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IDA MEMORANDUM REPORT M-439

CONTAMINATION SUBPANEL REPORT TO THE PHENOMENOLOGY PANEL OF THE SDIO MIDCOURSE SENSORS STUDY

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March 1988

Prepared for
Strategic Defense Initiative Organization

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This memorandum report presents a brief summary of sensor contamination issues relevant to the Midcourse Sensors Study of the Strategic Defense Initiative Organization.

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PREFACE

This memorandum report was prepared for the Strategic Defense Initiative Organization (SDIO) as part of Task T-R2-404, Physics of Plume Signatures, under the technical cognizance of Dr. Barry Katz, Sensors Office (T/SN). The report documents the results of work by the Contamination Subpanel of the Phenomenology Panel of the SDIO Midcourse Sensors Study (MCSS). The material herein has not been subjected to formal IDA review.

CONTENTS

I. INTRODUCTION

This report addresses the problem of contamination. Contamination is particularly troublesome if plumes from rockets are fired in the vicinity of the sensor suite; this will thus be relevant if the midcourse system is to be collocated aboard the space-based intercept (SBI) carrier vehicles (CVs). Contamination will also result from the interactions of the sensor and its associated platform with the ambient environment. An example of such an interaction is the shuttle glow phenomenon which has been observed on all surfaces facing the ram direction; the intensity of the glow is dependent on O atom concentration, [O], which varies with altitude. This phenomenon may interfere with the sensing function of advanced systems. Another type of interaction arises from the reaction of high-velocity O atoms with surface materials; these reactions may lead to the generation of small particulates, for example, or gaseous species which alter the effective response of the sensor. Aside from interactions with the atmosphere, surfaces may be degraded by the solar ultraviolet (UV) flux, micrometeorites, or other space debris. It is difficult to provide quantitative estimates of these effects, since little experimental data exists.

Not covered here are two very important issues regarding contamination. First, the issue of contamination due to ground operations, payload preparation, and vehicle ascent is not discussed. This is a fairly well documented area and is primarily a technology issue, involving handling procedures, detection, and cleaning techniques. Second, the issue of contamination removal techniques is not discussed. Research in this area, which is also viewed as primarily a technology issue, is being supported by SDIO through the Rome Air Development Center.

II. PLUME CONTAMINATION

A. CARRIER VEHICLE

A possible midcourse surveillance system option is to mount some of the sensors aboard the SBI carrier vehicle (CV) platforms. This option, while possibly providing advantages in cost and systems design, raises the question of operability in a dirty environment. As part of this study, the SBI contractors were asked to tell the MCSS participants what impact contamination effects have had on their design. It is important to realize that the SBI system concepts are not fully developed, and that the baseline scenarios described by the contractors have not yet reached the preliminary design phase. A final contract for an SBI system has not yet been let. Thus, the various fuels, ranges, and mission scenarios discussed are at present very tentative, and may in fact be strongly influenced by the need to collocate midcourse sensors with the SBI sensor suite.

The principal source of contamination aboard the CVs is the use of kinetic kill vehicles (KKVs), which, after all, are the reason for the platform. Contamination of the optics aboard a CV (as well as other sensitive surfaces) may result from the process of ejection of a KKV from the CV toward the point where its thrusters are ignited, and from the KKV plume itself during flyout; interference with the sensor mission may occur if particulates and hot gases are in the field of view (FOV) of the sensor.

Initially, the KKVs are ejected from their tubes out to 260 m (Rockwell) or 400 m (Martin Marietta) before the thrusters are ignited. The ejection mechanism in both cases has been baselined as a gasbag similar to those used in automobile safety systems, typically powered by a solid charge. The specified ranges are driven by mission timelines. The Rockwell coast time, for example, appears to be dictated by the need to update the guidance system of the KKV. Indeed, the Rockwell ejection scenario has the KKV attitude control system (ACS) motors (N_2F_4/N_2H_4) firing throughout the 13 s of "drift" in order to acquire a star. The Martin Marietta concept seems, however, to be driven solely by contamination concerns; the KKVs will also be somewhat "behind" the CV at the ignition point. In the

Martin Marietta concept the 400 m distance might be increased, although mission timelines may not allow a significant increase in the 40 s drift time.

There are three concerns at this stage. First, the firing of ACS engines during ejection (Rockwell scenario) appears to be extraordinarily unwise. Second, the ejection will introduce perturbations to the CV platform. An analysis by Martin Marietta appears to show acceptable excursions (0.1 deg/s^2, 0.2 deg/s, 0.1 deg); Martin Marietta is planning to use servo isolation of the sensors. Analysis in the context of the midcourse mission would have to be done, of course. Finally, the possibility of a gasbag rupture needs to be examined; the subsequent release of particulates and gases around the CV would almost certainly be catastrophic to the sensors aboard.

Interference from the presence of hot gases in the FOV of the sensor may be mitigated by using a fuel whose products do not radiate in the bands of interest. Rockwell has proposed the use of N_2F_4/N_2H_4 as the propellant for the KKV; aside from a high I_{sp}, the products consist chiefly of HF and thus do not radiate (or absorb) between about 4 microns and about 14 microns. Combustion inefficiencies, or other nonequilibrium effects, may produce small amounts of ammonia, which will radiate at around 10 microns. The Martin Marietta concept uses a solid fuel loaded with beryllium; the combustion products are shown in Table 1. These products will radiate in the short-, medium-, and long-wavelength infrared (SWIR, MWIR, and LWIR); particles of solid BeO will emit and scatter radiation throughout the spectrum, and CO, H_2O, and HCl will radiate at their fundamentals and overtones. The Martin Marietta group feels that its concept can allow for momentary blinding of a sensor.

Although temporary blinding of the sensor FOV due to the bright plume may be a problem for a single sensor, this may be overcome by appropriate battle management. The radiation due to the plume gases will dissipate after the KKV has left the vicinity; the time constant is expected to be of the order of milliseconds. At the altitude of interest (i.e., 500 km), atmospheric excitation of the spent plume gases will be insignificant (although excitation of spent plumes at lower altitudes far from the sensor will constitute part of the cluttered background against which the sensor must operate).

Of further significance is the presence of particulates from the solid-fuel plume envisaged by the Martin Marietta group. Particulates in a solid-fuel plume can be expected to be mostly between 1 micron and 20 microns in size. Particles as large as 200 microns

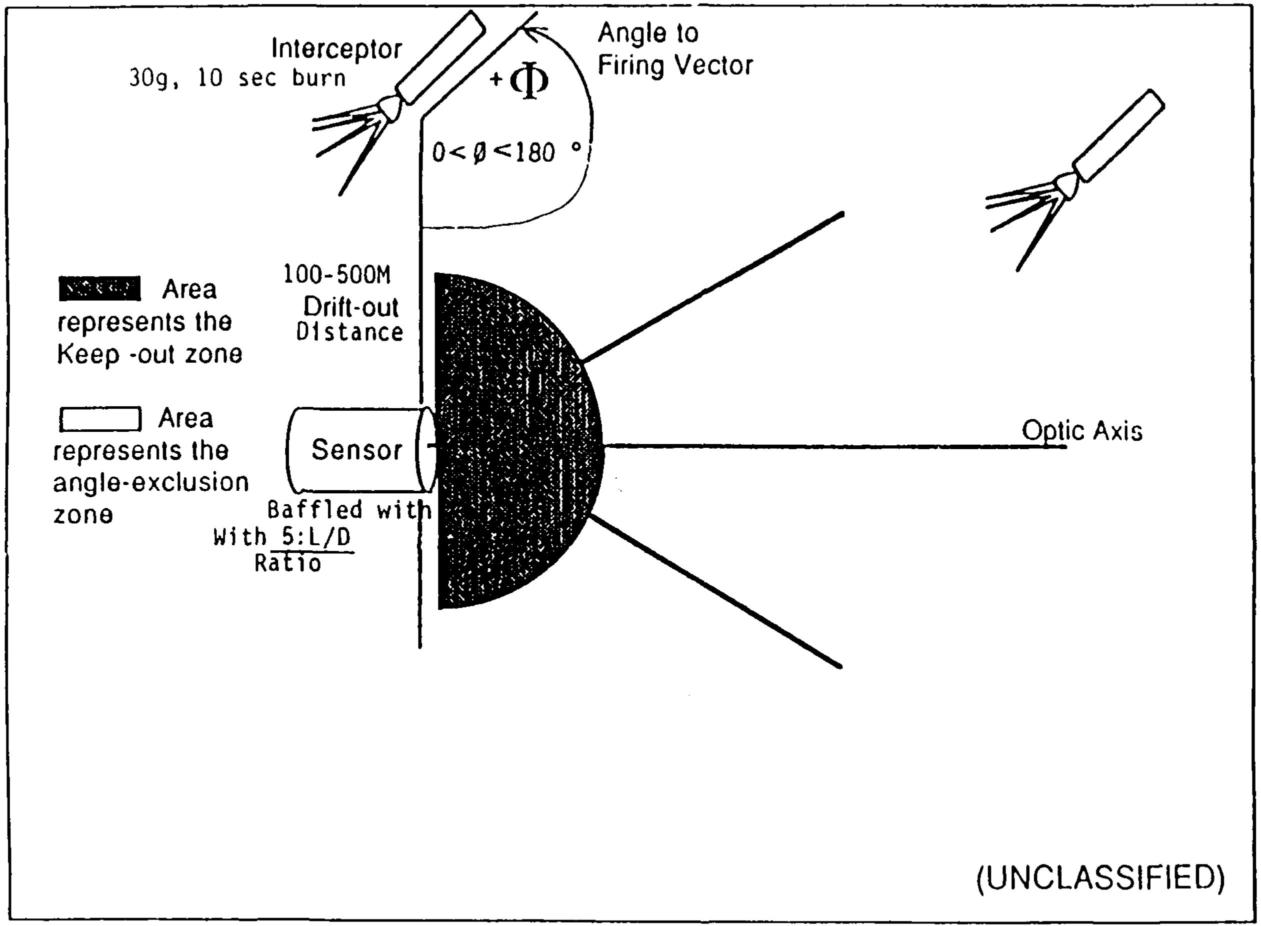
Table 1. Interceptor First-Stage Characteristics Define Contamination Scenario (Courtesy Aerojet ElectroSystems/Martin Marietta)

Propulsion Parameters	Contamination Products		
	Species	Mole Fraction	Weight Fraction
$W = 2.2\text{-}3\ (2.5)$ kg/s	$BeCl_2$	0.00170	0.00940
	$Be(HO)_2$	0.00004	0.00030
P_c = 1880 psia	Cl	0.00027	0.00167
	HCl	0.07767	0.49425
G = 137:1	CO	0.10939	0.53400
	CO_2	0.00001	0.00732
$A_{exit} = 440\ cm^2$	OH	0.00001	0.00003
	H_2	0.46863	0.16318
$T_{chamber} = 3369$ K	H_2O	0.01830	0.05736
	$BeO_{(solid)}$	0.27959	1.21862
Fuel = BeH_2 /HAP			2.5 kg/s

are possible. The particles will cool radiatively, and thus the larger particles will remain warm for longer periods of time than the smaller particles; an aluminum oxide particle with a 10 micron radius will cool from 500 K to 450 K in about 0.5 s. At distances within a few kilometers of the sensor, depth-of-field effects will severely smear the image of the particle, and furthermore the image will be vignetted. Hot particles, while emitting substantially more energy than cool particles, still will not clutter the image; the Planck curve provides insufficient compensation (at reasonable temperatures) for the blurred image. If exposed to earthshine, of course, particulates will reach radiative equilibrium at around 300 K.

The effect of the particulates within the FOV, aside from the effect of deposition onto sensitive surfaces, is thus to scatter radiation away from the sensor. Extinction cross sections for Al_2O_3 1 μm particles vary from about 10^{-14} m^2 at 10 μm (the scattering cross section for Al_2O_3 is unusually low around 10 μm) to about 10^{-12} m^2 at 16 μm; assuming similar orders of magnitude for BeO (for which detailed optical properties could not be found), and assuming that all the significant particle concentration occurs within 1 km of the sensor, about 1 g/m^3 of 1 μm particles from a KKV would cause a 5 dB signal loss. Shorter optical paths through the particulate cloud require higher concentrations of particles, of course, but it should be noted that the KKV will be putting out about 1000 g/s of BeO. Liquid-fueled systems may have similar difficulties; film cooling or mixing anomalies in the combustion chamber may lead to the production of liquid fuel droplets, which will evaporate partially and then freeze. If cold gas ACS jets are used on the KKV (or on the CV, for that matter), ice may form in the nozzle, creating clouds of particles ranging in size from a few angstroms up to microns. Clearly, careful and detailed analysis of the effect of particulates in the sensor field of view is required.

A typical flyout scenario (Martin Marietta) is shown in Fig. 1. The KKV is at a range of between 100 m and 500 m, with 400 m nominal. The sensor is baffled, so that direct impingement of sensor optics can only occur for those parts of the plume that enter the 30 deg exclusion angle zone with the appropriate flux vector. The flux of condensable gas for that scenario at the aperture is shown in Fig. 2; all the species except H_2 shown in Table 1 are assumed to be condensable. For a baffled sensor, Fig. 3 shows the expected film thickness as a function of firing angle, assuming that all condensables do in fact condense. Clearly, this "worst case" scenario will lead to films between 100 and 1000 Å in thickness. Since the fuel is solid loaded, there will be pitting of the primary mirror; the



Aerojet ElectroSystems

MARTIN MARIETTA

Figure 1. Analysis Considered Lateral Drift Out With Baffled Sensor. (Courtesy Aerojet ElectroSystems/Martin Marietta)

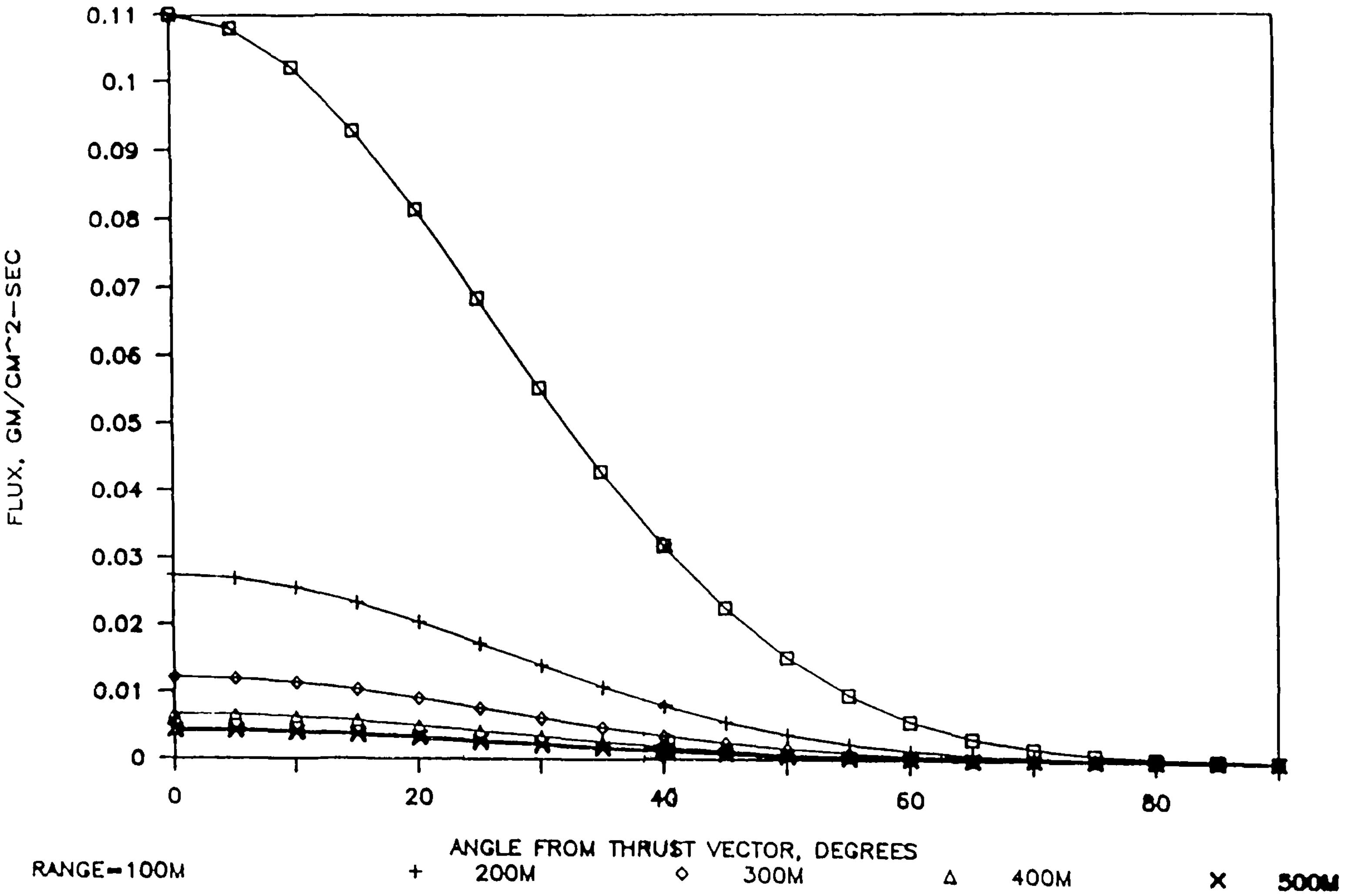


Figure 2. Total Condensable Gas = F(Angle, Range); Be Loaded Motor; Excludes Hydrogen. (Courtesy Aerojet ElectroSystems/ Martin Marietta)

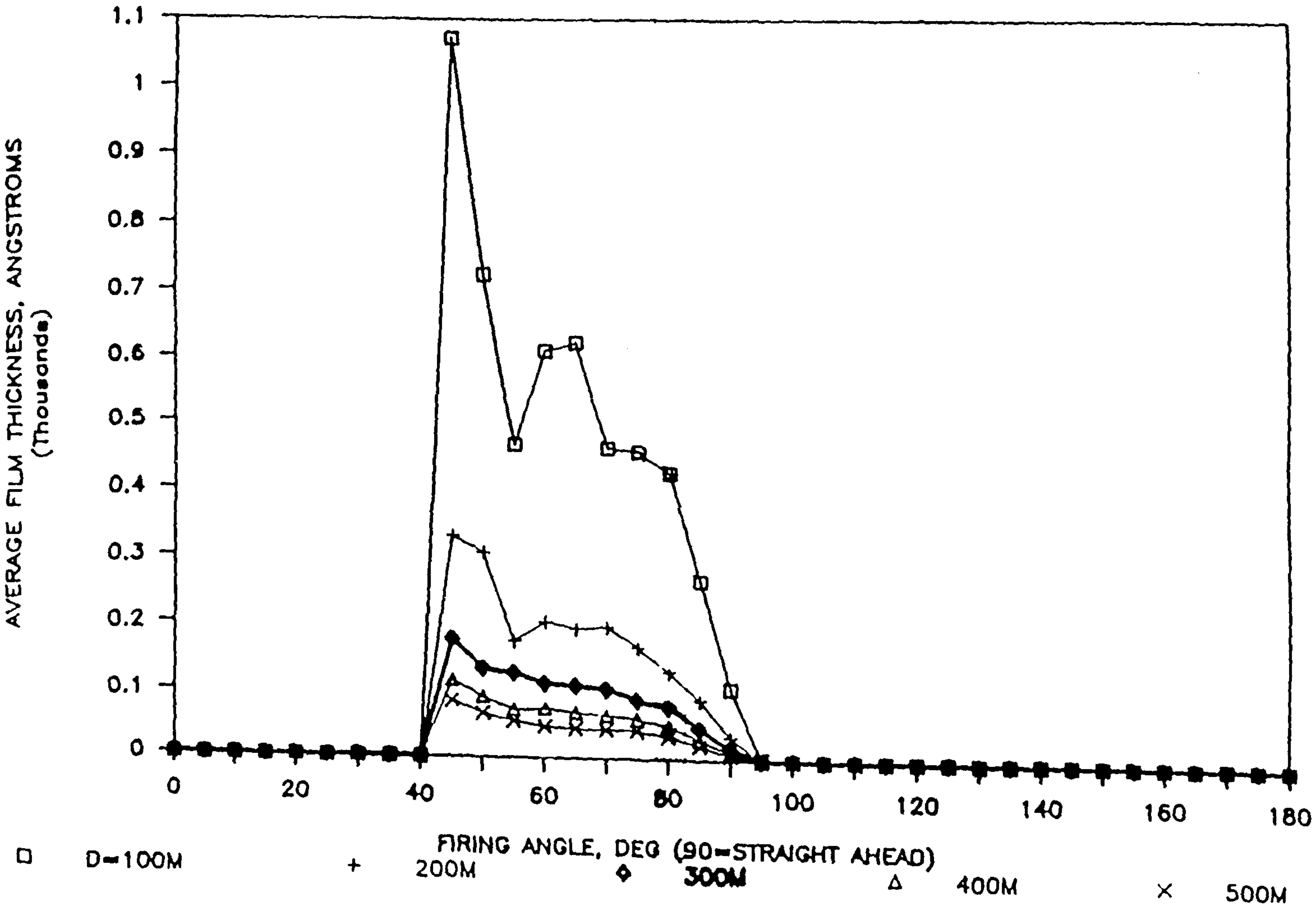


Figure 3. Condensation Limited by Baffles; 5 deg Baffle Angle.
(Courtesy Aerojet ElectroSystems/Martin Marietta)

predicted pitting fraction for the baffled sensor is shown in Fig. 4 as a function of firing angle and range. The major effect, however, as predicted by Aerojet under subcontract to Martin Marietta, is the buildup of particulates on the mirror. Figure 5 shows the expected thickness to be several thousand angstroms, and Fig. 6 shows the relative contributions between particulates and gas.

The effect of this flux on sensor performance is primarily the degradation in bidirectional reflectance distribution function (BRDF). Figure 7 shows the expected BRDF as a function of film thickness for a particular distribution of particle sizes, at wavelengths of 3.3 microns, 10 microns, and 30 microns. Note that the curves flatten, as expected. The effect of pitting on the primary mirror, which manifests itself, aside from BRDF degradation, as an increase in mirror emissivity, is shown in Figs. 8 and 9 for a 2.7 micron sensor (S-band), a 4.3 micron sensor (M-band), and an 8-12 micron sensor (L-band). Figures 8 and 9 show the reductions in signal-to-noise ratio (SNR) if the primary mirror is kept at 50 K and 70 K, respectively.

In liquid-fueled systems the effects from particulates will be less severe. However, much higher mole fractions of condensable species are expected, and similar problems can arise. Experiments at Aerojet have demonstrated that molecular fluxes on the order of 10^{-18} molecules/m^2-s will degrade mirror BRDF from 10^{-4} to about 10^{-3}. This is due to the formation of "islands" of condensed material on the cold mirror, rather than to a uniform thick film, and will, of course, be a strong function of mirror coating material. Fluxes of this magnitude are expected from estimates based on KKV deployment geometry and thruster mass flow. Pitting of mirror surfaces is also expected because of the formation of fuel crystals and liquid droplets; experiments at the Technical University of Hamburg-Harburg (TUHH) in West Germany have shown dramatic pitting and gouging effects from liquid-fueled engine nozzles. Experiments at the same place have also shown that cold optics will cause some condensables to form lacy "frost" patterns on the surface, degrading BRDF even further.

In both liquid- and solid-fueled engines, startup transients may lead to serious effects. A liquid engine at startup will generate large quantities of unburnt fuel for a few milliseconds, giving rise to greater droplet production rates. A solid ignition system yields similar effects: pyrotechnic igniters may lead to the presence of large particles, for example. Similarly, hypergolic liquids may lead to frozen droplets, and so on. Study of these effects, particularly in liquid systems, requires sophisticated modeling tools such as the CONTAM III computer code.

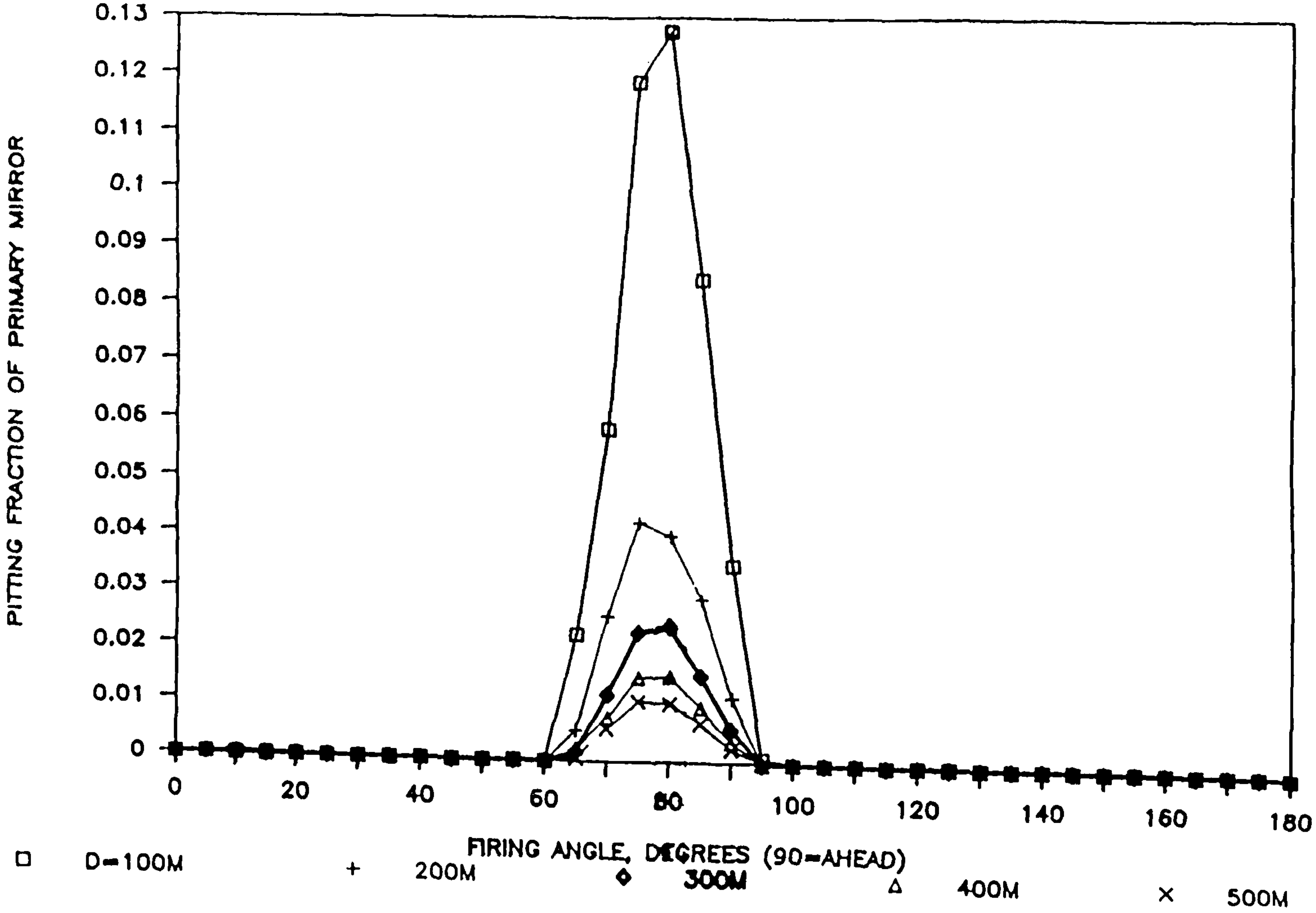


Figure 4. Mirror Pitting Limited to <2% at 400 m; Baffle L/D = 5. (Courtesy Aerojet ElectroSystems/Martin Marietta)

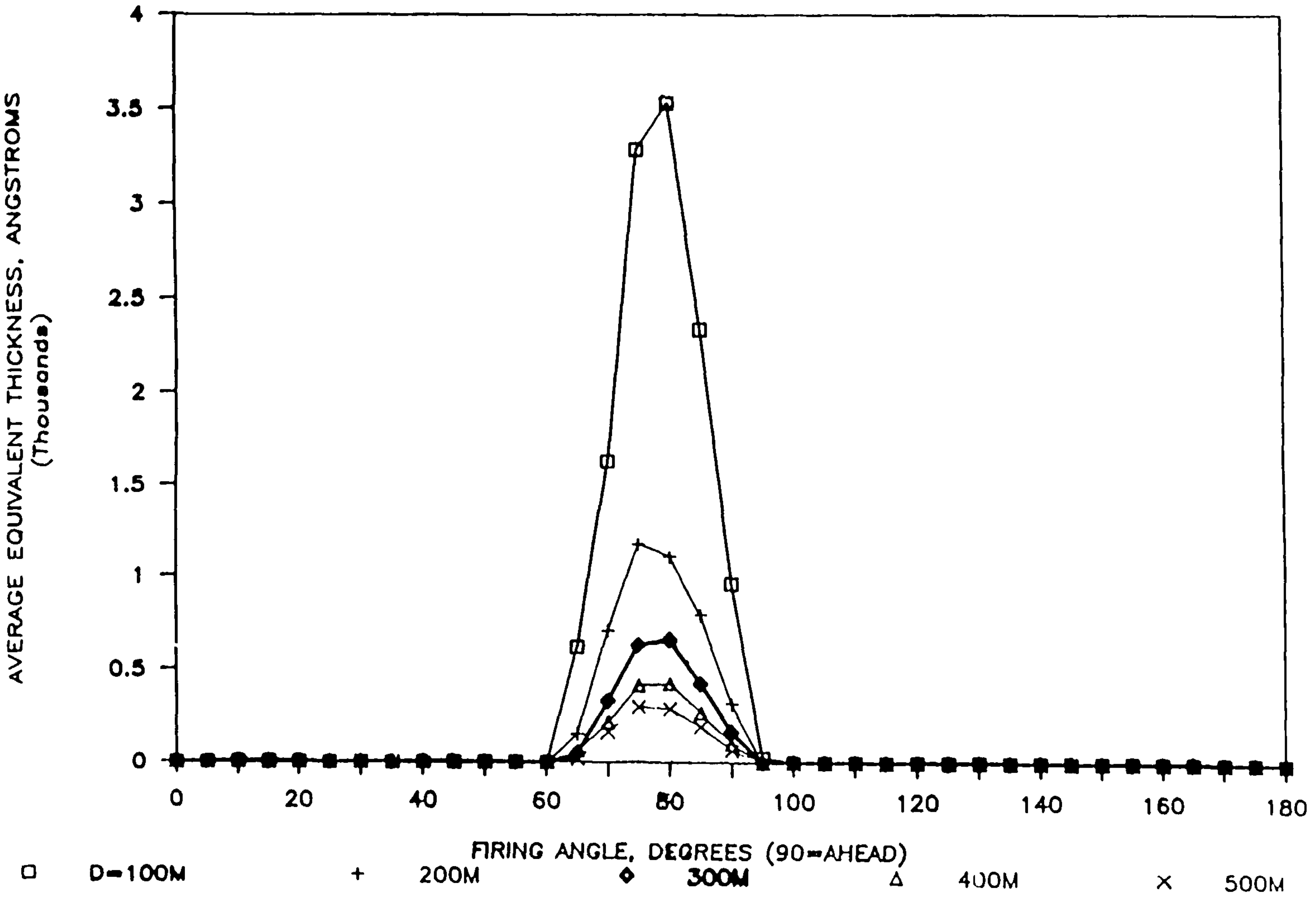


Figure 5. Particle Scattering is Major Effect; 2-11 Micron Mixed Particle Size Distribution. (Courtesy Aerojet ElectroSystems/Martin Marietta)

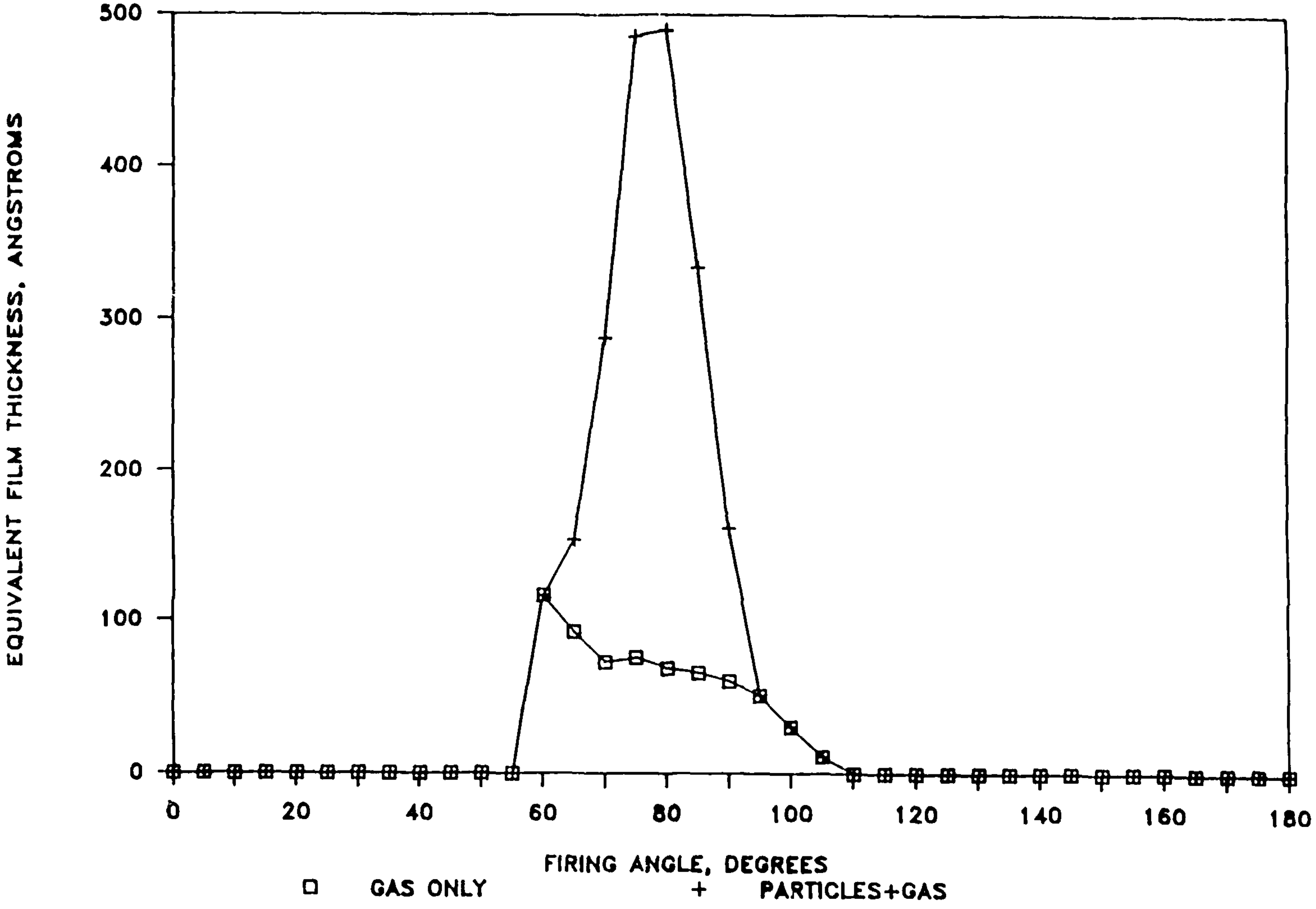


Figure 6. Particle Scattering Predominates Over Gas; 400 m Range; Mixed Plume Particles. (Courtesy Aerojet ElectroSystems/Martin Marietta)

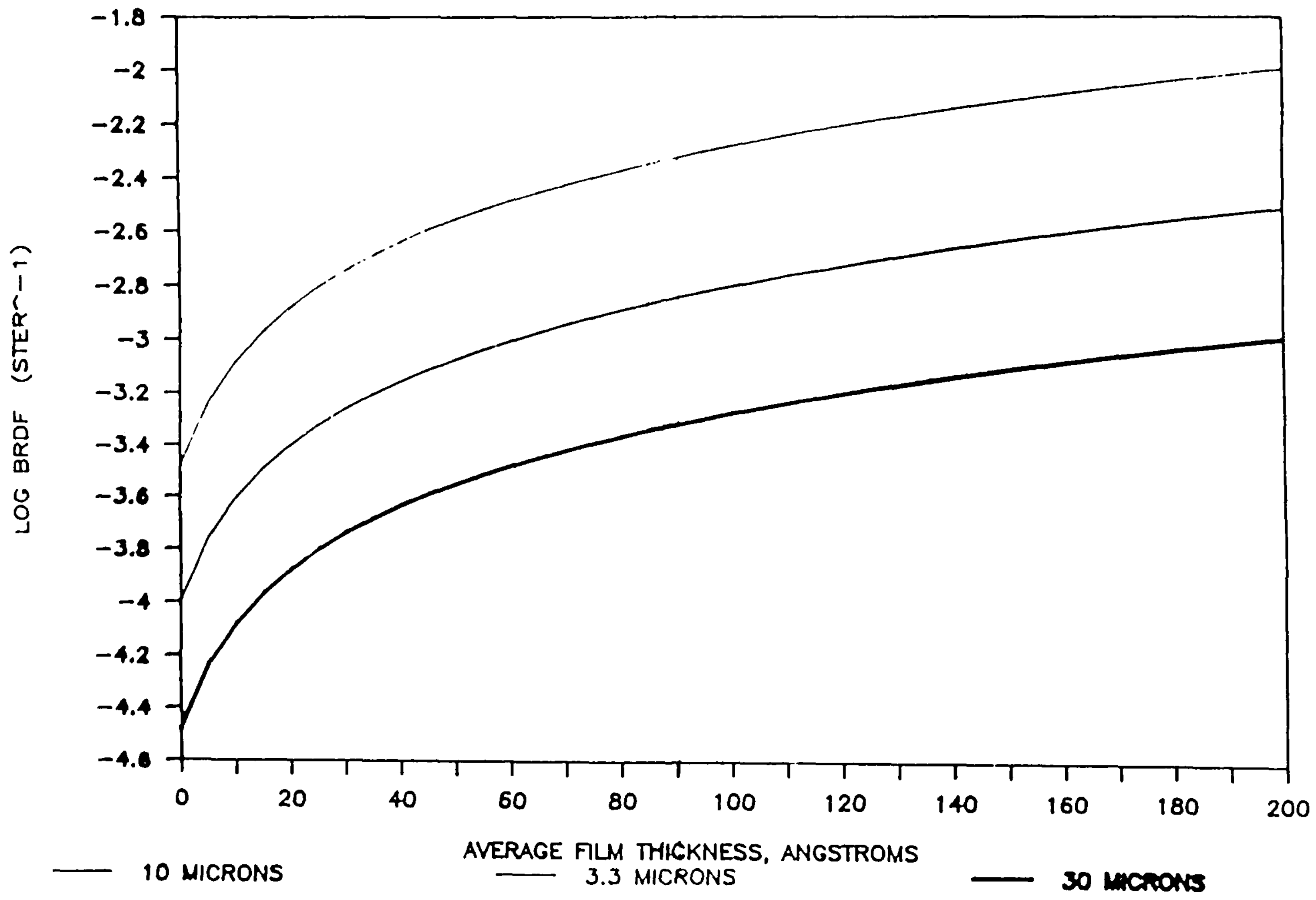


Figure 7. BRDF Varies with Wavelength; 2-11 Micron Mixed Particle Sizes. (Courtesy Aerojet ElectroSystems/Martin Marietta)

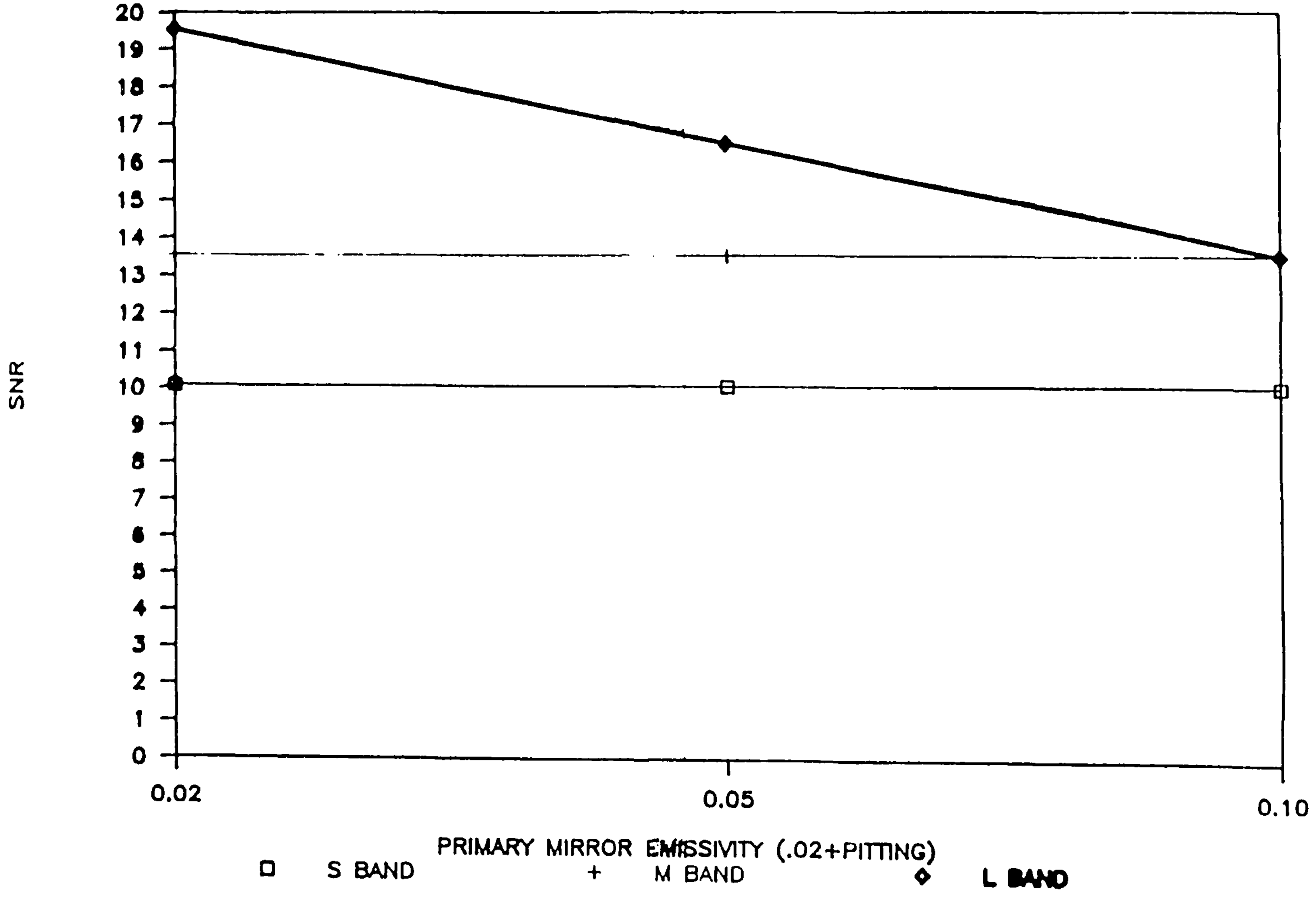


Figure 8. Pitting Degrades SNR in L-Band of CV Sensor; BRDF = 10^{-4}, Mirror at 50 K. (Courtesy Aerojet ElectroSystems/Martin Marietta)

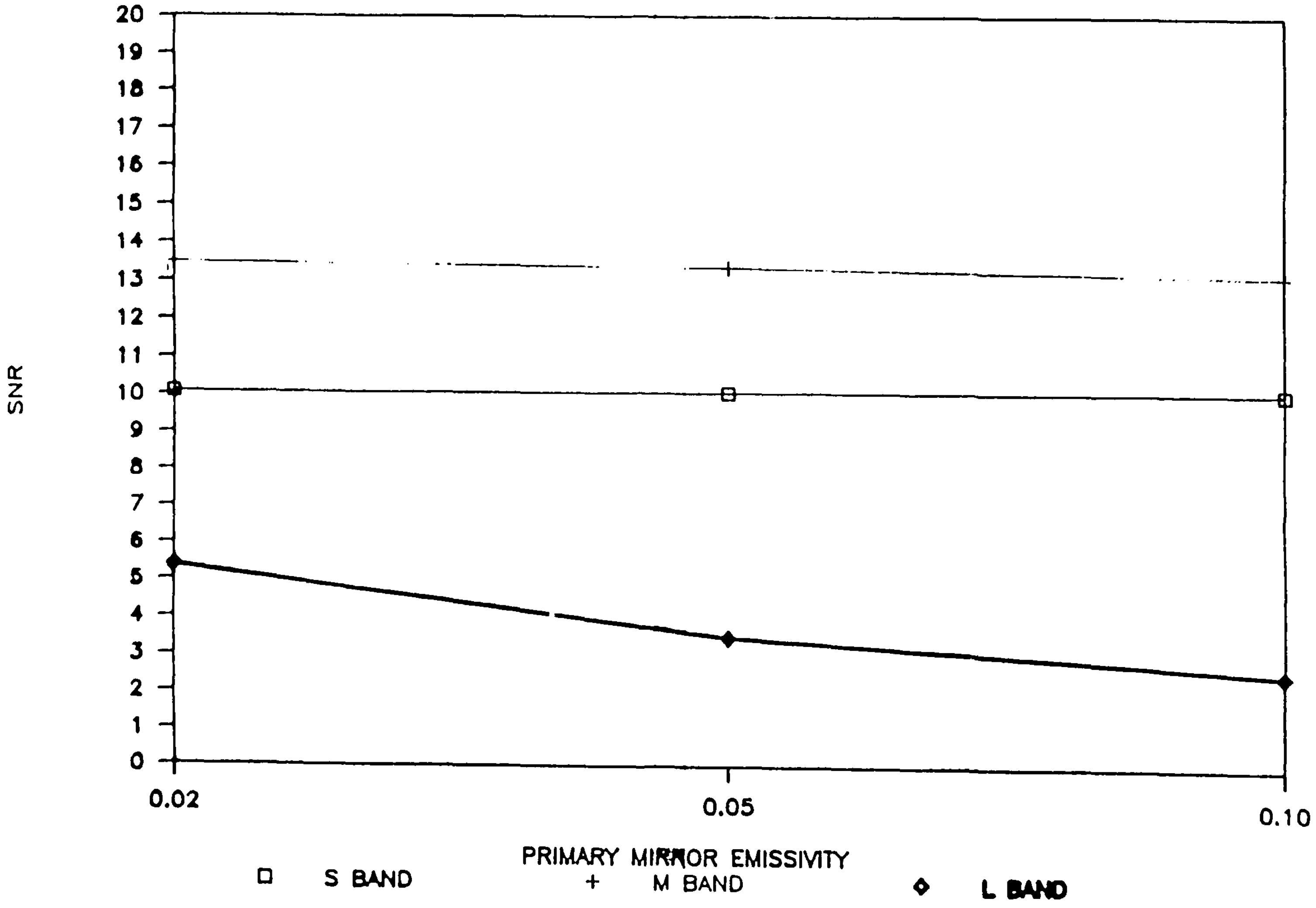


Figure 9. Cold Mirror Needed with Pitting; CV Sensor, 70 K Mirror Temperature. (Courtesy Aerojet ElectroSystems/Martin Marietta)

Thus, the effects of KKV contamination on collocated midcourse sensors are to reduce BRDF down to about 0.01/sr; to increase emissivity of primary mirrors, baffles, etc., and thus to reduce SNR; and to place objects (metal oxides, frozen fuel droplets) into the FOV of the sensor, leading to an increase in false alarm rates. Furthermore, the return flux from outgassing (and ACS emissions), which is a function of altitude and can be of the order of 1% of the total emitted gas in the ram direction at 250 km altitude,[1] will result in a contaminant cloud remaining about the platform for a significant period of time, particularly if "pumped" by sequential thruster firings.

No attempt has been made to determine the full system implications of mounting the midcourse sensors aboard the CVs. For example, the fraction of KKV flyouts that do not lead to the above effects in a significant way has not been determined. It may be possible to mitigate contamination by optimizing KKV flyouts, thus requiring much tighter envelopes than shown, for example, in Fig. 1. The possibility of mitigating contamination by cleaning the optics with lasers, or ion beams, has not been studied. The impact of covering the sensor (and of the generation of particulates by opening the cover), particularly in the context of birth-to-death surveillance and battle management, has not been studied. Without including such systems questions, it cannot be determined if the contamination issue is in fact workable or is rather a showstopper. Furthermore, a complete contamination analysis requires sophisticated tools such as the CONTAM III code (which addresses in great detail the generation in rocket motors of contaminants such as liquid droplets, the subsequent relevant thermal and flow processes, and the deposition of the contaminants throughout the region of interest) and SOCRATES (which treats the flow and collisional reactions of gaseous contaminants from the point of origin on the platform to various other locations on a large space structure). SOCRATES is being developed by Spectral Sciences, Inc., under contract to the Air Force Geophysics Laboratory (AFGL).

Recommendations are as follows:

- Collocation of midcourse sensors aboard the SBI CVs will require changes in the direction of the SBI program, which is rapidly approaching preliminary design status. Thus, the midcourse sensor problem needs to be factored into the SBI system concept now. Full contamination analyses using state-of-the-art tools such as CONTAM III need to be begun as soon as possible.

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[1] J. Scialdone et al., *J. Geophys. Res.* A53, 195 (1978).

- Additionally, experimental programs such as that at TUHH in West Germany need to be expanded, so that the impact of contamination on optical systems of interest can be evaluated.
- Mitigation techniques, such as flushing, cleaning, alternative fuels, baffles, and the optimization of flyout scenarios, need to be studied in detail.

B. SEEKER

A seeker, which is defined as a fly-along scout sensor, also has severe contamination problems. The problem here is similar to that addressed by SBI system contractors, who are involved in the design of a sensor suite aboard the KKV.

The impact of atmospheric species on the seeker optics and other surfaces can cause a phenomenon known as shuttle glow. This is addressed in the next section and is an altitude-dependent process, of course.

The process to be discussed here is the effect of plume self-interference with the sensors; it is assumed that seekers will be far enough apart from each other that mutual interference is not a problem.

Radiances from divert engines aboard the SBI KKVs (as noted above, a similar system) are expected to generate signals at the sensor in the LWIR (8-12 microns) as high as 10^{-6} W/cm^2-sr. This may be mitigated by canting the burners, using baffles, cooling the gas via high-expansion-ratio nozzles, and using plug nozzles or aerospike engines for the axial and divert thrusters in order to reduce plume expansion into the sensor line of sight. However, it should be noted that forward-looking sensors aboard the Delta 180 stage 2 saw strong emissions in the UV when the (aft) thrusters fired, indicating that the plume wrapped around 180 deg; the LWIR Maverick seeker would not have seen this effect, as it is an AC-coupled device.

It thus appears that the contamination issues for a seeker are not nearly as serious as for the CV sensors. However, contamination must be taken into account early in the system design in order to implement effective interference-reduction techniques.

III. SHUTTLE GLOW

At low altitudes a glow in the visible has been noted on the ram-directed surfaces of the space shuttle and other satellites.[2] Spectra obtained in the visible indicate a near continuum, with a peak[3] at 670 nm. Estimated radiances on the shuttle are about 10^{-9} W/sr-cm^2. In the visible region of the spectrum the glow has an e-folding distance of about 20 cm.[4] The emissions seem to depend on the surface material properties, although temperature may be the driver.[5,6] Shuttle thruster firings enhance the glow; the decay time is altitude dependent and several seconds in duration. Glow has also been observed on satellites.[7] At altitudes above about 180 km the intensity of the emissions seems to scale with [O], while at lower altitudes the emitted intensity scales[8] with the product of any two of [NO], [N_2], [O_2]. Several proposed mechanisms for the glow are reviewed in Ref. 2. The best theory at present is that the glow is due to surface recombination of NO and O to form NO_2.

As noted above, observations of the glow effect have been limited to the UV and visible parts of the spectrum. If current ideas about the cause of the glow are correct (i.e., surface-catalyzed recombination of O and NO), one would expect a large extended region of emission in the IR,[9] since the electronic radiative lifetimes, which are responsible for the visible and UV emissions, are of the order of 10^{-7} s, while vibrational lifetimes, which are responsible for IR emissions, are of the order of about 10^{-3} s. NO_2 radiates very strongly at 6.2 microns [band strength = 230 × 10^{-8} cm^2/s; this is 10 times greater than the band

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[2] E. Murad, "Glow of Spacecraft in Low Earth Orbit," in T. Chang, J. Belcher, J.R. Jasperese, and G.B. Grew, eds., *Physics of Space Plasmas*, Vol. 6, Scientific Publishers, Cambridge, MA.

[3] G.R. Swenson et al., *Geophys. Res. Lett.* **12**, 97 (1985).

[4] J.H. Yee and A. Dalgarno, *J. Spacecraft Rockets* **6**, 635 (1986).

[5] S.B. Mende et al., *J. Spacecraft Rockets* **23**, 189 (1986).

[6] G.R. Swenson et al., *Nature* **323**, 519 (1986).

[7] M.R. Torr et al., *Planet. Space Sci.* **25**, 173 (1977).

[8] J.H. Yee et al., *Geophys. Res. Lett.* **12**, 651 (1985).

[9] I.L. Kofsky and J.L. Barret, *J. Spacecraft Rockets* **24**, 133 (1987).

strength of the $H_2O(v_3)$ emissions] and has a lifetime of 7 ms, so the emissions may occur over a fairly extended region, and not just on the ram-directed surfaces as seen for the electronic transitions. Other chemiluminescent processes may also take place that give rise to optical emissions when surfaces are in the ram direction.[10] The intensities of ram-surface glow in different regions of the spectrum are shown schematically in Fig. 10; the column lengths are not drawn to scale. The IR component of the glow would be much less intense than that in the visible but would extend over a much larger region.

Shuttle glow may become very significant for concepts requiring a "fly-along" scout vehicle to track targets at close range. At altitudes below about 300 km, and particularly at high velocities (e.g., in excess of 7 km/s), the performance of forward-looking sensor systems would almost certainly be degraded, and even apertures pointed away from the ram direction may see radiation convected into the field of view. Sensor platforms at 500 km altitude would suffer from a diminished problem; the number density of O atoms changes by about 1.5 orders of magnitude between 300 km and 500 km, and thus the emissions ought to change correspondingly, given the correctness of the assumed mechanism. Furthermore, orbital velocities are correspondingly lower (although translational temperatures are higher). However, if careful attention is not paid to the selection of materials for the exterior surfaces of the platform, emitting species may be produced very efficiently.

Fortunately, it will soon be possible to produce beams of energetic O atoms in ground laboratories. Thus, spacecraft (and optical) materials may be tested for collision-induced emissions without requiring the use of space platforms to any great degree.

Recommendations are as follows:

- Measure the intensity and (at high spectral resolution) the spectral distribution of the glow over controlled surfaces as a function of altitude.
- Conduct laboratory experiments to determine the effect of long-term exposure of surfaces to fast atomic oxygen.

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[10] B.D. Green et al., *Planet. Space Sci.* 34, 879 (1986).

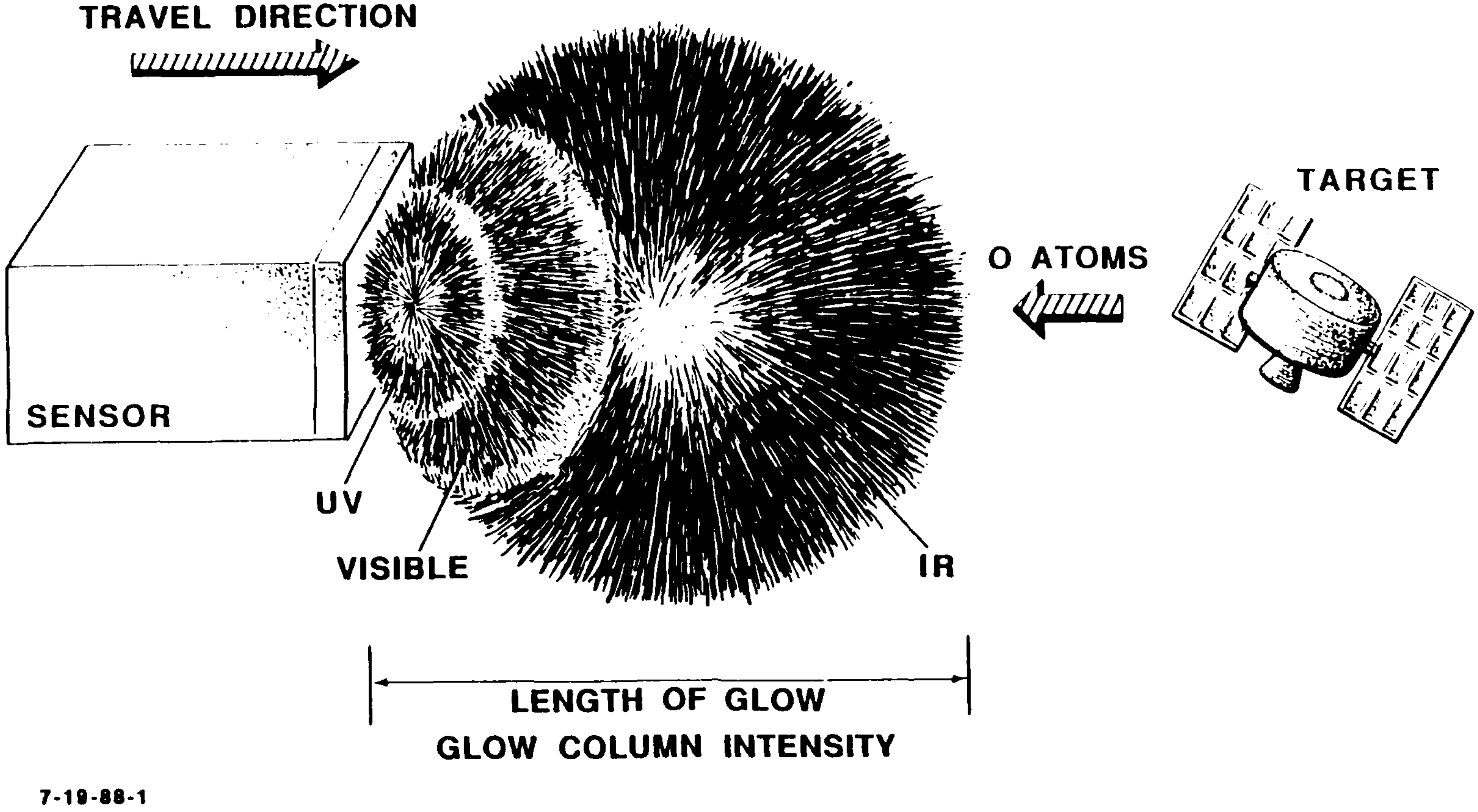

Figure 10. Ram-Surface Glow Intensities in Different Spectral Regions. Column Lengths Not to Scale.

IV. LONG-TERM EFFECTS

Long-term degradation of spaceborne sensor systems has several origins. Ambient atomic oxygen may recombine on cooled optical surfaces to form O_2. Degradation of optical systems due to long-term exposure to UV radiation is known to occur; the presence of sunlight is known to enhance the binding of molecules to exposed spacecraft surfaces, through either induced chemisorption or polymerization.[11] Outgassing may occur for very long periods of time as volatiles diffuse to the surface. Furthermore, the radiative environment may cause spacecraft materials to break down chemically, leading to lower molecular weight molecules, and thus contributing to the continual outgassing. Material degradation by radiation may also lead to the production of particulates, either directly by corrosion or indirectly from lowered resistance to other forms of attack (e.g., atomic oxygen, micrometeorites). The presence of charged particles may increase deposition rates because of charge transfer mechanisms. Moreover, reactions with O atoms can, over a long period of time, alter the electrical characteristics of surfaces. For example, a study conducted on STS-4 showed that films of Ag and Al gained mass due to the formation of AgO and Al_2O_3 on the surfaces;[12] this metamorphosis changed a surface from a conductor to an insulator.

The atomic oxygen flux at 1000 km altitude is about $< 10^{-13}$ atoms/m^2-s; this corresponds to about a monolayer every 4 hours, provided every atom sticks to a surface. However, since the atoms are very fast, the probability of sticking to a cryogenic surface will be small, and in any case it is almost certain that no optical element will be ram-exposed. Over a 5 year span, however, it is possible that significant degradation of BRDF can occur if cold surfaces are exposed to the incoming atmosphere. Aside from cryodeposition, however, a flux of such energetic O atoms can corrode exposed surfaces,

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[11] D.F. Hall, "Flight Experiment to Measure Contamination Enhancement by Spacecraft Charging," *SPIE Proceedings*, Vol. 216 (1980).

[12] J.C. Gregory, "Interaction of Hyperthermal Atoms on Surfaces in Orbit: the University of Alabama Experiment," *Proceedings of the NASA Workshop on Atomic Oxygen Effects*, Jet Propulsion Laboratory, JPL Publ. 87-14, p. 29 (1987).

creating, for example, a continuous source of dust. At higher altitudes the effect is less severe; results from the Spacecraft Charging at High Altitudes (SCATHA) satellite indicate that films of Ag and Al did not change their optical properties appreciably after 1000 days in geosynchronous orbit.[13] As an aside, it should be noted that on the same experiment the contamination of optical surfaces due to the backflow from hydrazine thrusters was found to be negligible.[14]

Additional sources of particulates are the condensation products from cold-gas attitude control thrusters and from micrometeorites and other space debris. The first source can be significantly mitigated by an appropriate choice for the propellant.[15] Estimates of the micrometeorite flux at the earth run as high as 2×10^{-13} kg/m^2-s. The flux as a function of size distribution has been reported;[16] the flux of 1 micron particles is on the order of 10^{-3} particles/m^2-s. Larger particles occur with exponentially lower fluxes. Thus, over an extended period of time significant deposition on a platform can occur.

Dust particles can be created and stirred up by thermal stresses (i.e., terminator crossings), mechanical perturbations (e.g., by opening a cover), micrometeorite impact, and atmospheric flux. This is a critical problem for a midcourse surveillance system, since the presence of micron-sized particulates in the sensor field of view represents a source of possibly significant signal degradation that is difficult to prevent. This problem does not seem to be amenable to any simple solution.

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[13] D.F. Hall, "Current Flight Results from the P78-1 (SCATHA) Spacecraft Contamination and Coatings Degradation Experiment," *Proceedings of the International Symposium on Spacecraft Materials in the Space Environment*, ESA-SP-178, p. 143 (1982).

[14] D.J. Carre and D.F. Hall, "Contamination Measurements During the Operation of Hydrazine Thrusters on the P78-2 (SCATHA) Satellite," *Proceedings of the AIAA 20th Aerospace Sciences Meeting*, American Institute of Aeronautics and Astronautics, AIAA-82-0079 (1982).

[15] C.E. Kolb et al., *J. Spacecraft* **20**, 383 (1984).

[16] J.C Bremer, "General Contamination Criteria for Optical Surfaces," *SPIE Proceedings*, Vol. 287, p. 10 (1981).

V. SURFACE INTERACTIONS

A. CHEMICAL REACTIONS

Collisions by fast O atoms with, for example, carbonaceous materials such as polymers might lead to radiation in the CO band; studies conducted on STS-8 indicate that some paints, such as Chemglaze $Z30_2$ (used for optical studies), are extremely reactive.[17] Experiments carried out on STS-4, which had an orbit of 310 km, showed that films of $C_{(graphite)}$ and Os were quickly removed.[18] Although the products of this removal were not determined, it is reasonable to assume that the graphite reacted with O to form CO_2 and CO, and that the osmium reacted with O to form gaseous OsO. In a later experiment[19] it was observed that at 225 km altitude Al and Ni gained mass (presumably from the formation of the condensed oxides Al_2O_3 and NiO), while W and Nb lost mass (presumably from the formation of gaseous oxides). Because of the high kinetic energy of the incoming O atoms, it is likely that the gaseous products of these interactions (e.g., CO, CO_2, OsO, WO) will be vibrationally excited, leading to emissions in the fundamentals and overtones (e.g., 4.6 μm for CO, 4.3 μm for CO_2, and 10^{-12} μm for OsO and WO). Furthermore, as was noted earlier, chemical degradation of a surface may lead to enhanced production of particulates caused, for example, by a lowered resistance to ablation when mechanically or thermally stressed.

B. DEBRIS AND MICROMETEORITES

The effect of debris and micrometeorites will be the damage caused to surfaces by impact. Aside from the primary deposition of material from these sources, the high kinetic energy of impact is likely to cause the formation of secondary particulates and may also

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[17] A.F. Whittaker et al., "Orbital Atomic Oxygen Effects on Thermal Control and Optical Materials--STS-8 Results," *Proceedings of the AIAA 23d Aerospace Sciences Meeting*, American Institute of Aeronautics and Astronautics, AIAA-85-0416 (1985).

[18] P.N. Peters et al., *Geophys. Res. Lett.* 10, 569 (1983).

[19] P.N. Peters et al., *Appl. Optics* 25, 1290 (1986).

render surfaces less resistant to attack from other sources. The effect will be altitude dependent, since space debris predominates between about 600 km and 1100 km in altitude, and micrometeorites predominate at higher altitudes. Because of the lack of experimental data, the effects cannot be quantified.

C. PHOTODEGRADATION

Alteration of surface properties by the solar UV flux may lead to effects similar in consequence to chemical degradation: changes in surface mechanical, thermal, and electrical properties. The paucity of experimental data makes it difficult to quantify the effects. However, many questions should be answered when the Long-Duration Exposure Facility (LDEF) satellite is retrieved from space in 1989.