Space Shuttle Contamination Measurements from Flights STS-1 Through STS-4

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Successful completion of many scientific/technical measurements and safe Orbiter/payload operations during Space Shuttle flights requires limitations on the Orbiter-induced molecular and particulate environment. Four orbital flight tests have provided the opportunity to verify the results of efforts to keep the Orbiter contamination levels within defined goals. Contamination measurements were performed using various instruments on the induced environment contamination monitor. Results of these measurements indicate that, with the exception of special circumstances related to the Space Shuttle development, molecular contamination density and deposition as well as particulate contamination generally are within the requirements and are close to predicted levels.

Introduction

THE initial four flights of the Space Shuttle Orbiter, which provided for an extensive evaluation of system performance and a verification of many requirements, have come to a conclusion with the fourth flight of the Space Transportation System (STS). A preliminary contamination assessment for missions STS-1 and STS-2 has been published previously.[1] This report extends that assessment to include STS-3 and STS-4 preliminary results. Emphasis is placed on correlating measured data with specific goals outlined in terms of requirements in several documents. The requirements basically originated from the early Particles and Gases Contamination Panel (PGCP) and were included in the Space Shuttle Flight and Ground System Specifications, Volume X.[2] More detailed requirements were later formulated by the Contamination Requirements Definition Group (CRDG).[3] A summary of requirements is provided in Table 1.

Establishment of these requirements led to the development of two different tools for use in performance assessment. One tool, the Shuttle/Payload Contamination Evaluation (SPACE) program, predicts contamination levels depending on individual circumstances. The other, referred to as the Induced Environment Contamination Monitor (IECM), is a complement of ten instruments for contamination flight measurements. Both tools were used extensively in the contamination assessment process.

Mission Description

The major mission events that significantly influence induced contamination levels as well as the contamination measurements are briefly summarized in this section. Specific events occurring normally at one time or another in all missions are cabin leakage, outgassing (of heavy molecules), desorption (of lighter molecules), water dumps, Flash Evaporator System (FES) operation, and Reaction Control System (RCS) engine firings. In addition, specific particle or gas releases have occurred on occasion as a result of either planned specific mission objectives or because of peculiar unplanned circumstances related to the development of the STS. Such planned events included the controlled release of isotopically labeled gases to measure scattering cross sections and unusually long duration engine firings to support engine tests and measurements such as the aft left up firing engine (L2U) test on STS-3. During this test, however, two other upfiring engines (forward and aft right) were activated within a time-frame of 100 s. Events not planned were water release due to abnormally high moisture content of thermal protection tiles (STS-2 and STS-4) and particle releases as the result of the intense activity during the turnaround between flights. Events and data associated with particular flights are summarized in Table 2.

The fact that most of the STS-2 flight time was spent in Z Local Vertical (ZLV) attitude was especially beneficial for an initial contamination assessment. This condition made data analysis relatively easy compared to the subsequent missions since one critical parameter, the angle between the velocity vector and the Orbiter $+Z$ axis (see Fig. 1) into which most IECM instruments point (sometimes called angle of attack) is constant (90°) in this case. The STS-3 and STS-4 missions provided for significant surface temperature changes, resulting in varying outgassing and desorption rates. The STS-4 mission finally permitted direct contamination flux measurements from Orbiter sources, also referred to as the contamination survey, with the IECM carried on the Remote Manipulator System (RMS).

IECM Description and Performance

The IECM measured particles and gases during prelaunch, ascent, on orbit, descent and postlanding mission phases during flights STS-2 through STS-4. It was mounted in the payload bay on top of the Development Flight Instrumentation (DFI) system by means of a Release/Engage

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Mechanism (REM) at the approximate location $X_0 = 1179$. The REM allowed unberthing and reberthing of the IECM when grapped by the RMS to perform the mapping of the Shuttle effluents.

The IECM and the REM were developed, tested, and operated by the NASA Marshall Space Flight Center (MSFC). The IECM (Fig. 2) weighs 355 kg with dimensions of $121.3 \times 82.2 \times 79.1$ cm. It contains ten instruments, a set of batteries, a programmable data acquisition and control system (DACS), and a magnetic tape recorded to store the data for later retrieval. Real-time data transmission was not available. However, IECM power consumption was monitored at times, permitting limited checks on instrument operation. The individual instruments, some of their characteristics, and their operating time are listed in Table 3. A detailed description of the IECM, systems and instruments is provided in Ref. 4.

The following few instrument characteristics are restated here only for quick reference. The cascade impactor periodically measures particle concentrations within three particle size ranges using a small air pump (250 ml/min volumetric flow rate) in conjunction with a system of four Quartz Crystal Microbalance (QCM) pair stages. Each sensor is covered with Apiezon grease to capture particles. The Optical Effect Module (OEM) peridically measures scattered/transmitted light from five optical samples mounted on a rotating carousel.

The temperature-controlled QCM's (TQCM's) located as shown in Fig. 2 measure temporal deposition rates and were operated on orbit in cycles of certain temperature levels such as $+80°C$, $+30°C$, $0°C$, $-30°C$, and $-60°C$. The time at each of these temperatures varied from mission to mission as the result of the previous operating experiences. Sensor crystal temperature was not controlled during ascent and descent to conserve battery power. The temperatures of the cryogenic QCM's (CQCM's) were not controlled, except for an occasional surface cleanup. CQCM crystal temperature adjusts to passive radiative interaction with the environment and may reach low values (e.g., $-133°C$) in 12 h under optimum conditions. These conditions, however, never materialized during the missions. The cameras take stereo photographs of particles at the rate of 24 frames per h while integrating photometers monitor background brightness and conrol camera film exposure time. A quadrupole is the sensing element of the neutral gas Mass Spectrometer (MS), with a mass range of amu 1 through amu 150. A special gas collimator system in association with a zirconium pump limits the field of view for many gases essentially to 0.1 sr. The normal cycle time is ten minutes, half of which is dedicated to amu 18. However, during the "survey," the MS scans ten times faster. The slow scan rate provided for maximum sensivity but limited the monitoring of fast events such as engine firings (80 msec pulses). In its bay-mounted position, the MS measures ambient and return flux. A special gas source containing $H_2{}^{18}O$ and ^{22}Ne was incorporated to measure return flux parameters such as collision cross sections.

All systems and instruments of the IECM performed very well during the missions. A few problems arose, mainly due to

Table 1 Summary of contamination specification and measurement requirements on-orbit

Contamination specification		Specific references
Molecular column density less than:		
10^{12} molecules/cm^2 for H_2O		2
10^{11} molecules/cm^2 for $H_2O + CO_2$		3
10^{13} molecules/cm^2 for $N_2 + O_2$		3
10^{10} molecules/cm^2 for all other species		3
Scattered/emission light background less than:		
$m_v = 20$th magnitude star per square arc second in the ultraviolet region		
3.5×10^{-11} W/m^2/sr/nm, $\lambda = 155$ nm	In ultraviolet and visible at 90° Sun angle	3
1.9×10^{-11} W/m^2/sr/nm, $\lambda = 191$ nm		
1.3×10^{-11} W/m^2/sr/nm, $\lambda = 246$ nm		
5.9×10^{-11} W/m^2/sr/nm, $\lambda = 298$ nm		
1.0×10^{-10} W/m^2/sr/nm, $\lambda = 332$ nm		
2.5×10^{-10} W/m^2/sr/nm, $\lambda = 425$ nm		
2.0×10^{-10} W/m^2/sr/nm, $\lambda = 550$ nm		
1.0×10^{-10} W/m^2/sr/nm, $\lambda = 1000$ nm		
10^{-11} W/m^2/m^2/nm, $\lambda \leq 30\ \mu m$	in infrared	3
10^{-10} W/m^2/sr/nm, $\lambda > 30 \mu m$		3
Fewer than one particle larger than $5 \mu m$ per orbit in 1.5×10^{-5} sr field of view within 5 km		2,3
Molecular return flux (RF) such that:		
RF $< 10^{12}$ molecules/cm^2/s for H_2O		2
Deposition $< 10^{-7}$ g/cm^2/s for H_2O 0.1 sr on 300 k surface at 400 km altitude		3
Deposition $< 10^{-5}$ g/cm^2/30 days 2π sr on 300 k surface		3
Deposition $< 10^{-5}$ g/cm^2/30 days 0.1 sr on 20 k surface at 400 km altitude		3
Degradation of optics < 1		2

Table 2 STS mission description

Parameter	STS-1	STS-2	STS-3	STS-4
Launch date	4-12-81	11-12-81	3-22-82	6-27-82
Duration, h	54	54	192	168
Inclination/beta angle, °	40/-26 to -19	38/-50 to -45	38/-36 to -23	28.5/-1 to +20
Altitude, km (n. mi.)	240-278 (130-150)	222-259 (120-140)	241 (130)	306 (165)
Major attitude(s)	-ZLV, Y-POP payload bay to Earth	-ZLV, Y-POP payload bay to Earth	Tail to Sun 24 h Nose to Sun 80 h Bay to Sun 27 h Passive thermal control (PTC) 23 h	Tail to Sun 61 h Bottom to Sun 32 h Top to Sun 7.5 h PTC 22 h Gravity gradient 7 h
Payload(s)	DFI	OSTA-1 IECM + DFI	OSS-1, IECM, and DFI	DOD 82-1, IECM, and DFI
Comments	—	Gas release	Door tests	Door test, contamination survey gas release

Table 3 Instrument characteristics and description summary

Instrument[a]	Measurement	Operation[b]
Humidity monitor	Relative humidity, temperature	GPL, A, D, PL
Dewpoint hygrometer	Dewpoint	GPL, A, D, PL
Air sampler	Gaseous contaminants	GPL, A, D, PL
Cascade impactor	Particulate contamination of nonvolatile residue	GPL, A, O, D, PL
PSA	Optical degradation due to accumulated contamination	GPL, A, O, D, PL
OEM	Degradation of optics at 253.65 nm	GPL, O, D, PL
TQCM	Condensed molecular contamination at 213 to 303 K ($-60°C$ to $+30°C$)	GPL, A, O, D, PL
CQCM	Condensed molecular contamination at 133 K ($-140°C$) to ambient	GPL, A, O, D, PL
Camera/photometer	Particulate velocity, direction; photometry	O
Mass spectrometer	Molecular return flux	O

[a] PSA = passive sample array, OEM = optical effect module, TQCM = temperature-controlled quartz crystal microbalance, and CQCM = cryogenic quartz crystal microbalance.
[b] GPL = ground prelaunch, A = ascent, O = on orbit, D = descent, and PL = postlanding.

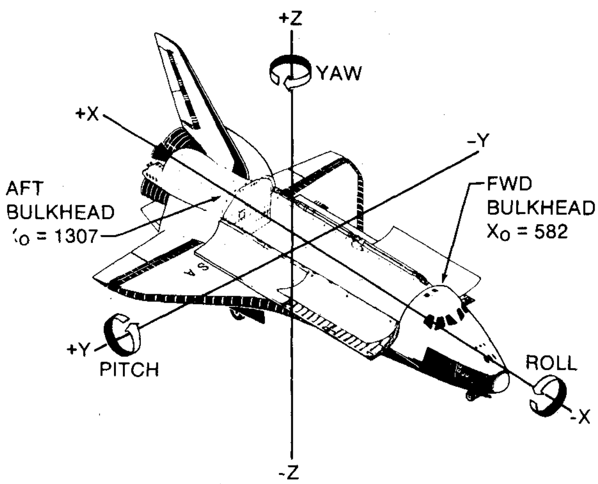

Fig. 1 Orbiter coordinate system.

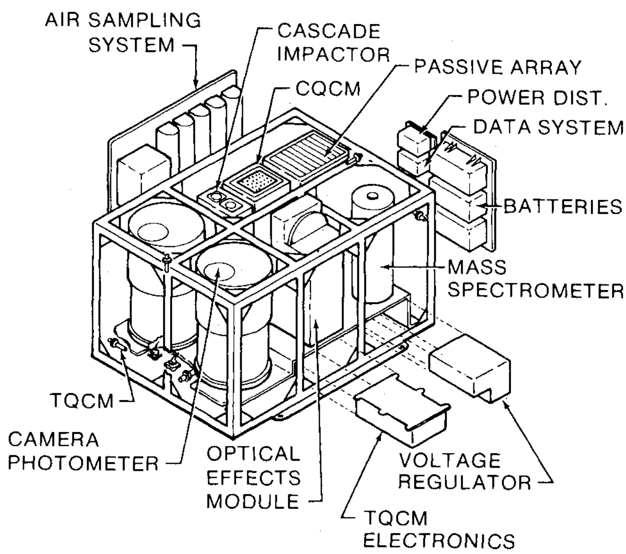

Fig. 2 Induced environment contamination monitor (IECM).

instabilities in the supplied power. All data were properly recorded and retrieved.

Results

Preflight

Preflight activities were extensive and included thermal protection tile debonding and bonding as well as other repairs expected to occur during development phases. Because of this condition, as well as a need to better understand the existing contamination control capabilities of the Orbiter ground processing facilities, only limited control of contamination was exercised.

Preflight particle fallouts were measured primarily on the witness samples of the Passive Sample Array (PSA). Both particle count and size distribution were determined using an omnicon optical imaging particle counting system. The results of the particle counts are summarized in Table 4 for exposures in the Orbiter Processing Facility (OPF) and the Payload Changeout Room (PCR) and during the OPF to pad time period as applicable for each flight. Particle size distribution from the OPF samples is shown in Fig. 3. The 2- to 4-μm diam particle is the most abundant.

Postflight

Passive Sample Array (On Orbit and Ferry Flight)

The various samples of the PSA were analyzed from an optical as well as a particulate (contamination) standpoint. The measured optical change of the samples is generally small, limited in magnitude to levels comparable to or less than the associated levels of measurement uncertainty. Since no molecular contaminant films were detected, the measured optical degradation has been attributed to particulates. Measurement results show average particle densities of 1.7×10^3, 3.8×10^3, 2.7×10^3, and 0.5×10^3 particles/cm^2 for flights STS-1 through STS-4, respectively. The values shown are the difference in levels measured on samples exposed to the entire mission and levels on samples exposed only on the ferry flights.

Figure 3 shows the distribution of the ferry flight particulates and its similarity to the preflight distribution. The particulate distribution obtained from the flight PSA is also shown after ferry flight counts were subtracted. This distribution peaks at 4 to 6 μm and smaller peaks at 12 to 16 μm and 20 to 25μm are indicated.

Orbiter Inspection

Orbiter payload bay surfaces were inspected after each of the four flights for evidence of deposits or change. With one exception (deposits on DFI thermal control blankets which were due to DFI outgassing and were previously reported), no deposits that were caused by flight could be visually detected on any bay or payload surfaces.[1] No change was evident except for that described below.

Thermal control blankets associated with the Orbiter television cameras (Kapton surfaces) and payload surfaces showed significant changes after each flight. The normally glossy surface of the Kapton was changed to nonglossy. Shadow patterns were detectable on this surface and were generally associated with exposure to the vehicle velocity vector (ambient atmosphere impingement). Changes in paint surfaces and other nonmetallic surfaces were also noticed. These effects have been attributed to a proposed interaction between atomic oxygen in the low-Earth orbit environment and organic surfaces, leading to oxidation and complete removal of some of the surface involved.[5,6] As much as 5.5 μm surface loss occurred on STS-3 on the Kapton thermal blanket surfaces. This amount of mass loss obviously increases outgassing rates above what is expected for the unaffected material. The oxidation process is believed to result in the release of only noncondensable products, in that no deposits have been detected which are relatable to this effect.

Sampling of Orbiter radiator surfaces such was done for STS-1 and STS-2 was not repeated for STS-3 and STS-4.[1] Visual observation of these surfaces on STS-3 and STS-4 showed no change from earlier flights.

Erosion of the coating on thermal protection system tiles on the top surface of the body flap did occur on STS-3 and STS-4. It appears that this erosion is caused by extremely long operation of the downfiring vernier reaction control jets and the resultant high-velocity liquid droplets released by the engines. No erosion on any other surfaces has been noticed, including the membrane on the IECM pressure gage and the QCM crystals that were exposed to the primary engine core plumes during the STS-4 mission.

Table 4 PSA Preflight particle fallout measurements (in particles per square centimeter)

Mission	OPF	OPF to PCR	PCR
STS-2	1.4×10^4 (19 days)	—	—
STS-3	6.5×10^3 (19 days)	—	—
STS-4	1.3×10^3 (5 days)	6.7×10^2 (26 days)	5×10^2 (16 days)

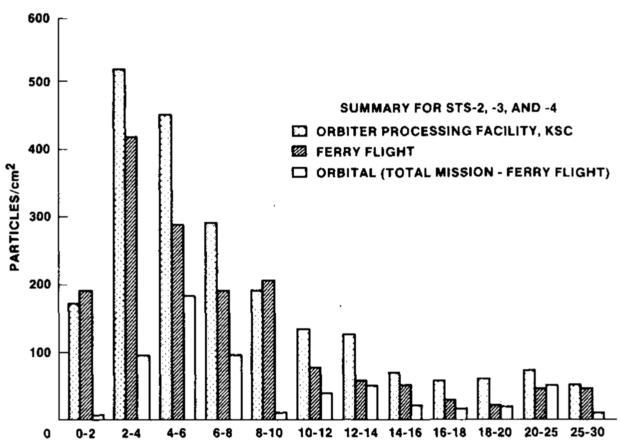

Fig. 3 Passive sample array particle distributions.

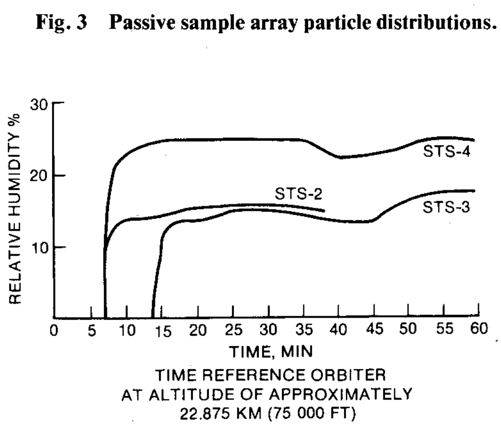

Fig. 4 Ascent/descent humidity monitor measurement during descent.

Ascent and Descent

Air Sampler

The analysis of the reactive samples for STS-2, STS-3, and STS-4 is summarized in Table 5. No detectable reaction with HCl was noted during ascent and there was a minimum amount of volatile hydrocarbons present. During ascent and descent, the reactive species of concern (NO, NO_2, and NH_3) were not detected (1 ppm minimum detection limit). Also, volatile hydrocarbon levels were low. Air sampler results indicate that engine and Auxiliary Power Unit (APU) exhaust products were not ingested into the payload bay during ascent and descent as expected, although no specific requirements are applicable.

Cascade Impactor

The analysis of particulate size distribution from cascade impactor measurements is shown in Table 6. Concentrations of particles during STS-4 were generally lower than for STS-2, except for particles larger than 5μm. The particle concentrations appeared to be lowest overall during the STS-3 mission. The evaluation is based on the theory of operation for this instrument.

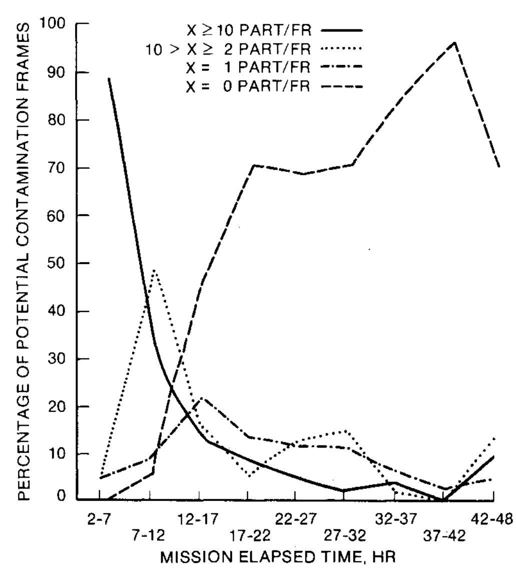

Fig. 5 Particle density on frames.

Table 5 Air sampler results' contaminant totals for representative ground, ascent, and descent phases

Location	Species	Detection method[a]	Observed
Preflight (OPF)	Volatile hydrocarbons[b]	A	~3 ppm by weight ~1 ppm by volume
Ascent	Volatile hydrocarbons[b]	A	~50 ppm by weight ~10 ppm by volume
Ascent	Reactive: HCl	B	None detected to 1 ppm sensitivity
Descent	Reactives: NO, NO_2, NH_3	C	None detected to 1 ppm sensitivity
Descent	Volatile hydrocarbons[b]	A	~20 ppm by weight ~4 ppm by volume

[a] A—concentration on absorbent; postflight gaschromatograph/MS analysis; B—reaction with silver oxide/hydroxide surfaces; C—reaction with ruthenium trichloride surfaces. [b] Covers C_9 to C_{24} range and uses $\sim C_{12}$ as average molecular weight to obtain ppm by volume.

Table 6 Cascade impactor particulate measurements summary STS-2, 3, and 4

Particle size, μm	Mission	Flight results, μg/m³	
>5	STS-2	Ascent	~30
		Descent[a]	~10
	STS-3	Ascent	~10
		Descent	~10
	STS-4	Ascent	Nonfunctional
		Descent	~20
1 to 5	STS-2	Ascent	~500
		Descent	~250
	STS-3	Ascent	<10
		Descent	<10
	STS-4	Ascent	~400
		Descent	<10
0.3 to 1	STS-2	Ascent	~250
		Descent	~125
	STS-3	Ascent	<10
		Descent	<10
	STS-4	Ascent	~150
		Descent	Nonfunctional

[a] Descent values may be largely instrumental (thermal) and should be considered upper limits.

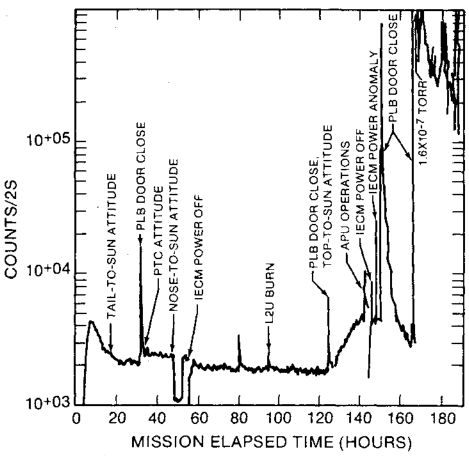

Fig. 6 Mass spectrometer (STS-3) output vs time at amu 18.

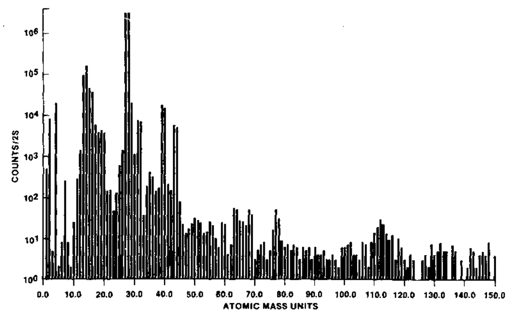

Fig. 7 STS-3 mass spectrum at 135.25 h MET.

Humidity Monitor and Dewpoint Hygrometer

The humidity monitor measured less than 1% relative humidity during ascent, reflecting the environment provided by the payload bay dry nitrogen gas purge prior to launch. The dewpoint hygrometer correspondingly indicated a dewpoint below its lower measurement limit of -6.7° C. Comparisons of relative humidity during descent are shown in Fig. 4. The values were highest for STS-4 and were in the range of approximately 25% R.H.

On Orbit

Camera/Photometer

The number of exposed frames for STS-2 exceeded 1075; for STS-3, 1100; and for STS-4, 3330. Only a portion of these frames, referred to as potential contamination frames, were taken under lighting conditions allowing particle detection. Figure 5 illustrates the overall decrease of particle concentration with Mission Elapsed Time (MET) observed for each of these flights. After approximately 20 h MET, the fraction of frames showing no particles exceeded 70%. The origin of most particles is not known. However, occasionally there were events that led to significant brief increases in the particle count. These events included payload bay door tests and water dumps, which produced large amounts of ice particles (>100 counts/frame). After dump termination, the particle count decays rapidly with a time constant of 5 min for a 1/e drop. Particle count increases have not been seen during operation of the FES. Detail analysis of the particle count of the frames taken during quiescent periods indicates a level on the order of 0.03 particle/1.5×10^{-5} sr per orbit for particles of the size 25μm and greater in the vicinity of the Orbiter. This value is extrapolated from a limited number of frames, an instrument field of view of 0.24 sr, and an average rate of 500 per orbit. The average stay time for a typical particle in the camera/photometer's field of view is 5 s.

Optical Effects Module

The average changes in transmittance (at 253.7 nm) were generally within the range of uncertainty (± 0.01 or 1% for highly transmitting samples) for all missions and for LiF_2, CaF_2, and MgF_2 samples. No mission event caused any significant change in the OEM output.

Mass Spectrometer

Two characteristics of the MS put significant limits on its capabilities and had to be considered carefully in the data analysis. These are the relatively slow scan rate and the relatively high background of gases such as H_2O and CH_4. The scan rate, for instance, did not allow measurements of engine effluents. However, the effects of long test firing of RCS engines, such as the L2U engine test burn, were recorded.

Ambient constituents such as helium, oxygen (O, O_2), and nitrogen contributed significantly to the MS output. Measured data appear to agree satisfactorily with standard atmospheric data. Helium and argon measurements were used to verify proper MS calibration and operation.

Return flux depends on vehicle attitude, ambient density, and contamination flux and direction, among other factors, all of which are generally varying with time. Therefore, this analysis requires considerable detailed data. Fortunately, as mentioned before, data analysis was simplified somewhat for the STS-2 mission ZLV attitude timeframe and will be covered in greater detail.

STS-2 flight results for return flux of water are briefly summarized and updated from previous results.[1] The FES operational phases are clearly reflected in the amu 18 output of the MS. Measured data agree well with SPACE[7] predictions. Molecular column densities were on the order of 1.4×10^{13} molecules/cm^2 as derived with the aid of SPACE. Water vapor density due to Orbiter early desorption decreased by approximately two orders of magnitude within a period of 40 h. Measured fluxes were about three decades larger early in the mission than predicted by modeling. This has been attributed to an abnormally high moisture content of the thermal protection tiles at the start of the mission due to prior heavy rains and system development difficulties. This moisture desorbed on orbit at a relatively high rate. The amu 18 output during the STS-3 flight indicates only a few significant events and hardly any dependence on vehicle attitude. This seems to indicate a very low induced water vapor density and mostly instrument background. The MS reaction to payload bay door closures, L2U engine firings, and APU use was significant as shown in Fig. 6.[8]

The level of desorbed water during the STS-4 mission was again much higher than normal due to the high moisture content of the tiles as the result of the heavy rain and hail that occurred just before launch and similar development difficulties as on STS-2. The level decreased significantly as the result of on-orbit sublimation. Several water dumps occurred on each flight; however, none was registered by the MS with certainty. This may be an indication that most of the water is dumped in the form of ice particles and the rest is blocked by the open doors. The MS has not unambiguously detected increased return flux during the STS-3 and STS-4 FES operations. On STS-4 this was probably due to blockage of the effluent by the upward tilted elevons.

Table 7 TQCM preflight programmed measurement and cleaning temperature cycles

Mission	Temperatures, °C −60	+80	−30	+80	0	+80	+30	+80[a]
STS-2	120	30	120	30	120	30	120	30
STS-3	255	20	255	20	100	20	100	20
STS-4	240	20	240	20	240	20	240	20

[a] Cycle repeated throughout on-orbit period.

Table 8 Data from all TQCM sensors at 30° C

MET, h[a]	Measured value, ng/cm^2/h	Value extrapolated to 30-day mission, g/cm^2/30 days
2.1 (2)	<0	<0
3.8 (3)	<0	<0
13.8 (2)	20	1.4×10^{-5}
16.6 (4)	<0	<0
21.9 (3)	5	3.6×10^{-6}
25.4 (2)	7.7	5.5×10^{-6}
34.9 (4)	1.8	1.3×10^{-6}
38.2 (3)	4.6	3.3×10^{-6}
40.0 (3)	23	1.7×10^{-5}
50.0 (2)	22.6	1.6×10^{-5}
58.3 (3)	9.7	7.0×10^{-6}
76.3 (3)	7.9	5.7×10^{-6}
84.7 (4)	<0	<0
94.4 (4)	35.3	2.5×10^{-5}
102.9 (4)	2.5	1.8×10^{-6}
112.5 (3)	11.1	8.0×10^{-6}
121.4 (4)	3.8	2.7×10^{-6}
125.7 (3)	<0	<0
139.5 (4)	2.7	1.9×10^{-6}
157.9 (4)	<0	<0

[a] Mission numbers are given in parentheses.

Nitrogen, oxygen, and carbon dioxide are the major species of cabin leakage and early desorption (besides H_2O). Their contribution to the molecular column density is of special interest and needs to be determined. However, it is very difficult to separate the MS output for these gases as to their origin (Orbiter, ambient, background).

Return flux of heavy molecules and their fractions was not expected to be observed. Indeed, no amu above 44 seems to rise out of the instrument background noise, as shown by a typical spectrum (Fig. 7). This particular spectrum was acquired during the "hot case," after the Orbiter bay was pointed toward the Sun for approximately 10 h. The angle between the Orbiter $+Z$ axis and the flight direction was approximately 40°. Peaks associated with Freon 21 from an Orbiter coolant system minor leak were seen on STS-4.

Gas release maneuvers were performed on STS-2 and STS-4, with only partial success. The gases were released on STS-2 while the Orbiter payload bay faced the Earth. The angle of attack was therefore 90° and did not change from 180° to 0° as originally intended. The return flux of ^{22}Ne, as measured, was stable and quantitatively agreed with model predictions. The $H_2{}^{18}O$ release, however, did not work as planned. The STS-4 gas release associated with a wake-to-ram maneuver is still under analysis.

Direct contamination flux measurements (contamination survey) with the IECM instruments pointed at various Orbiter surfaces were successfully accomplished during STS-4. These measurements are important, since they eliminate the uncertainties which the collision processes add to the data analysis of return flux. However, the analysis of these data was complicated by atmospheric and instrument backgrounds. Results are still being evaluated; however, they seem to confirm the results of return flux measurements and predictions indicating low molecular contamination levels. Cabin leakage was not detected.

The MS measured methane in significant amounts during each of the last three missions, although this gas was not expected to be observed at such high levels. Studies and investigations indicate that the zirconium getter material within the MS system may act as a desorbent as well as an absorbent of methane and, therefore, may be a source of this gas.[9] The observed relatively high methane levels and their variations during the mission are thus believed to be largely due to reactions internal to the MS. The details of these reactions are not yet well enough understood.

TQCM's

The TQCM output signals were taken with a time resolution of 1 min and varied considerably with crystal temperature, time, and sunlight intensity. In order to study the overall trend, the relatively long time periods of stable crystal temperature within each temperature cycle step (see Table 7) were selected for analysis. In most cases, the difference of the frequencies at the start and at the end of each such collection period was used to determine average accretion rate for this time period. Table 8 presents a summary of mass deposition rates for various mission time slices. The rates are averaged over all TQCM sensors with a temperature of $+30°$ C. The rates are also extrapolated to a 30-day period for easy comparison with the requirements, assuming that no unusual event occurs.

One mission event, the L2U RCS engine test firings on STS-3, resulted in high deposition rates, totaling up to 175 ng/cm^2 deposition on the TQCM's at $+30°$ C. This deposition dissipated with a time constant of ~ 15 min.

CQCM's

The minimum temperature reached by a CQCM was -102° C during the tail-to-the-Sun attitude of STS-3. The maximum temperature of $+34°$ C occurred on STS-4 just before the first payload bay door opening.

The average on-orbit mass accumulation rates (in ng/cm^{2}h) were 5 for STS-2, 2 for STS-3, and -1 for STS-4. The corresponding collection periods were 49.3, 188, and 162 h, respectively. Extrapolation of the first two rates to a 30-day period leads to 3.6×10^6 and 1.4×10^{-6} g/cm^2/30 days.

Comparison of Measurements and Requirements

Molecular Column Density (MCD)

MCD's can be derived from direct flux or return flux measurements using appropriate modeling techniques such as the SPACE program.[7] Based on return flux measured near the end of the STS-2 flight, the MCD for H_2O was not more than 9.7×10^{11} molecules/cm^2. This compares with a requirement level of 1×10^{12} molecules/cm^2 maximum. This same level was measured near the end of the STS-4 flight. The MCD measured during the STS-3 mission was considerably lower. It is expected that the excessive initial desorption rate for H_2O observed on STS-2 and STS-4 should not recur beyond STS-5 because of actions being taken to improve the waterproofing technique for the thermal protection tiles. The measurement and comparison with requirements of MCD's for other gases such as N_2, O_2, CO_2, etc., will have to be done more directly using optical instruments.

Molecular Deposition

The average molecular deposition rates on an ambient surface with a field of view of 2π sr measured by the TQCM's as well as the CQCM's generally fell within a factor of 2 of the specified maximum level or were lower. Deposition rate measurements on a cryogenically cooled surface as well as additional measurements on ambient temperature surfaces are planned to be performed during the Spacelab II mission. The TQCM's of the Office of Space Science OSS-1 package on STS-3 measured deposition rates very similar to those reported here.

Particle Background

Requirements state that the average production of particles by the STS shall be limited to less than one discernible particle (diameter >5 μm within 5 km) per orbit within a 1.5×10^{-5} sr field of view.[3] The results show that this requirement has been met for particles larger than 25 μm for significant periods of time. Verification of particle releases at <25 μm will be made on Spacelab II using a cryogenic infrared telescope for the on-orbit exposure.

Background Brightness

None of the direct spectral intensity measurements specified in the requirements have been performed so far. The intent of these requirements is to ensure that the contribution due to the induced environment is much less than the natural brightness background. The camera/photometer system on the IECM was used to verify this point in the visible light range. Sky background brightness after about 15 h MET and during the absence of water dumps consistently shows no differences during orbital nighttimes and daytimes, indicating no contribution from molecular or particulate scattering. Stars as faint as $m_v = 10$ are consistently seen during these day and night sky observations, the photometer-controlled exposures being terminated by integrated starlight in both cases.

Spectral measurements of the background brightness in the infrared range are scheduled to be performed by the Infra Red Telescope (IRT) aboard Spacelab II.

Degradation of Optics

Measured transmittance change was within the 1% limit requirement.[2] Extrapolation of results to longer time periods such as 30 days is not meaningful, since the data were, on average, within measurement uncertainties of the instruments.

Additional details on the STS-2, STS-3, and STS-4 IECM results can be found in Ref. 10.

Conclusions

Measurements were performed on STS missions 2, 3, and 4, with the IECM to assess the performance of the Space Shuttle Orbiter system with regard to the induced contamination environment. Results were compared with requirements and goals. The comparison shows that, in general, the measured data either meet or are close to the requirements. The environment, as determined thus far, appears to be adequate for most payloads with minimal need for covers or other forms of protection. Occasional events such as water dumps and operation of engines, flash evaporators, and payload bay doors, etc., were, as expected, causes for excessive molecular and/or particulate contamination. Such events may require protective action for some sensitive experiments.

The complete approach for control of contamination during ground turnaround is still being developed at this time. Part of the reason for this delayed development was the lack of an experience base associated with operation of the Shuttle in ground facilities. The necessity for the development of this data base was recognized during the development of the requirements; however, progress has been somewhat slow in this area. This problem was highlighted by the contamination concerns that developed during preparations for launch of the Tracking and Data Relay Satellite B (TDRS B) on STS-6. With the emphasis generated by this event and some additional test data, detailed contamination control procedures can be developed that will be acceptable to all.

Data from other payloads have also been examined and have aided in understanding the data presented here. A flux measuring device with frequent data output, such as the pressure gage of the OSS-1/Plasma Diagnostics Package (PDP) payload flown on STS-3, for instance, has recorded individual vernier as well as primary engine firings. Data from other near-term payloads will be evaluated and used to provide a complete definition of the environment and acceptable operational technique for hopefully all types of payloads. The IECM will be part of Spacelab I and II, permitting correlation of data with other Spacelab instruments and forming an updated reference for the present data base. The measurement results presented here are characteristic only of a practically empty payload bay, enclosing just a few instruments. The contribution to the induced environment from certain payloads may be significantly larger and should be determined in each such case.

The contamination control program for the Shuttle system marks a giant step from the control of small free-flying instrument packages to the control of a large and complex space vehicle. Its development has been a great challenge to all those who participated in it. The approach used for the development of contamination control program was very effective in developing a system with excellent performance and in definition of the vehicle associated environment. Broad participation in panel activities led to a better understanding of payload concerns by system design engineers and also to a better understanding of Shuttle development problems on the part of payload developers and the scientific community in general. Indeed, contamination control was treated in Shuttle development as a full-fledged discipline for perhaps the first time, in that the program provided support from requirements development to the final environmental measurements.

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