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CONTAMINATION OF OPTICAL SURFACES

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Introduction

Self-contamination has long been recognized as potentially limiting the performance and ultimately the useful life of spacecraft. Demands for increasing system lifetimes have increased the need for understanding and control of contamination. The proposed NASA Space Station, with its requirement for 30 years performance, has potentially the most challenging contamination requirements ever to be considered.

If the Space Station is to provide a clean and durable environment for research in space science, Earth observation, and space exploration, then contamination control must be considered continuously, from the very outset in defining and refining the Space Station configuration. This workshop, and the efforts of other workshops and working groups, stand in recognition of this fact. Furthermore, the very performance life of major elements of the Space Station itself will be limited if contamination control is not effectively implemented.

This paper addresses the effect of molecular contamination on Space Station optical surfaces. One can imagine all sorts of optical surfaces which might populate the Space Station at some time in its life. The examination in this paper will be primarily directed at two sorts: solar voltaic power sources and optical solar reflectors for thermal control or solar dynamic power generation. The effect of contaminants on optical surfaces has been the subject of multiple theoretical, laboratory, and space flight investigations. An exhaustive review of these various investigations is clearly beyond the scope of this short paper. Rather, an examination of the published Space Station requirements for molecular contamination accretion and for the monitoring of such accretion will be discussed, in the context of the historical performance of space systems.

The ML12 experiment which is flying on the USAF Space Test Program's P78-2 vehicle, more commonly known by the acronym SCATHA (Spacecraft Charging at High Altitudes), provides a benchmark against which satellite contamination performance can be judged. This experiment has provided some 7 years worth of data on contamination accretion and thermal control coatings performance in the geosynchronous environment. A bibliography of papers, presentations, and reports describing this data base appears at the end of this paper.

Contamination Accretion

The requirement for molecular contamination by and on the Space Station (Aaron, 1986) is:

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> The flux of molecules emanating form the core Space Station must be limited such that... The mass deposition rate on two 300 K surfaces both located at the PMP with one perpendicular to the +Z axis and the other whose surface lies ... at critical power locations with an acceptance angle of 2 π sr shall be no more than **1×10^{-14} g cm^{-2}s^{-1}** (daily average).

Comparison of this requirement to the performance of actual satellite systems reveals that it is an ambitious requirement, indeed. Table 1 shows such a comparison.

Table 1. Comparison of Spacecraft Contamination Accretion to the Space Station Requirement.*

	dM/dt ($g\ cm^{-2}\ s^{-1}$)	dx/dt⁺ (Å yr^{-1})	dα/dt (Å yr^{-1})	Solar Array Loss# (% yr^{-1})
Space Station budget	1×10^{-14}	30	0.0003	0.015
SCATHA belly band TQCM	6×10^{-14}	190	0.002	0.1
Typical OSR radiator	6×10^{-13}	1900	0.02	1
Sunlit, vent-viewing OSR	1.2×10^{-12}	3800	0.04	2
Mature, large satellite	2×10^{-13}	600	0.007	0.35

*dα/dx = 0.001/100 Å assumed, measured/specified property underlined

⁺Assuming a density of 1 g cm^{-3}

#100(dα/dt)/2

This comparison shows contaminant mass accretion rates for the Space Station requirement (Aaron, 1986) and the deposition rate on a quartz crystal microbalance on the SCATHA ML12 experiment (Hall, 1982) along with fused silica mirror degradation rates for SCATHA, typical geosynchronous satellite silica mirror radiator performance (D. Gluck, private communication, 1982), degradation of a warm, vent-viewing, sunlit radiator in elliptic Earth orbit (Hall et al., 1985), and the performance of the cold radiator on a large, mature (late edition) geosynchronous satellite (Hall et al., 1985; D. Gluck, private communication, 1982).

For the purposes of this comparison, the solar absorptance increase has been related to the mass accreted by the simple, linear approximation of

$$d\alpha/dx = 0.001/100 \text{ Å} \tag{1}$$

which results from the SCATHA experiment (Hall, 1982) The measured, or specified quantity shown in Table 1 is underlined. (There is some room for debate on the exact value of the proportionality constant in equation (1), but this debate does not affect the qualitative conclusions on draws from Table 1.) Spacecraft radiator degradation can be simply related to the increase in solar absorptance (Kan, 1985), as can be the decline in solar dynamic power production. The decay of solar voltaic power generation is approximately one half the increase in solar absorptance (of a solar reflector) (D. Marvin, private communication, 1987).

Note that the quartz crystal microbalance on SCATHA had a very small portion of its field-of-view filled with potential outgassing sources. Note further that the solar absorptance data shown in Table 1 are for fused silica mirror radiators, which are not subject to degradation in solar absorptance as a result of natural geosynchronous radiation damage (Kan, 1985).

The lessons to be gleaned from the information summarized in Table 1 are:

(1) The Space Station specification requires a vehicle environment which is substantially cleaner than experienced by the nearly clear field-of-view SCATHA contamination monitor.

(2) The typical performance of geosynchronous spacecraft radiators of fused silica is dramatically worse than required by Space Station.

(3) Sunlit silica surfaces which are warm in comparison to the typical radiator but which have a direct view of major spacecraft vents accrete even more deleterious contamination by photochemical deposition.

(4) Mature satellite programs can effect substantial reduction in contamination (by a combination of materials control and re-direction or sealing of spacecraft vents).

A reminder that contamination is a space system problem is provided by the experience of the Space Shuttle (McKeown et al., 1985; Miller, 1983). Table 2 shows the rate of contamination of 273 K surfaces (of various orientation) on the Induced Environment Contamination Monitor on four flights of the Shuttle. The accretion rates on the the early flights define a contamination level inherent to a relatively empty Shuttle bay. The STS-9 Spacelab flight shows that loading the bay with a variety of experimental hardware can seriously degrade the environment.

Table 2. Space Shuttle Induced Environment Contamination Monitor Contamination Rates for a 273 K Surface.

Mission	Contamination Rate[*] ($\mathrm{\AA}\ hr^{-1}$)				
	-X	+X	-Y	+Y	-Z
STS-2[+]	0.9	3.5	-.2	1.5	
STS-3[+]	3.8	6.0	1.9	2.2	2.8
STS-4[+]	0.9	1.2	0.9	0.6	0.4
STS-9[#]	0.7	16.4	6.7	3.1	0.5

[*] For various sensor orientations (vehicle fixed coordinates)
[+] (Miller, 1983)
[#] (McKeown et al., 1985)

Contamination Monitoring

The Space Station requirements document (Aaron, 1986) states that

> ...monitoring of the environment to a limited extent will be required. Verification and monitoring measurement requirements shall consider ... molecular and particulate deposition ... and returned gas flux.

It is conventional to use 10 MHz quartz crystal microbalances (QCM) for monitoring molecular contamination rates. These devices have a sensitivity of about 4.4 ng cm^{-2} Hz^{-1}. The Space Station mass accretion rate requirement therefore corresponds to about 70 Hz/year decrease in QCM frequency. One usually measures the beat frequency between two quartz crystals, one exposed to the contaminant flux and one shielded, to enhance the sensitivity of the QCM. Even so, one must anticipate QCM frequency/temperature coefficients on the order of ±5 Hz/K. Although the nature of long-term fluctuations in QCM frequency is not well understood, one can expect slow drift on the order of ±1 Hz/week in QCM beat frequency (D. F. Hall, private communication, 1987). Therefore, even monitoring the required contamination level on Space Station will be difficult if straightforward conventional approaches are used.

Conclusions

The Space Station contamination requirements are so stringent that they cannot be approached without considering contamination at every step in the design of the Station. Numerical contamination models of proposed geometries should be assembled early and exercised often, as the basis for estimating the contamination risk presented by a given geometry or operation. Such models have been described by Fong et al. (1987) and elsewhere in this volume.

Furthermore, a contamination model of the final configuration can serve as a guide for locating contamination monitoring devices near major sources of contamination, and interpreting the impact on sensitive surfaces. In this way, one can hope to provide a monitoring system which provides early warning of problems.

Because the Space Station requirements are so stringent, the generosity in margin and systematic error in contamination predictions that have been used in the past may no longer be acceptable. This means that modeling must incorporate more physically realistic information. In addition to the obvious requirements for more accurate and detailed data on outgassing and thermal/vacuum aging of materials, models must include (substrate temperature dependent) photochemical deposition and a better accounting of non-line-of sight (NLOS) contaminant transport.

The mass accretion on the SCATHA QCM is a case in point. First, is the preponderance of the detected mass accreted by photochemical deposition. Second, one is unable to account for the mass deposition rate measured, by many orders of magnitude, if one uses simple models of NLOS transport by contaminant self-scatter described by Scialdone (1983).

More elegant contamination modeling tools have been developed, the code SPACE II being one well-known example (Bareiss et al., 1987). This sort of code is a powerful tool, indeed. However, one must recognize that at the current state-of-the-art even these powerful tools have their limitation. For example, SPACE II accounts for a significant source of NLOS transport in low Earth orbit with which the Space Station must contend: atmospheric return flux. The validity of SPACE II predictions of return flux were tested on the Atmosphere Explorer (AE) satellite (Bareiss et al., 1987). The test was to measure the return of vented neon by mass spectrometry. The SPACE II prediction overestimated the return flux by 50%. Note that rare gas scattering by the atmosphere around a small vehicle like AE is probably the least stringent test of the scattering dynamics approximations conventionally used in contamination codes. Herm et al. (1987) and Harvey and Herm (1981) have demonstrated the risk in using simple hard-sphere scattering models for spacecraft design, even for helium-ambient collisions.

The comments in the previous paragraph are not intended to be specific criticisms of SPACE II, but rather to point out that the current state of contamination modeling admits to uncertainties which may loom large when one tries to meet the Space Station design requirement. Improvement in modeling, and verification of models with more realistic tests (for example with hydrocarbon rather than rare gas vents, with long-term instrumented vehicle tests, and with laboratory measurement of reactive, elastic, and inelastic scattering cross sections), would facilitate the assignment of margins in contamination budgeting.

Furthermore, an improvement in the state of understanding of contaminant effects would help in the design of the Space Station. The uncertainty in the thickness dependence of contaminant solar absorptance was mentioned above is a case in point. This uncertainty currently stands at about an order of magnitude (Hall, 1982). Therein lies an order of magnitude in contamination budget margin. This subject, too, admits to further laboratory and space flight research.

Summary

The Space Station requirements for performance life and cleanliness are among the most stringent ever considered for a space vehicle. The historical experience of space systems suggests that the contaminant mass accretion rate required for the Space Station will be extremely difficult to realize. Therefore, these requirements mandate the quantitative consideration of molecular contamination at every stage of Space Station design.

There is an active national effort of space flight and laboratory research in the various aspects of spacecraft self-contamination. It is clear that the Space Station can benifit from these efforts. However, the specific requirements of orbit, size, and lifetime of the Space Station may warrant an advance in the quantitative understanding of non-line-of-sight contaminant transport, of contamination effects, and in verification of modeling techniques.

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