-2}	6.20^{-15}	1.19^{-6}
$9P_{1/2}$	0.3618	0.725^{-4}	2.58^{-16}	1.92^{-8}
$9P_{3/2}$	0.3612	0.125^{-2}	2.22^{-15}	3.15^{-7}
$10P_{1/2}$	0.3481	0.289^{-4}	1.027^{-16}	5.96^{-9}
$10P_{3/2}$	0.3478	0.620^{-3}	1.101^{-15}	1.28^{-7}
$11P_{1/2}$	0.3401	0.124^{-4}	4.40^{-17}	2.19^{-9}
$11P_{3/2}$	0.3399	0.356^{-3}	6.32^{-16}	6.26^{-8}
$12P_{1/2}$	0.3350	0.620^{-5}	2.20^{-17}	9.74^{-9}
$12P_{3/2}$	0.3348	0.208^{-3}	3.70^{-16}	3.26^{-8}
			Total	2.01^{-5}

[a] Exponents are powers of 10; e.g., $0.284^{-2} = 0.284 \times 10^{-2}$.
[b] Polaris energy gives a relative response of 1.31×10^{-5}.

showed that a negative spacecraft potential could be obtained by adjusting the neutralizer to spacecraft potential at constant neutralizer current. Attempts to bias the neutralizer negatively resulted in increased neutralizer current. It was not immediately determined if this was due to flow of electrons from space or due to a loop current from the neutralizer cathode to nearby positive surfaces.[56] If it were the former, then the problem would be a function of altitude (electron population). The interaction mechanisms and effects are discussed in more detail by Ogawa.[57]

Pawlik[58] has reported upon an electrical interference generated within an ion thruster and power conditioner. Other interference signals that were related to the space plasma have been reported, and if there is a significant interaction between the ion thruster plasma and the spacecraft, similar phenomena may be of interest.[59,60] There is also a possibility of *rf* interference with signals which pass through the beam but we are not aware of any quantitative studies with ion thrusters. Finally, there is a possibility that exposure to propellants will degrade electrical insulators and electrode gaps.[13]

Teflon Thrusters

A number of Teflon thrusters have been studied in the past several years and four are in use on the LES-6 satellite.[61] (Guman[62] reported in 1968 that more than one hundred different thrusters had been placed on test.) Despite this experience, we have found no studies of the effects of Teflon thruster exhaust upon spacecraft. Further, upon initiating such a study we found that behavior of the exhaust from a Teflon thruster is not understood. Nevertheless, sufficient experimental "feel" exists that postulated characteristics may be obtained.

Two basic types of "Teflon" thrusters have been reported. One utilizes solid Teflon[61–68] and the other a so-called liquid Teflon.[69,70] The latter is a perfluorocarbon wax consisting of a polymer built up from a basic C-3F-Cl structure.[71] The exhaust from the two appears similar, but more outgassing can be expected from the wax-like polymer because of its higher vapor pressure.‡ Our study[11] concentrated on the solid Teflon propellant.

Teflon thruster principles appear straightforward although the details are not understood. Operation is initiated by charging a storage capacitor to its operating voltage. This voltage is impressed across an interelectrode spacing located adjacent to the surface of the end of a Teflon fuel rod. An igniter plug is fired which initiates a microdischarge in the interelectrode spacing. Apparently, a small portion of Teflon is depolymerized and promptly vaporized. A portion of this ablated portion is ionized and accelerated within the interelectrode gap due to the voltage difference impressed by the capacitor. This causes further depolymerization and ionization until a microdischarge results which closes the circuit and allows the capacitor to discharge. The main discharge depolymerizes a surface layer of Teflon which is ionized and ejected through the thruster nozzle by the electrical effects. Virtually all of the thrust comes from the ions. Only a small portion is associated with the neutral components. Efficiency is relatively low since only a small fraction of the effluent is ionized. (Vondra[67] furnishes further information and a theoretical treatment.)

Experimental measurement shows that the entire process requires only a few microseconds.[61] The ionized constituents are ejected at about 40,000 m/sec and the neutral effluent comes off at roughly 3000 m/sec.[67]

Four Teflon thrusters have been in operation on the LES-6 satellite since October 15, 1968.[61,68] There has been no interference with the telemetry, communications, or solar panels on the satellite.[68,72] These thrusters are located so that the nozzle protrudes slightly from the curved surface of a cylindrical spacecraft. There are no objects which can see the opening of the exhaust nozzle.[61,72]

Plume Characteristics

Limited observations of the exhaust plume have been performed with a calibrated RCA-1-P42 phototube.[61,68] This tube, positioned to look directly along the thrust axis into the thruster nozzle, showed a peak light intensity at 1.45 μsec after discharge initiation. Light was observed for 10 μsec. With the detector at right angles to the plume centerline, a signal could not be obtained for distances of more than 4 or 5 in. downstream of the exhaust opening. Guman[72] suspects, because of this and other observations, that most chemical and ionic reactions and recombinations occur very close to the thruster.

Spectroscopic analyses of LES-6 type thruster exhaust plumes have shown neutral carbon and fluorine atoms as well as singly, doubly, and triply ionized atoms of these species.[66,67,73] Iron also has been identified, probably originating from the stainless steel electrodes or the spark plugs. The amounts are small since erosion has not been a problem. Unidentified molecular species also were observed. (The data were obtained at a position close to the exhaust opening.)[74] Since a highly reactive environment exists at the exhaust opening, but there is no evidence of chemical reaction several feet away (see below) we probably can conclude the reactive species recombine within a few inches of the exhaust opening and few or no reactions occur within the exhaust further out.

Vondra[73] has provided preliminary data that show the ion distribution is Gaussian with a $1/e$ value at $\pm 13°$. On a spherical surface located a constant distance from the Teflon face, 90% of the charge is contained within an included cone angle of 36° (18° half angle). If the total charge collected is integrated over the entire plume, we find that 9–10% of the exhaust is ionized. The remainder is neutral.[73] (See also Ref. 67.)

From roughly 10cm out, the charge behaves as an inverse distance squared relationship. This indicates no recombinations. Charge still behaves in this manner at a 50–75 cm distance.[74] Deviations occur closer than 10cm, indicating that recombination processes are occurring. Vondra has plotted voltage data from 10 cm to about 80 cm on a log plot.[63,67] These data follow a straight line which behaves with the cube of distance, behavior which should occur if no recombinations take place.

Deposit Observations

Virtually every extended test of a Teflon thruster has resulted in observable deposit formation. Mirrors located in the beam become coated with a translucent deposit, the end of vacuum chambers used for engine testing become coated, and deposits are observed in bell jars. No chemical reactions with surfaces or erosion have been found.[72,75–80] An object in the beam will shade any region downstream.[62,77] A slight diffraction pattern also is evident. The coating changes color and some of the deposit will flake off a mirror when it is left in air for a half hour. Apparently a reaction is taking place. This complicates deposit analysis. Analysis of deposits indicates material which could have come from Teflon, as well as showing various constituents which could have come from diffusion pump oil or other test chamber materials.[79,81–83]

Material distribution within the plume is basically unknown.[76] The maximum turning angle probably is less than

---

‡ The oil has a 5 μ vapor pressure at 140°F. The waxes have vapor pressure in the $\frac{1}{10}$–$\frac{1}{100}$ μ range.[71] A mixture of oils and waxes that has been outgassed to remove lighter elements may have a lower vapor pressure.

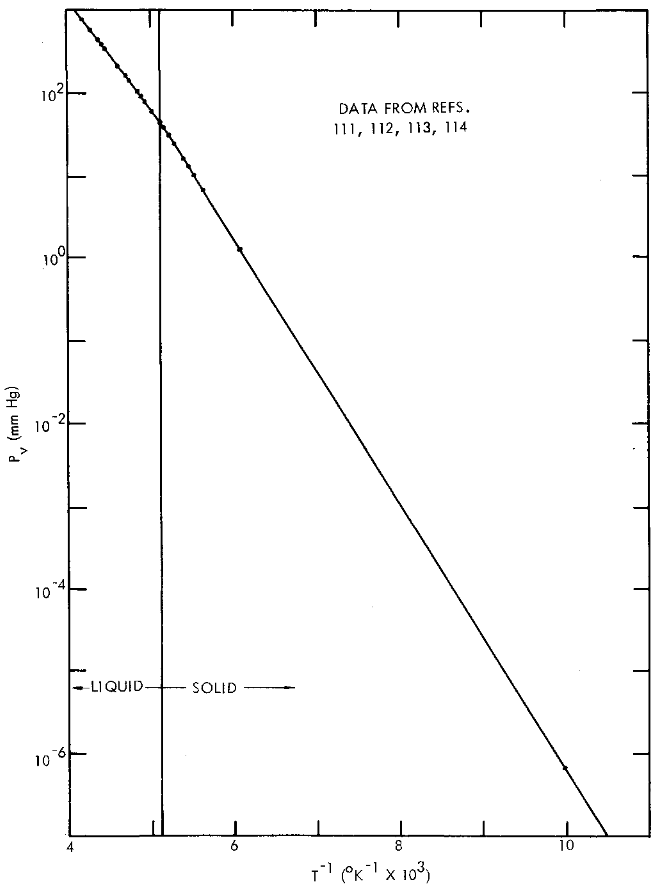

Fig. 8 Ammonia vapor pressure. Data from Refs. 112–115.

90°. Vondra[78] feels the total included angle for most of the materials is 20%. LaRocca estimates that 98–99% of all condensable material is within a 15° semiangle. (He cautions that this is very approximate.)[77] Apparently, any object placed close to the beam centerline will become coated with a Teflon-like polymer material with incorporated contaminants if any are in the vicinity of the exhaust beam.

One interesting observation concerns some of the tests that have been performed in a bell jar. In the vicinity of the centerline of the plume, the wall of the bell jar was completely clean; however as one moved outward in a radial direction the deposit appeared to build up and then decreased.[75] One possible explanation for this behavior may be sputtering of the same type as referred to for the ion thrusters. (This must be regarded as a postulation, we have not looked at the behavior to see if such could be the case.)

Theoretical Understanding

Since we have only a limited understanding of the composition and distribution, theoretical understanding of beam characteristics is poor. Charge distribution and characteristics have been estimated and we can postulate condensable behavior from test experience. Deposits analysis indicates a repolymerization reaction. We may use Teflons known characteristics to postulate what is taking place, (see Refs. 84–88). Apparently, the reaction is one of depolymerization of the Teflon followed by partial decomposition of the monomer with partial ionization. The radicals, atoms, and ions then recombine within a few inches of the exhaust opening. Whether the monomer recombines significantly prior to leaving the vicinity of the thruster has not been investigated. We do know that surfaces will serve as a catalyst. Probably, some monomer remains uncombined after the beam has become frozen (in a rarified atmosphere).

Teflon impurities should not cause a problem. Virgin Teflon is extremely pure and for practical purposes the quantity of impurities cannot be determined. (It is beyond the sensitivity range of most tests.)[89] However, scrap Teflon commonly is saved for reuse. This, despite all precautions, becomes contaminated. Only virgin Teflon should be used for this application.

Spacecraft Effects

Most of the neutral and charged material is concentrated within a 20° semiangle of the beam centerline. The beam is highly reactive close to the thruster exhaust nozzle and appears to become less so as one increases distance. Consequently, anything placed very close to the exhaust nozzle and close to the centerline will react strongly. Anything placed in the vicinity of the beam further out will become coated. Probably, a cone of about 40 or 50° semiangle should be used as an exclusion zone for spacecraft components. It would be desirable to avoid a cone of 90° semiangle. Further, anything placed within the recommended exclusion zone could bounce material back to other spacecraft components. These "bounces" probably would be specular or semispecular since anything that stuck long enough to give diffuse behavior probably would remain on the surface.

There is a visible light plume which extends outward a few centimeters from the Teflon surface and has a lifetime of only microseconds per pulse. Any light sensor which saw this plume probably would be temporarily disturbed. The material in the plume probably would provide sufficient absorption that sensitive instruments such as star trackers would be perturbed, as we found for the cesium ion thruster. Tests have been conducted to determine RFI behavior.[61] These included bell jar tests, as well as prelaunch tests with the LES-6 flight system. No problems were found, although there were indications that changing the thruster exhaust cone would change the amount of interference. No problems have been found with the LES-6 flight.[68]

A preliminary analysis for indirect effects which could return exhaust to spacecraft uncovered no problems. Apparently, the ions leave the thruster prior to appearance of neutrals external to the thruster. This eliminates charge exchange as a potential return mechanism. (Were the process reversed, there might be a serious problem.) Similarly, elastic collisions between the two species (ions and low speed neutrals) appear to be eliminated. The over-all beam appears to be neutral, and generation of a net charge would appear not to be a problem. The ionic and electron velocities emitted from the thruster exhaust may be different, but since the process requires only a few microseconds, the charge effect, if any, would be short lived. There remains the possibility of collisions between exhaust and environment atoms or molecules. This would appear to be slight, but was not investigated. For most spacecraft experiments, it should be no problem. Experiments which depend upon an exceedingly clean environment, such as radiation coolers which are to operate at cryogenic temperatures, may experience a long term change by such an effect.

One final caution appears in order. There has been considerable experience with the thruster exhaust interacting with back-streamed diffusion pump oil and with recently cured epoxy. There is a possibility that material from this source could make its way back to spacecraft components during system testing and could later introduce problems unless suitable precautions were taken.

Hydrazine Thrusters

Operation Principles

In principle, hydrazine thruster operation is straightforward. Cold hydrazine, under pressure, is forced through an injector into a catalyst bed, decomposes, and is ejected through a nozzle. The catalyst normally is an alumina vehicle containing iridium (the active ingredient), although rhodium is also considered.

Hydrazine injected into a cold iridium catalyst bed (70°F) begins to decompose in 10–100 msec. The reaction is exothermic, causing rapid bed heating with increasing decomposition rate. Initially, the effluent may contain a small portion of hydrazine, but after 0.1 sec little hydrazine appears. The principle decomposition products are ammonia and nitrogen. A portion of these products undergo a endothermic reaction to form nitrogen and hydrogen. Once the three constituents leave the catalytic bed, the composition is chemically frozen.

Hydrazine decomposition has been studied by many investigators.[90–102] The basic reaction with iridium catalyst is

$$N_2H_4 \rightarrow 4/3(1 - x)NH_3 + 1/3(1 + 2x)N_2 + 2xH_2$$

where x is the fraction of originally formed ammonia that is dissociated. Typically, the temperature at the exit of the catalytic bed is less than 1800°F (Ref. 91). Price[98] has found the decomposition reaction to be transport process controlled with the following ammonia reaction rate limited. Consequently, the exhaust composition and temperature can be controlled by varying catalytic bed length and reactant residence time. The decomposition behavior with rhodium catalyst is similar, with the exception that N_2 and H_2 are produced as well as NH_3 (see Ref. 102).

Kesten[99–101] has determined reactant concentrations as a function of position within the catalyst bed. Typically, in the steady state the exhaust will be composed of about 10–20% NH_3, 30% N_2, and 50–60% H_2 (on a mole basis). The N_2H_4 has decomposed within the first 5–10% of the bed length. In a transient, the initial exhaust composition might be 40–50% NH_3 and then, as steady state is approached, it approaches the lower value. The exhaust will contain contaminants from the hydrazine feed and from the catalyst bed. The major reported contaminants are H_2O, NH_3, and amines.[103] There are small quantities (mg/l) of dissolved metals and particulate matter. Water and NH_3 appear to introduce few problems. These are present in less than about a percent and, in the case of the first two, problems are unlikely. Water has a relatively high vapor pressure and in the amounts that are returned to the spacecraft in most circumstances, it will not accumulate. The NH_3 from N_2H_4 decomposition is much greater than the NH_3 contaminant and therefore the presence of NH_3 in the N_2H_4 is not a problem. This is not the case with the amines. Hydrazine aniline content is quite variable from batch to batch, and ranges from about 0.02%–1%. Typical is about 0.4%.[104] There is concern that this will carbonize as it passes through the catalyst and become a contamination source to optical and thermal control surfaces. Even the unchanged portion is of concern because of the potential that it may undergo reactions in the presence of sunlight on spacecraft surfaces, although it probably would not remain on such surfaces for a long time because of its relatively high vapor pressure. The potential problem requires further investigation.

Catalyst loss has been reported in the literature,[91,105,106] but this appears to be for some of the older motors and later tests appear to have eliminated the problem.[107,108] Esenwein[109] has reported that tests with new Shell 405 catalyst resulted in the expulsion of hydroxylamine hydrochloride with traces of ammonium chloride (apparently from chlorine in the catalyst). This has a melting point of 304°F, and probably would remain on the surface of a spacecraft, and particularly upon the cold patch of a cooler, for some time. Tests with old (used) catalyst did not show the problem, nor did tests with a specifically prepared catalyst that was depleted of chlorine. Probably, the chlorine is exhausted after the thruster has been operated several times. The catalyst also can absorb significant quantities of gases. These will outgas when exposed to a vacuum and, for practical purposes, will be exhausted the first time the thruster is operated.[110]

Exhaust properties

Both N_2 and H_2 have high vapor pressures and should not collect on spacecraft surfaces unless there is a strong chemical or physical attraction. Chemical reactions are unlikely with N_2. Hydrogen is a strong reducing agent at elevated temperatures but it is inert at room temperature.

Ammonia is alkaline and is compatible with many organic and most inorganic materials. Most metals are no problem, and most plastics and elastomers resist attack to temperatures which approach the softening point. Boyd[111] provides a detailed listing of compatibility data. Ammonia has a boiling point of 431.59°R and a melting point of 351.74°R (Ref. 112). Specific gravity is 0.6817. Its vapor pressure is shown in Fig. 8. Since the data are sparse, the Clausius-Clapeyron equation, with the usual assumptions, was used as an aid in the correlation. Note that the vapor pressure is high enough that NH_3 normally will not accumulate on spacecraft surfaces.

Hydrazine is a clear oily liquid with an ammonia-like odor. It melts at 1.4°C, freezes at 0°C, and boils at 236°F (Refs. 112 and 116). Hydrazine compatibility data may be inconsistent. Some investigators report satisfactory behavior if a surface in contact with hydrazine is unaffected; others require that both the hydrazine and surface be unaffected. Most metallic materials are compatible with hydrazine, and many plastics and rubber are compatible at room temperature.[103,105,111] Brill[117] has exposed a number of samples to N_2H_4 vapors and found all except one to be compatible; the exception was an antireflection coating of the type used on bolometer lenses, and this dissolved.

Thin films of hydrazine absorb strongly in the 2.5–20 μ region. Reported transmittances as a function of wavelength range from almost 0– ~80% in a reference sample and from 60–95% in a specification grade sample.[103]

Little data for low-temperature hydrazine vapor pressure exist and the small amount we could find was correlated as previously mentioned and is shown in Fig. 9. The values are somewhat lower than NH_3, but still accumulation on most surfaces should not be a problem.

Exhaust Effects

Plume impingement and shape calculations have been the subject of many investigations. References 122–130 are appropriate for estimating the exhaust plume. Brill,[117] in a combination of tests and analyses, found that there was good correlation between the two. We did not attempt to attain precise values, but instead approximated the behavior with straightforward manual calculations.[14,131] Typical thrusters with an exit semiangle of 15° showed a limiting

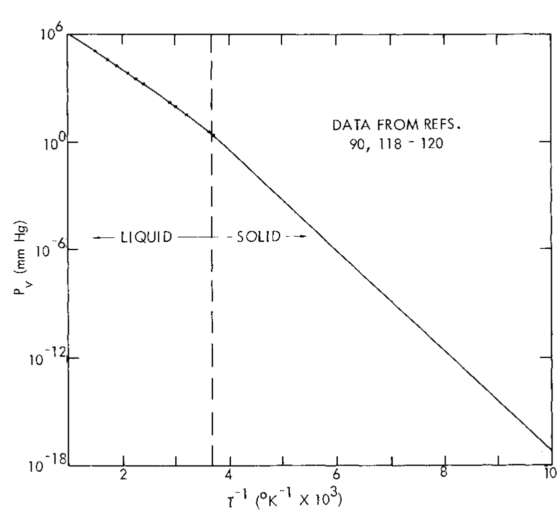

Fig. 9 Hydrazine vapor pressure. Data from Refs. 90, and 119–121.

streamline angle of 91° (the Prandtl-Meyer value). Most of the exhaust from these thrusters is confined to one hemisphere. Only minor propellant fluxes will occur in the hemisphere behind the exhaust plane. The high vapor pressures and chemical compatibility data indicate that for most spacecraft surfaces, no problem will exist. Low-temperature surfaces, such as 70–100°K cold patches used in instrumentation, may be susceptible to NH_3 and N_2H_4 accumulation. Hydrazine from a cold start-up could collect on these surfaces. Ammonia should be no problem on a 100°K surface, but could accumulate on a 70°K surface. In either event, heating the surface to 150–200° would evaporate the NH_3 or N_2H_4. A remaining question then would be whether significant contaminant from the N_2H_4 or the catalyst had reached the cold surfaces. These might not evaporate rapidly and the problem might be of a permanent nature. One would also have to establish whether there were any chemical or surface effects remaining due to the presence of the NH_3 or N_2H_4. (This probably is unlikely, in part because of the low temperature, but one is not sure until the potential problem has been investigated.)

Placement of an object directly in the plume would be of concern if any of the material could be returned with an effect upon spacecraft components as mentioned in the previous paragraph. If an insensitive component were placed in the plume, and the scattered material were not of concern, then there probably would be little effect, provided of course that the net thrust vector was not disturbed significantly. (The thrust effect would, of course, be of concern with all types of thrusters.) In one test, a 25 lb thrust engine with Shell 405 catalyst and 2×2 cm 10 ohm-cm solar cells with 20 mil fused silica covers was evaluated.[132] The cells were exposed to 200 firings of 200 msec duration each at locations five and nine feet downstream of the nozzle directly in the plume. Firings were spaced about 10 min apart and sample temperature increases were less than 100°K. Pre- and postexposure electrical data showed no significant changes as a result of plume impingement. Optical examination of the cells uncovered no apparent mechanical damage. (See Ref. 133 for additional information.)

Esenwein,[109] in tests with a simulated motor and Shell 405 catalyst, found no detectable deposit or condensate on surfaces above 0°F when they were placed directly in the plume. Visible effects occurred when the temperature was lower and when the temperature subsequently was raised, some of the deposit would evaporate. The residue after evaporation was a function of the catalyst history, with used catalyst producing less "permanent" effect than new catalyst. A specifically prepared low chlorine catalyst produced less permanent deposit than new catalyst. Slight stains, which were not identified, were found on a number of specimens. Temperature effects also were reported, as was the effect of adding water to the hydrazine to reduce the heating rate. High temperature for most surfaces would be no problem as long as firing times were short and surfaces were more than a few exhaust nozzle diameters from the motor.

Brill[117] reported liquid droplets from transient operation of thrusters, and stated this could accumulate on surfaces in the plume. Testing showed some temporary deposits, perhaps due to the liquid that was lost during the first part of the transient, but these would disappear after a few hours. Posttest Alzak samples indicated up to 10% decrease in solar absorptivity and there were minor changes in some of the other samples, but these had a tendency to disappear prior to analysis (in the presence of air). This is the only report we have seen that referenced liquid in the exhaust. This may have been due to the motor design and could be unique to the one test configuration.

As would be the case with any thruster, there would be an effect upon the environmental density that becomes worse when an object is placed in the plume. One additionally would expect an effect on sensitive equipment such as star trackers if the plume were visible from the tracker and particularly if the plume was illuminated by the sun.

Ammonia Thrusters

Propellant Properties

Most of the properties of ammonia have been discussed in the previous section. There remains only the contamination in the original material. Flight certified ammonia contains <33 ppm water, <2 ppm oil, and <10 ppm salt (borax, silicon).[113] Page[134] reports that in the highest purity ammonia obtainable at a reasonable cost the impurities are 0.8 ppm oxygen and 0.7 ppm water. Ammonia purity was reported as 99.99%. Additional information is given by Page and by Knox.[135] Contaminants probably will not be a problem (unless significant water is returned to low-temperature coolers).

Exhaust Effects

No exhaust effects were found which would change any conclusions presented in the hydrazine thruster section. Additional studies were performed[14,131] in an attempt to define other interaction effects, but none were found.

Conclusions

Few problems exist with ammonia thrusters. The major effects appear to be a small visibility perturbation in the plume and an effect upon environment density. (Interaction with environmental matter was not considered.) An ammonia thruster may perturb operation of a cold patch if it is designed to maintain 70°K. The temperature of 100°K should be no problem for most configurations. Ammonia accumulation on a cold patch could be removed by warming the patch to about 150 or 200°K. Impurities in high purity ammonia should not cause a problem since the quantities are small.

Hydrazine thrusters will introduce the same perturbations mentioned with the ammonia, but there are additional potential problems. Hydrazine is not as pure as ammonia and the impurities could cause problems. Additional work to define the magnitude of the problem is necessary. Further, the catalyst can introduce a problem. The catalyst loss reported in the earlier literature appears to have been corrected, but there still remains a potential problem associated with chlorine contained in new catalyst. This causes ejection of a high melting point compound early in the thruster life. We have not determined how rapidly the chlorine is eliminated. There appears to be no erosion problem and few other effects of placing a surface directly in the plume of a hydrazine thruster. There will be a temperature increase, but this will be small for short firing times provided the surface is not too close to the thruster. For a long firing times, close locations, or temperature sensitive devices, one should investigate the potential temperatures since the exhaust temperature is high. The vapor pressure of hydrazine is lower than that of ammonia, and it will collect on surfaces at a higher temperature. This should not be a problem for most components, but there is a possibility that it could collect in a 100°K cooler. Heating to 150 or 200°K would outgas the hydrazine. The question of whether any of the impurities would remain has not been determined. (There were stains on a number of samples that were exposed to the plume of hydrazine thrusters, but the exposure rates were much higher than would occur with a cooler cold patch.)

A Teflon thruster will coat anything placed within its exhaust plume (roughly 45° semiangle). The coating, being of a Teflon-like nature, will have a high vaporization and decomposition temperature. For practical purposes it cannot be removed by heating. Conceivably, anything placed within the plume could scatter Teflon monomer back toward the spacecraft, and other portions could receive a coating. The coating probably would be inert so that the only change would be of an optical nature. Unless located extremely close to the thruster nozzle, no chemical reactions would be expected. Minor perturbations in optical viewing from the satellite can be expected in the vicinity of the exhaust plume. Again, the potential exists for a significant perturbation of the environmental density and composition.

Mercury and cesium ion thrusters can cause coating of spacecraft surfaces. Sputtered material from the thruster accelerator grid will collect on surfaces that have a view of the exhaust opening with a rate that is dependent upon the location. In the range of interest for spacecraft, there will be little effect with temperature. A problem can exist close to the spacecraft or with sensitive surfaces. If the temperatures are low enough, then cesium or mercury also may accumulate. The cold patches required by some spacecraft instruments may be particularly sensitive because of the directional nature of the plume charge exchange ions. A minor optical problem can exist. The flow from the thrusters is so rarefied that little absorption occurs. However, if sensitive star tracker equipment is onboard, the scattering of energy from the sunlight may be great enough that the tracker operation is perturbed. The primary beam from an ion thruster will sputter material from a surface at a rapid rate for locations close to the thruster. There may be an erosion problem with extremely thin coatings that are located out of the primary beam but still receive a significant flux of ions. This should be considered if such surfaces must be located near to the thruster.

References

[1] Blome, J. C. and Upton, B. E. "Gemini Window Contamination Due to Outgassing of Silicones," *The Effects of the Space Environment on Materials*, Vol. 11, 11th National Symposium and Exhibit, Society of Aerospace Material and Process Engineers, St. Louis, 1967.

[2] Bonner, G. P. et al., "Postflight Optical Evaluation of the Right-Hand and Left-Hand Windows of Gemini Missions IV, V, VI, and VII," TN D-4916, Dec. 1968, NASA.

[3] Grenda, R., Neste, S., and Soberman, R., "Contaminant Particle Trajectories Near a Spacecraft," Committee on Space Research, Plenary Meeting, Tokyo, Japan, 1968.

[4] McNaney, J. J., Palmer, B. A., and Shipiro, R., "Nimbus II Flight Evaluation and Engineering Report, Launch through Orbit 5275," TN D-4881, Feb. 1969, NASA.

[5] McNaney, J. J., "Nimbus III Monthly Flight Evaluation Report Number 3, 14 June to 13 July 1969 Orbits 800–1200," 69 SD 4338, Aug. 8, 1969, General Electric, Philadelphia, Pa.

[6] Frankel, H. E., "Degradation of the Radiant Cooler of the Nimbus III High Resolution Infrared Radiometer (HRIR)—Report of the Committee," Memorandum, Oct. 21, 1969, NASA.

[7] Hallgren, D. S., and Hemenway, C. L., "Direct Observation of Particulate and Impact Contamination of 'Optical' Surfaces in Space," Committee on Space Research, Plenary Meeting, May 1968.

[8] McNaney, J. J., "Nimbus III Monthly Flight Evaluation Report Number 1, 14 Apr. to 14 May 1969, Orbits 1 through 400," 69 SD 4295, June 10, 1969, General Electric, Philadelphia, Pa.

[9] McNaney, J. J., "Nimbus III Monthly Flight Evaluation Report Number 4, 13 July to 12 August 1969, Orbits 1200 to 1600," 69 SD 4350, Sept. 10, 1969, General Electric, Philadelphia, Pa.

[10] "A Study of Cesium Exhaust from a Ion Engine and its Effect Upon Several Spacecraft Components," HIT-399, June 26, 1969, Hittman Associates, Columbia, Md.

[11] Lyon, W. C., "A Study of the Effects of Teflon Thruster Exhaust Upon a Spacecraft," HIT-443, April 1970, Hittman Associates, Columbia, Md.

[12] Lyon, W. C., "A Study of the Effects of Hydrazine Thruster Exhaust Upon a Spacecraft," HIT-454, June 1970, Hittman Associates, Columbia, Md.

[13] 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.

[14] Lyon, W. C., "Thruster Exhaust Effects Upon Spacecraft," X-460-70-401, Oct. 1970, NASA.

[15] Lyon, W. C., "Propellant Condensation on Surfaces near an Electric Rocket Exhaust," *Journal of Spacecraft and Rockets*, Vol. 7, No. 12, Dec. 1970, pp. 1494–1496.

[16] 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.

[17] 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.

[18] Hall, D. F., "Evaluation of Electric Propellant Beam Divergence and Effects on Spacecraft," 08965-6013-R0-00, Sept. 1969, TRW Systems, Redondo Beach, Calif.

[19] Reader, P. D., "Durability Tests of Mercury Electron-Bombardment Ion Thruster," AIAA Paper 66-231, San Diego, Calif., 1966.

[20] Kerslake, W. R., Byers, D. C., and Staggs, J. F., "SERT II: Mission and Experiments," *Journal of Spacecraft and Rockets*, Vol. 7, No. 1, Jan. 1970, pp. 4–6.

[21] Reynolds, T. W., and Richley, E. A., "Distribution of Neutral Propellant from Electric Thrusters Onto Spacecraft Components," TN D-5576, Dec. 1969, NASA.

[22] Byers, D. C., and Staggs, J. F., "SERT II: Thruster System Ground Testing," *Journal of Spacecraft and Rockets*, Vol. 7, No. 1, Jan. 1970, pp. 7–14.

[23] Bechtel, R. T., "Performance and Control of a 30-cm-diam, Low-Impulse, Kaufman Thruster," *Journal of Spacecraft and Rockets*, Vol. 7, No. 1, Jan. 1970, pp. 21–25.

[24] Hall, D. F., Cho, A. Y., and Shelton, H., "An Experimental Study of Porous Metal Ionizers," AIAA Paper 66-218, San Diego, Calif., 1966.

[25] Staggs, J. F. and Lathem, W. C., "Experimental Performance of a Low-Thrust, Divergent-Flow, Contact—Ionization Electrostatic Thruster," *Journal of Spacecraft and Rockets*, Vol. 4, No. 5, May 1967, pp. 610–615.

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

[27] Miller, N. L., "A Survey and Evaluation of Research on the Discharge Chamber Plasma of Kaufman Thrusters," *Journal of Spacecraft and Rockets*, Vol. 7, No. 6, June 1970, pp. 641–649.

[28] Bartlett, R., personal communication, July 16, 1970, NASA Goddard Space Flight Center.

[29] Dushman, S., *Scientific Foundations of Vacuum Technique*, 2nd ed., edited by J. M. Lafferty, Wiley, New York, 1962.

[30] Langmuir, I., "The Condensation and Evaporation of Gas Molecules," *Collected Works of Irving Langmuir*, Vol. 9, edited by C. G. Suits, Pergamon Press, New York, 1961, pp. 69–74.

[31] Langmuir, I., "The Evaporation, Condensation, and Reflection of Molecules and the Mechanism of Adsorption," *Collected Works of Irving Langmuir*, Vol. 9, edited by C. G. Suits, Pergamon Press, New York, 1961, pp. 43–46.

[32] Reynolds, T. W. and Richley, E. A., "Contamination of Spacecraft Surfaces Downstream of a Kaufman Thruster," TN D-7038, Jan. 1971, NASA.

[33] Hall, D. F. and Kelley, L. R., "Experimental Techniques to Determine Electrostatic Rocket Exhaust Effects on Spacecraft Surfaces," AIAA Paper 70-1144, Stanford, Calif., 1970.

[34] Hunter, R., personal communication, April 1969, NASA Goddard Space Flight Center.

[35] Lyon, W. C., "A Study of the Effects of a Cesium Ion Thruster Upon a Polaris Star Tracker for ATS-F and G," HIT-452, May 1970, Hittman Associates, Columbia, Md.

[36] *RCA Electron Tube Handbook*, HB-3, Radio Corp. of America, Harrison, N. J., pp. 92cm—9779.

[37] Nottingham, W. B., and Hernquist, K. G., "Energy Levels of the Cesium Atom," *Proceedings of the IEEE*, Vol. 51, No. 12, Dec. 1963, pp. 1771–1772.

[38] Moore, C. E., *Atomic Energy Levels*, Vol. III, Circular 467, May 1, 1958, National Bureau of Standards.

[39] Norcross, D. W. and Stone, P. M., "Recombination Radiative Energy Loss, and Level Populations in Nonequilibrium Cesium Discharges," *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 8, 1968, pp. 655–684.

[40] Cole, R. K. et al., "Ion Beam Neutral Component Determination by Resonance Radiation Absorption," *AIAA Journal*, Vol. 3, No. 2, Feb. 1965, pp. 263–269.

[41] Aller, L., "Atomic Line Strengths," Cp. 3, Pt. 7, edited by E. V. Condon, and H. Odishaw, *Handbook of Physics*, 2nd ed., McGraw-Hill, New York, 1967, pp. 7-54–7-65.

[42] Corliss, C. H. and Bozman, W. R., "Experimental Transition Probabilities for Spectral Lines of Seventy Elements," Monograph 53, July 20, 1962, National Bureau of Standards.

[43] Stone, P. M., "Cesium Oscillator Strengths," *Physical Review*, Vol. 127, No. 4, Aug. 15, 1962, pp. 1151–1156.

[44] Leighton, R. B., *Principles of Modern Physics*, McGraw-Hill, New York, 1959.

[45] Richtmyer, F. K., Kinnard, E. H., and Lauritsen, T., *Introduction to Modern Physics*, McGraw-Hill, New York, 1955.

[46] Gregory, C., "Resonance Broadening of Caesium," *Physical Review*, Vol. 61, April 1 and 15, 1942, pp. 465–469.

[47] Pollock, D. H. and Jensen, A. O., "Absorption of Resonance Radiation and Formation of Molecular Ions in Cesium Vapor," *Journal of Applied Physics*, Vol. 36, No. 10, Oct. 1965, pp. 3184–3192.

[48] Johnson, F. S., "The Solar Constant," *Journal Meteorology*, Vol. 11, No. 6, Dec. 1954, pp. 431–439.

[49] Cleavinger, R. L., Gutshall, R. L., and Morgan, C. A., "Final Report for Polaris Star Tracker Breadboard Model," May 23, 1967–Aug. 1, 1968, Ball Brothers Research Corp., Boulder, Colo.

[50] Staskus, J. and Burns, R., "Deposition of Ion Thruster Effluents on SERT II Spacecraft Surfaces," AIAA Paper 70-1128, Stanford, Calif., 1970.

[51] Richley, E. A. and Reynolds, T. W., "Condensation On Spacecraft Surfaces Downstream Of a Kaufman Thruster," TM X-52746, Jan. 2, 1970, NASA.

[52] Hunter, R. E., Bartlett, R. O., Worlock, R. M., and James, E. L., "Cesium Contact Ion Microthruster Experiment Aboard Applications Technology Satellite (ATS)—IV," *Journal of Spacecraft and Rockets*, Vol. 6, No. 9, Sept. 1969, pp. 968–970.

[53] Goldman, R. G. et al., "Description of the SERT II Spacecraft and Mission," AIAA Paper 70-1124, Stanford, Calif., 1970.

[54] Rulis, R. J., "Design Considerations and Requirements for Integrating an Electric Propulsion System into the SERT II and Future Spacecraft," AIAA Paper 70-1123, Stanford, Calif., 1970.

[55] Hall, D. F., "Electrostatic Propulsion Beam Divergence Effects On Spacecraft Surfaces," Final Report, Vol. 1, Contract 952350, Aug. 17, 1970, TRW Systems, Redondo Beach, Calif.

[56] Jones, S. G. et al., "Preliminary Results of SERT II Spacecraft Potential Measurements Using Hot Wire Emissive Probes," AIAA Paper 70-1127, Stanford, Calif., 1970.

[57] Ogawa, H. S. et al., "Factors in the Electrostatic Equilibration Between a Plasma Thrust Beam and the Ambient Space Plasma," AIAA Paper 70-1142, Stanford, Calif., 1970.

[58] Pawlik, E. V. et al., "Solar Electric Propulsion System Evaluation," *Journal of Spacecraft and Rockets*, Vol. 7, No. 8, Aug. 1970, pp. 968–976.

[59] Osborne, F. J. F. et al., "Plasma-Induced Interference in Satellite v.l.f. Receivers," *Canadian Journal of Physics*, Vol. 45, No. 1, Jan. 1967, pp. 47–56.

[60] Hayakawa, M. and Iwai, A., "Plasma-Induced Radio Frequency Interferences from Space Vehicle," *Research Institute of Atmospherics, Proceedings*, Vol. 17, Jan. 1970, pp. 99–106.

[61] Guman, W. J. and Nathanson, D. M., "Pulsed Plasma Microthruster Propulsion System for Synchronous Orbit Satellite," AIAA Paper 69-298, Williamsburg, Va., 1969.

[62] Guman, W. J., "Pulsed Plasma Technology in Microthrusters," AFAPL-TR-68-132, Nov. 1968, Fairchild-Hiller Corp., Farmingdale, N.Y.

[63] Vondra, R., Thomassen, K., and Solbes, A., "Analysis of Solid Teflon Pulsed Plasma Thruster," AIAA Paper 70-179, New York, 1970.

[64] Guman, W. J. and Peko, P. E., "Solid-Propellant Pulsed Plasma Microthruster Studies," *Journal of Spacecraft and Rockets*, Vol. 5, No. 6, June 1968, pp. 732–733.

[65] Guman, W. J., "Pulsed Plasma Technology in Microthrusters," AFAPL-TR-68-132, AD845757, Nov. 1968, Air Force Aero Propulsion Lab., Wright-Patterson Air Force Base, Ohio.

[66] Guman, W. J. et al., "Pulsed Plasma Propulsion System Studies," AIAA Paper 70-1148, Stanford, Calif., 1970.

[67] Vondra, R. J. et al., "Analysis of Solid Teflon Pulsed Plasma Thruster," *Journal of Spacecraft and Rockets*, Vol. 7, No. 12, Dec. 1970, pp. 1402–1406.

[68] Guman, W. J. and Nathanson, D. M., "Pulsed Plasma Microthruster Propulsion System for Synchronous Orbit Satellite," *Journal of Spacecraft and Rockets*, Vol. 7, No. 4, April 1970, pp. 409–415.

[69] LaRocca, A. V. and Perkins, G. S., "Pulsed Plasma Microthruster Applications and Techniques," AIAA Paper 68-554, Cleveland, Ohio, 1968.

[70] LaRocca, A. V., "Pulsed Plasma and Low Pressure Detonator Thrusters for Secondary Propulsion of Spacecraft," AIAA Paper 70-1147, Stanford, Calif., 1970.

[71] Ehrenfield, personal communication, March 4, 1970, Halocarbon Corp., Hackensack, N.J.

[72] Guman, W. J., personal communication, March 31 and April 7, 1970, Fairchild-Hiller Corp., Farmingdale, N.Y.

[73] Vondra, R., personal communication, March 30, 1970, MIT Lincoln Labs., Cambridge, Mass.

[74] Vondra, R., personal communication, April 7, 1970, MIT Lincoln Labs., Cambridge, Mass.

[75] Lyon, W. C., personal observations of Fairchild-Hiller test chamber, March 31, 1970.

[76] McClellan, D., personal communication, March 5, 1970, MIT Lincoln Labs., Cambridge, Mass.

[77] LaRocca, A. V., personal communication, March 4, 1970, General Electric Co., Valley Forge, Pa.

[78] Vondra, R., personal communication, March 5, 1970, MIT Lincoln Labs., Cambridge, Mass.

[79] Murphy, E. B., personal communication, March 5, 1970, MIT Lincoln Labs., Cambridge, Mass.

[80] Nathanson, D. M., personal communication, March 5, 1970, MIT Lincoln Labs., Cambridge, Mass.

[81] Murphy, E. B., "Analysis of Char From Teflon Arc Thruster," Materials and Processing Memo #4E, June 6, 1968, MIT Lincoln Labs., Cambridge, Mass.

[82] Murphy, E. B., "RFI Teflon Vacuum Arc Thruster Vs. Ground Plain Antenna," Memo, Aug. 5, 1968, MIT Lincoln Labs., Cambridge, Mass.

[83] Murphy, E., "VAT Deposit-Fairchild-Hiller Sample (Memo #4G)," May 1, 1969, MIT Lincoln Labs., Cambridge, Mass.

[84] Rudner, M. A., *Fluorocarbons*, Reinhold, New York, 1958.

[85] Sperati, C. A. and Starkweather, H. W., Jr., "Fluorine-Containing Polymers. II. Polytetrafluoroethylene," *Advances in Polymer Science*, 1961, pp. 465–495.

[86] Settlage, P. H., and Siegle, J. C., "Behavior of 'Teflon' Fluorocarbon Resins at Elevated Temperatures," *Planetary and Space Science*, Vol. 3, 1961, pp. 73–81.

[87] Mathias, E. and Miller, G. H., "The Decomposition of Polytetrafluoroethylene in a Glow Discharge," *Journal of Physical Chemistry*, Vol. 71, No. 8, July 1967, pp. 2671–2675.

[88] Brandkamp, W., DeCecco, A., and Hanson, J. "Laser-Induced Teflon Char," *Journal of Spacecraft and Rockets*, Vol. 6, No. 9, Sept. 1969, pp. 1087–1088.

[89] Bro, M. I., personal communication, March 4, 1970, E. I. duPont de Nemours & Co., Wilmington, Del.

[90] Audrith, L. F. and Ogg, B. A., *The Chemistry of Hydrazine*, Wiley, New York, 1951.

[91] Price, T. W. and Evans, D. D., "The Status of Monopropellant Hydrazine Technology," NASA CR-92742, Feb. 15, 1968, Jet Propulsion Lab., California Inst. of Technology.

[92] Eberstein, I. J. and Glassman, I., "Consideration of Hydrazine Decomposition," ARS Propellants, Combustion, and Liquid Rockets Conference, Columbus, Ohio, 1960; also *Liquid Rockets and Propellants*, Academic Press, New York, 1960, pp. 351–366.

[93] Fresenius, W. and Karweil, J. "The Normal Oscillations and the Configuration of Hydrazine," *Zeitschrift für physikalische Chemie, Abt. B*, Bd. 44, Heft I, pp. 5–12.

[94] Lucien, H. W., "Thermal Decomposition of Hydrazine," *Journal of Chemical and Engineering Data*, Vol. 6, No. 4, Oct. 1961, pp. 584–586.

[95] Eberstein, I. J., "The Gas Phase Decomposition of Hydrazine Propellants," TR 708, AD607334, 1964, Dept. of Aerospace and Mechanical Sciences, Princeton Univ., Princeton, N.J.

[96] Stief, L. J., DeCarlo, V. J., and Mataloni, R. J., "Vacuum-Ultraviolet Photochemistry. VII Photolysis of Hydrazine at 1236 and 1470 Å," *The Journal of Chemical Physics*, Vol. 46, No. 2, Jan. 15, 1967, pp. 592–598.

[97] Schreib, R. R., Pugmire, T. K., and Chapin S. G., "The Hybrid (Hydrazine) Resistojet," AIAA Paper 69-496, Colorado Springs, Colo., 1969.

[98] Price, T. W., "Hydrazine Monopropellant Provides 0.5–600 lb. Thrust," *Space/Aeronautics*, Oct. 1969, pp. 70–72.

[99] Kesten, A. S., "Analytical Study of Catalytic Reactors for Hydrazine Decomposition," CR-89791, May 1967, NASA.

[100] Kesten, A. S., "Analytical Study of Catalytic Reactors for Hydrazine Decomposition," CR-80336, Oct. 1966, NASA.

[101] Kesten, A. S., "Analytical Study of Catalytic Reactors for Hydrazine Decomposition," CR-92988, Jan. 1968, NASA.

[102] Sayer, C. F., "The Decomposition of Hydrazine on the Shell 405 Catalyst," AIAA Paper 70-606, San Diego, Calif., 1970.

[103] Salvinski, R. J., "Investigation of the Formation and Behavior of Clogging Material in Earth and Space Storable Propellants," Interim Report, CR-191569, Oct. 1968, NASA.

[104] Suddeth, D., personal communication, March 10, 1971, NASA Goddard Space Flight Center.

[105] Sutherland, G. S. et al., "Monopropellant Hydrazine Reaction Control Systems—A Five Year Status Report," *Aviation and Space: Progress and Prospects; Proceedings of the Annual Aviation and Space Conference, Beverly Hills, Calif., 1968*, ASME, New York, 1968.

[106] "Spacecraft Attitude Control Gas Systems Analysis," CR-86661, April 1967, NASA.

[107] Martinkovic, P., personal communication to E. N. Borson, June 1968, U.S. Air Force Rocket Propulsion Lab., Edwards Air Force Base, Calif., (see Ref. 108).

[108] Borson, E. N., "Rocket Plumes as Contamination Sources," paper presented at the Symposium for Optical Contamination In Space, Optical Society of America, Aspen, Colo. Aug. 13–15, 1969.

[109] Esenwein, F. T. and Walker, S. C., "Effects of Hydrazine Exhaust Plumes and Propellant Spills On Selected Spacecraft Materials," paper presented at the Hydrazine Monopropellant Technology Symposium, Nov. 28–30, 1967, published in CPIA Publication 160, Dec. 1967.

[110] Carlson, R. A., Blumenthal, J. L., and Grassi, R. J., "Space Environment Operation of Experimental Hydrazine Reactors," Rept. 4715.3.68-27, July 1968, TRW Systems, Redondo Beach, Calif.

[111] Boyd, W. K., Berry, W. E., and White, E. L., "Compatibility of Materials with Rocket Propellants and Oxidizers," DMIC Memo 201, Jan. 29, 1965, Defense Metals Information Center, Battelle Memorial Inst., Columbus, Ohio.

[112] Weast, R. C. and Selby, S. M., *Handbook of Chemistry and Physics*, 48th ed., Chemical Rubber Co., Cleveland, Ohio, 1967.

[113] Suddeth, D., personal communication, Oct. 1, 1969, NASA Goddard Space Flight Center.

[114] Knox, B. P. and Eberle, H. R., "Propellant Performance Handbook, Vol. IV, Part A, Fluorine/Ammonia," 8173-902008-Vol. 4, Pt. A, AD802908, June 1964, Bell Aerosystems, Buffalo, N.Y.

[115] Overstreet, R. and Giauque, W. F., "Ammonia. The Heat Capacity and Vapor Pressure of Solid and Liquid. Heat of Vaporization. The Entropy Values from Thermal and Spectroscopic Data," *Journal of the American Chemical Society*, Vol. 59, Feb. 1937, pp. 254–259.

[116] Mellor, J. W., *A Comprehensive Treatise on Inorganic and Theoretical Chemistry*, Vol. VIII, Wiley, New York, 1962.

[117] Brill, Y. C., Stechman, R. C., and Reis, R. J., "Effect of Hydrazine Rocket Fuel on Spacecraft Materials," paper presented at The Institute of Environmental Sciences, 14th Annual Technical Meeting, St. Louis, Mo., 1968.

[118] "Military Specification, Propellant, Hydrazine," MIL-P-26536B, March 13, 1964, DOD.

[119] Haws, J. L., and Harden, D. G., "Thermodynamic Properties of Hydrazine," *Journal of Spacecraft and Rockets*, Vol. 2, No. 6, Nov.-Dec. 1965, pp. 972–974.

[120] Washburn, E. W. et al., *International Critical Tables*, Vol. III, McGraw-Hill, New York, 1928.

[121] Scott, D. W., Oliver, G. D., Gross, M. E., Hubbard, W. N., and Huffman, H. M., "Hydrazine: Heat Capacity, Heats of Formation and Vaporization, Vapor Pressure, Entropy, and Thermodynamic Functions," *Journal of the American Chemical Society*, Vol. 71, 1949, pp. 2293–2297.

[122] Grier, N. T., "Back Flow From Jet Plumes in Vacuum," TN D-4978, Jan. 1969, NASA.

[123] Sibulkin, M. and Gallaher, W. H., "Far-Field Approximation for a Nozzle Exhausting into a Vacuum," *AIAA Journal*, Vol. 1, No. 6, June 1963, pp. 1452–1453.

[124] Mirles, H. and Mullen, J. F., "Expansion of Gas Clouds and Hypersonic Jets Bounded by a Vacuum," *AIAA Journal*, Vol. 1, No. 3, March 1963, pp. 596–602.

[125] Hill, J. A. F. and Draper, J. S., "Analytical Approximation for the Flow from a Nozzle into a Vacuum," *Journal of Spacecraft and Rockets*, Vol. 3, No. 10, Oct. 1966, pp. 1552–1554.

[126] Zucrow, M. J., *Aircraft and Missile Propulsion*, Vol. II, Wiley, New York, 1964.

[127] Brook, J. W., "Far Field Approximation for a Nozzle Exhausting into a Vacuum," *Journal of Spacecraft and Rockets*, Vol. 6, No. 5, May 1969, pp. 626–628.

[128] Shapiro, A. H., *The Dynamics and Thermodynamics of Compressible Fluid Flow*, Vol. 1, Ronald Press, New York, 1953.

[129] Draper, J. S. and Hill, J. A., "Rarefaction in Underexpanded Flows," *AIAA Journal*, Vol. 7, No. 7, July 1969, pp. 1400–1401.

[130] Grier, N. T., "Back Flow of Jet Plumes in Vacuum," TM X-52468, July 22–26, 1968, NASA.

[131] Lyon, W. C., "Study of the Effects of Ammonia Thruster Exhaust Products Upon ATS Spacecraft," HIT-422, Nov. 5, 1969, Hittman Associates, Columbia, Md.

[132] Massie, L. D. and Martinkovic, P. J., "Attitude Control Rocket Exhaust Plume Effects On Solar Cells," 7th Photovoltaic Specialists Conference, Pasadena, Calif., 1968.

[133] Martinkovic, P. J., "Monopropellant Exhaust Contamination Investigation," AFRPL-TR-69-72, April 1969, Air Force Rocket Propulsion Lab., Edwards Air Force Base, Calif.

[134] Page, R., Halback, C. R., Ownby, M. L., and Short, R. A., "Life Test of Six High Temperature Resistojets," AIAA Paper 69-294, Williamsburg, Va., 1969.

[135] Knox, B. P. and Eberle, H. R., "Propellant Performance Handbook, Vol. IV, Part A, Fluorine/Ammonia," 8173-902008-Vol. 4, Pt. A, AD 802908, June 1964, Bell Aerosystems, Buffalo, N.Y.