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SHUTTLE ON-ORBIT CONTAMINATION AND ENVIRONMENTAL EFFECTS

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ABSTRACT

One of the many challenges presented by the development of the Space Shuttle system was ensuring compatibility of the system with payloads and payload measurements. Early in the development of the system, the contamination environment associated with Shuttle flight was addressed through working group activities involving broad representation. Through these activities, an extensive set of quantitative requirements and goals was developed and implemented by the Space Shuttle Program management. Assessment of performance of the Shuttle system as measured by these requirements and goals has been partly obtained through the use of the induced environment contamination monitor on Shuttle flights 2, 3, and 4. Contamination levels are low and generally within the requirements and goals established. Additional data expected to be available from near-term payloads and already planned contamination measurements will complete the environment definition and allow for the development of contamination avoidance procedures as necessary for any payload.

INTRODUCTION

The Space Shuttle was originally conceived and developed to be the primary space transportation system for the United States through the 1990's. Development of the components of the system presented a unique challenge in many aspects such as development of reusable thermal protection systems and primary propulsion engines as well as other devices such as the remote manipulator system. Equally unique was the challenge of providing maximum operational flexibility and at the same time satisfying the needs of the wide range of payloads which were to use this orbital delivery system. Previous experience was very limited or not available since prior space programs had specific objectives to achieve and other delivery systems did not have to be reusable or manned or be compatible with measurements from attached payloads. To ensure a successful operational system, therefore, it was necessary to effectively integrate the wide range of requirements presented by Space Shuttle development.

To address requirement development and integration, the Space Shuttle Program management established working groups to address each of several critical areas. These working groups had broad membership, generally including each cognizant NASA center as well as representatives from the user community, and were responsible for addressing needs, developing requirements, and guiding program implementation of these requirements. One of the critical areas defined was control of the environment to which the payload would be exposed during Shuttle flight. Aspects of the environment which were to be addressed consisted of mechanical loads, both static and dynamic; thermal, electromagnetic, and contamination (used here to refer to particles and gases in the environment which produce undesirable effects primarily on payload optics). A historical description of the activities associated with the contamination requirement development is provided with emphasis on particular challenges and problems encountered. Also, measurements made to define this aspect of the environment are summarized and system performance is assessed by comparing the results of these measurements with program requirements.

SHUTTLE CONTAMINATION ORGANIZATION APPROACH

The Shuttle contamination working group (initially called the Particles and Gases Working Group (PGWG)) was established in 1973 at the NASA Lyndon B. Johnson Space Center (JSC) and initially consisted of representatives from JSC, the NASA Goddard Space Flight Center (GSFC), the NASA George C. Marshall Space Flight Center (MSFC), the NASA John F. Kennedy Space Center (KSC), the NASA Ames Research Center (ARC), NASA Headquarters, Rockwell International, Aerospace Corporation, and the European Space Research and Technology Center/European Space Research Organization (ESTEC/ESRO). This group, currently called the Particles and Gases Contamination Panel (PGCP), is primarily responsible for contamination requirements implementation. Concurrently, a group was formed at MSFC in 1974 (the Contamination Requirements Definition Group (CRDG)), with membership similar to that of the PGCP with the addition of U.S. Naval Research Laboratory and NASA Langley Research Center (LaRC) representatives. The CRDG was primarily responsible for developing a complete set of contamination requirements, the evolution and definition of which are discussed in the following section.

REQUIREMENTS DEVELOPMENT AND DEFINITION

No clear precedents existed at the inception of the Space Transportation System (STS) Program for the development and incorporation into documentation of a complete set of contamination requirements for a reusable space transportation system. Somewhat of a previous experience base had been developed for the Skylab Program in invoking contamination control measures for the Apollo telescope mount (ATM). At about the same time (circa 1972), a group of scientists with a common interest in using the Space Shuttle system convened at Wood's Hole, Massachusetts. Out of the discussions, which were centered around the Orbiter-induced environment and potential effect on payloads, came a set of proposed requirements for the environment surrounding the vehicle in orbit. Using this set of generalized requirements and the Skylab experience, the Particles and Gases Contamination Panel developed workable and realistic requirements which could be feasibly implemented into the STS Program documentation. Whereas molecular contamination on orbit was mainly addressed by the Wood's Hole group, ground facilities contamination control and the Orbiter's exposure to these ground facilities as well as to the launch, on-orbit, and entry environments from a molecular and particulate standpoint had to be addressed.

Part of the problem in addressing ground particulate contamination control was the nomenclature in use at the time for previous programs. Contamination control on the ground was based on the concept of "clean room cleanliness," such as class 10 000, class 100 000, and so on, specifying particles suspended in the air. This concept was not appropriate for use on the Shuttle program in that payload integration to the Orbiter required that any payload area be exposed to a large airplane, or at least part of it, for a considerable length of time. Therefore, a somewhat new approach to defining the cleanliness levels associated with Shuttle flight had to be developed. The "clean room" concept was replaced with a definition of the extent of control on all aspects of the environment such as temperature, humidity, condensable gases, and particulate control both on surfaces and in free air. Approaches developed had to be flexible enough to serve a wide variety of needs yet be constrained to be compatible with the relatively short Shuttle ground turnaround and with operational cost. As a result, the standard cleanliness approach developed was based on a "visibly clean" surface criterion. This category of requirements has been subsequently divided into three levels of surface contamination control and along with other parameters, such as free air cleanliness, and temperature and humidity, form the basis for ground contamination control. The complete set of requirements developed for contamination control was incorporated into the Shuttle documentation, specifically Volume X of JSC-07700 (ref. 1).

In contrast to contamination control during ground-based operation for which requirements are qualitative and general, requirements for on-orbit contamination control can almost be completely defined quantitatively. To address all aspects of the environment, these requirements are of necessity complex and extensive. This complexity presented problems in implementing these requirements in that program management was concerned about the difficulties created and the program capability to verify performance to these requirements. Because of this concern, most of the on-orbit environmental requirements were accepted by the Shuttle program as "goals." The key parameters of the environment such as gas cloud density definition and particle release requirements were included in the baseline Shuttle documentation. A more detailed set of environmental definitions developed by the CRDG (ref. 2) essentially constitutes the set of Shuttle goals for control of the gases and particles associated with the environment and their effect on background light scattering and emissions.

A summary of the requirements and goals applicable to the on-orbit, or more generally flight phase, environment is included in table 1. Key parameters addressed are molecular column density, which defines the gas cloud density associated with the Orbiter vehicle, and return flux, which addresses the component of this cloud which is scattered back to surfaces in the payload bay because of interaction with the ambient environment. Other requirements address deposition of matter on surfaces either directly or by scattering by the atmosphere and light background in the various spectral regions also essentially due to the gases or particulates in the environment. These requirements and goals were implemented in the Shuttle program in March 1974. No changes or revisions of these requirements have been necessary over the intervening years.

REQUIREMENT IMPLEMENTATION

As inferred previously, the STS Program management was hesitant in accepting the outlined requirements unless there was some reasonable assurance that these "goals" were viable; that is, assurance that they could be met by the STS. Two methods of "verification" were considered and implemented: analysis and measurements. The subject of performance assessment using onboard measurements is discussed in the next section. Although Skylab used math modeling somewhat in performing contamination analysis, the STS Program marked the first time that the development of a contamination math model coincided with the development of a space vehicle. This coincidence allowed, for the first time, the use of contamination modeling as a design tool in the performance of trade studies.

TABLE 1.- SUMMARY OF CONTAMINATION SPECIFICATION AND MEASUREMENT REQUIREMENTS ON ORBIT

Contamination specifications	Specific references	Measurement required
Molecular column density less than:		
- 10^{12} H_2O particles/cm^2	1	Molecular column density
- 10^{11} $H_2O + CO_2$ particles/cm^2	2	
- 10^{13} $N_2 + O_2$ particles/cm^2	2	
- 10^{10} other molecules/cm^2	2	
Scattered/emission light background less than:		
- m_v = 20th magnitude star/arc-s^2 (10^{-12} $B_\odot$ in ultraviolet)	1	Background spectral intensity
- $10^{-14.2}$ $B_\odot$ in visible	2,3,5	
- $10^{-14.0}$ $B_\odot$ in ultraviolet	2,3,5	
- 10^{-11} W/m^2/sr/nm λ <30 µm	2,3,5	
- 10^{-10} W/m^2/sr/nm λ <30 µm	2,3,5	
Fewer than one 5-µm particle per orbit in 1.5 × 10^{-5}-sr field of view	1,2	Particle size and velocity distribution
Molecular return flux such that:		
- H_2O < 10^{12} molecules/cm^2/s	1	- Molecular return flux
- Deposition <10^{-7} g/cm^2/30 days 0.1 sr on 300-K surface	2	- Molecular deposition on an ambient surface
- Deposition <10^{-5} g/cm^2/30 days 2π sr on 300-K surface	2	- Molecular deposition on an ambient surface
- Deposition <10^{-5} g/cm^2/30 days 0.1 sr on 20-K surface	2	- Molecular deposition on a cryogenic surface
- Degradation of optics <1%	1	- Degradation of optical surfaces

The (molecular) contamination math model, as developed by JSC with Martin-Marietta Aerospace as subcontractor, is a computer program which accepts certain time-dependent input parameters such as materials gas emission, reflection, and adsorption characteristics, engine and vent characteristics, ambient and emitted gas interaction, and their associated mass transport mechanism and vehicle geometry. The model provides a time-dependent output of such parameters as gas density, column density, return flux, and deposition which define the induced environment of the Space Shuttle Orbiter and payload on orbit. The model is currently being used for special studies associated with flight data correlation and STS performance assessment as well as payload integration activities.

During the 1973-74 time frame, the model was used to assess the effects of design changes such as reaction control engine location on the upper payload bay viewing region. Additionally, locations of the supplemental flash evaporator system (FES) nozzles, which are used to dump as much as 7.2 kilograms of water per hour in orbit, were selected on the basis of model output.

The larger benefit derived from having a functional model during the Space Shuttle development was the ability to understand the design relative to its performance from a contamination standpoint. This understanding not only provided confidence to program management that acceptable designs were being developed but also provided effective description of the evolving system and its associated environment to potential users. It is strongly recommended that such a model be formulated in future programs at the earliest stage of development.

PERFORMANCE ASSESSMENT

In addition to the extensive modeling efforts to describe and better understand the Shuttle contamination environment, a program was established to make measurements of the environment on the early flights to assess performance and provide data for correlation with and refinement of the model. The large number of environmental parameters to be measured resulted in the need for 10 instruments. This group of instruments was integrated into one package referred to as the induced environment contamination monitor (IECM), which was funded jointly by the Space Shuttle Program and the NASA Office of Aeronautics and Space Technology. The Marshall Space Flight Center provided the technical development and management for the IECM.

At the onset of this measurement program, it was understood that the IECM would provide definitions of most aspects of the environment. Certain parameters, especially those related to far infrared and far ultraviolet measurements, are best obtained from near-term payloads. Originally, the IECM was planned for six flights of the first Shuttle Orbiter. For several reasons, this schedule was abbreviated to three flights, which are reported here and seem adequate for the intended objectives.

INDUCED ENVIRONMENT CONTAMINATION MONITOR

Background

The objectives of the IECM project were to provide a self-contained instrument complement compatible with the development flight instrumentation (DFI) pallet and to provide capabilities to do the following.

1. Measure major aspects of the particle and gaseous contamination during ground handling, launch preparation, ascent, orbital operation, descent, landing, and payload removal to verify the requirements and goals developed by the PGCP and the STS Payload CRDG.

2. Provide diagnostic data to identify any sources that contribute to out-of-specification conditions so that corrective action may be taken.

3. Measure the contamination effects from delivery, deployment, retrieval, and landing of a free-flying payload.

4. Perform routine monitoring to detect any anomalous operation conditions such as leaks in the hydraulic, coolant, or fuel system; sloughing-off of particulates from the thermal protective surface, insulation, or experiments; and outgassing from new components or various experiments.

Brief IECM Description

The IECM (fig. 1) is a 355-kilogram, desk size (121.3 centimeters long by 82.2 centimeters wide by 79.1 centimeters high) package and consists of 10 instruments designed to obtain environment and induced contamination measurements during preflight ground operations and ascent, on-orbit, descent, and postlanding operations. The 10 instruments and their functions are (1) a humidity monitor; (2) a dewpoint hygrometer, which measures water vapor content and air temperature on the ground and during ascent and descent; (3) an air sampler, which provides sampling for hydrocarbons, hydrogen chloride (HCl), and nitrogen oxide (NO) products in the cargo bay; (4) a cascade impactor, which measures size and quantity of airborne particulates in the cargo bay; (5) an optical effects module (OEM); (6) a passive sample array (PSA), which provides a measure of molecular contamination effects on optical properties as well as size distribution and effects of particulate accumulation; (7) a temperature-controlled quartz crystal microbalance (TQCM); (8) a cryogenic quartz crystal microbalance (CQCM), which measures nonvolatile residue at various temperatures; (9) a camera/photometer, which measures size, range, and velocity of on-orbit particulates as well as background brightness; and (10) a mass spectrometer, which measures quantity and mass of molecular flux. Table 2 gives the IECM instrument characteristics and description summary.

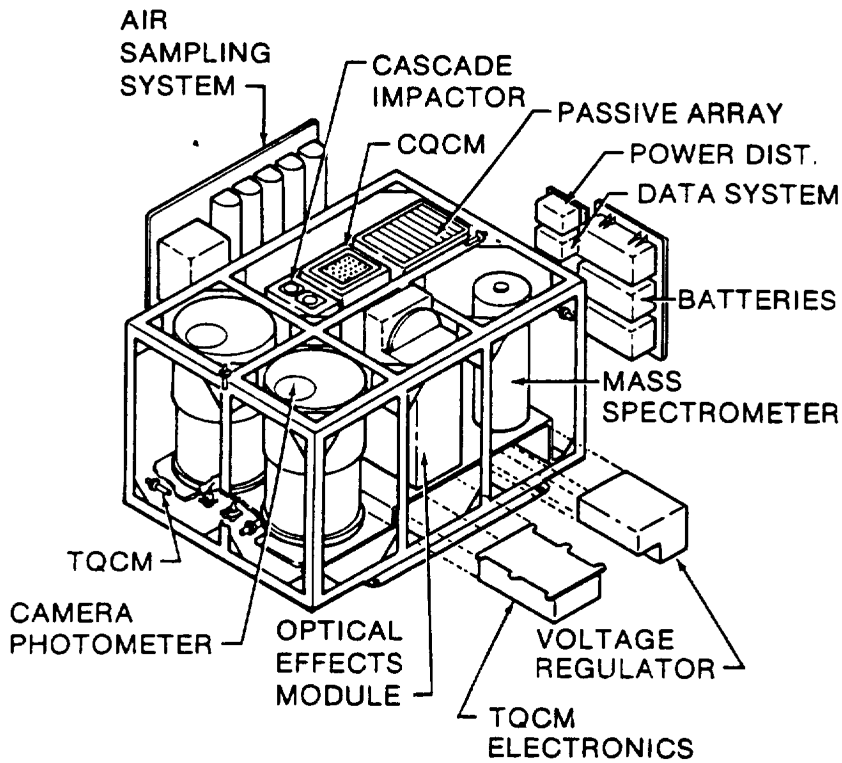


FIGURE 1.- INDUCED ENVIRONMENT CONTAMINATION MONITOR.

The IECM engineering subsystems consist of a programable, microprocessor-based data acquisition and control system (DACS), a power distribution and control unit (PDCU), and a thermal control system. Reference 3 gives a more complete description of the IECM instruments and subsystems.

The IECM and the release/attach mechanism (REM) were mounted on the DFI at station $x_0 = 1179$, $y_0 = 0$, $z_0 = 474$ (top center of IECM). The REM was developed at MSFC to provide release/attach capabilities for small payloads such as IECM and the University of Iowa's plasma diagnostic package (PDP).

Flight History

The IECM was installed in the Columbia for the STS-1 flight. It was later decided that the IECM would be deleted from the flight to improve weight margins. Considerable effort was made at this late date to install a passive optical sample assembly (POSA) to obtain some, albeit limited, contamination data from the first flight. Following the success of this effort, permission was obtained to install another POSA at the landing site for the ferry flight.

The IECM subsequently was flown on STS-2, STS-3, and STS-4. Between each flight, the entire package was returned to MSFC for refurbishment that included (1) postflight functional tests, (2) individual instrument refurbishment on changeout, (3) reprograming the DACS for next flight operational requirements, (4) cleaning and thermal vacuum bakeout, (5) installation of new batteries, and (6) preflight functional tests. Turnaround time for these activities at MSFC was as short as 10 days (between STS-3 and STS-4). The REM was also returned to the MSFC for checkout and refurbishment between each flight.

Measurements

The IECM measurements began on each mission following installation and checkout of the package in the Orbiter payload bay during the Orbiter Processing Facility (OPF) operations. Measurements of temperature, humidity, aerosols, hydrocarbons, and nonvolatile residues were made over a 12-hour period

TABLE 2.- IECM INSTRUMENT CHARACTERISTICS AND DESCRIPTION SUMMARY

Instrument (a)	Measurement	Operation (b)	Resolution
Humidity monitor	Relative humidity, temperature	GPL,A,D,PL	±0.5%
Dewpoint hydrometer	Dewpoint	GPL,A,D,PL	±0.5%
Air sampler	Gaseous contaminants	GPL,A,D,PL	~1 ppm
Cascade impactor	Particulate contamination of nonvolatile residue	GPL,A,O,D,PL	$\pm 1.5 \times 10^{-9}$ g
PSA	Optical degradation due to accumulated contamination	GPL,A,O,D,PL	(c)
OEM	Degradation of optics at 253.65 mm	GPL,O,D,PL	±0.8%
TQCM	Condensed molecular contamination at 213 to 303 K (-60° to +30° C)	GPL,A,O,D,PL	$\pm 1.56 \times 10^{-9}$ g
CQCM	Condensed molecular contamination at 133 K (-140° C) to ambient	GPL,A,O,D,PL	$\pm 1.65 \times 10^{-9}$ g
Camera/photometer	Particulate velocity, direction; photometry	O	25-μm particle at 1 m/s
Mass spectrometer	Molecular return flux	O	±1 count

[a]PSA = passive sample array, OEM = optical effects 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.
[c]Samples for lab analysis.

when Orbiter power was available and the payload bay doors were open. Dustfall and residues from the total stay time in the OPF were measured from PSA-exposed samples. On STS-4, the payload bay doors were opened on the pad and the preflight measurements were obtained for the periods between the OPF and the Payload Changeout Room (PCR) and during the time the payload bay doors were open to the PCR. These measurements were also performed during ascent and descent and after landing. In addition, air was sampled for exhaust gas products ingested into the payload bay.

The on-orbit measurements consisted of continuous monitoring of optical transmittance at a wavelength of 253.7 micrometers, return flux of molecular species emanating from the Orbiter, molecular mass deposition at various substrate temperatures, and particulates and induced brightness from scattered light. During the STS-4 mission, the IECM was maneuvered about the Orbiter to more directly measure outgassing, leaks, vernier reaction control system (VRCS) exhausts, and FES effects.

OTHER MEASUREMENTS

In addition to the aforementioned POSA and ferry flight POSA (flown on STS-1 to STS-4), Orbiter and payload facilities environment data were monitored by KSC personnel. Postflight nonvolatile residue measurements were made on the Orbiter radiator surfaces. Visual and laboratory measurements were made on various Orbiter and payload materials, surfaces, and paints (including the IECM paint) for contamination and environmental effects. Flight crewmembers were queried about contamination observations and impressions (window fogging, particles, engine firing, and water dump events). Onboard video and film photographs were reviewed for further information.

RESULTS AND COMPARISON TO GOALS

During the preflight 12-hour sampling periods, the IECM data showed that the facilities were within specifications for air temperature and relative humidity; 22° ± 2° C and 30 to 50 percent, respectively. Nonvolatile residue was not detected to $<10^{-7}$-g/cm² levels on surfaces exposed during the entire ground flow. (Goal is $<10^{-6}$ g/cm².) Table 3 gives the particle fallout measurements from the PSA during ground flow for STS-2 to STS-4. These results generally exceed Level 300A but show improvement on STS-4.

Particle accumulation was subsequently measured by the cascade impactor during ascent and descent, where redistribution is provided by airflows. These results are given in table 4 for different particle sizes contained in a volume of air. Comparing these results to 100K clean-room-air aerosol content goal, the results from STS-2 and STS-4 indicate that this goal was exceeded for particles as large as 5 micrometers diameter. These results are, however, highly dependent on assumed values for density and average diameter. The air sampler results indicate that engine exhaust products are not ingested into the payload bay during ascent or descent. Some volatile hydrocarbons were trapped and analyzed. Tables 5 and 6 summarize the air sampler results. Slight molecular mass depositions (~100 ng/cm²) detected on the TQCM's during the first minute after launch subsequently dissipated within 15 minutes.

Descent and postlanding temperatures of air pumped into the IECM air sampler manifold were between about 10° and 20° C and the relative humidity ranged between 15 and 25 percent on the three flights (figs. 2(a) and 2(b)). Ascent temperature change and relative humidity were not measurable in the dry nitrogen purge gas.

The on-orbit goals for molecular flux scattered back into the payload bay (-z-axis return flux) is $<10^{12}$ water (H_2O) molecules/cm²/s and mass deposition of $<10^{-5}$ g/cm²/30 days. Table 7 gives the mass spectrometer H_2O return flux and resultant calculated column densities for the three flights. This goal, a particular concern for infrared observations, was attained on the STS-3 mission, which was free from water absorption by the thermal protection system (TPS) as occurred on STS-2 and from hail damage as occurred on STS-4. The goal was exceeded, as anticipated, during door closing and primary reaction control system (PRCS) engine tests.

TABLE 3.- PREFLIGHT PARTICLE FALLOUT, PASSIVE SAMPLE ARRAY

Contamination specification	Averaged preflight exposure results	
Particle density - optical surfaces ≤ Level 300	STS-2	19 days exposure: OPF $\rho = 1.4 \times 10^4$ particles/cm² Level 750 to 1500
Orbiter Processing Facility (OPF) at KSC subjected to cleanup following rollout of STS-2	STS-3	19 days exposure: OPF $\rho = 6.5 \times 10^3$ particles/cm² Level 500 to 1500
During OPF operations, samples and instruments of the IECM designated for flight were protected by covers until final access prior to rollout	STS-4	5 days exposure: OPF $\rho = 1.3 \times 10^3$/cm² Level 500 to 750
		In-transit OPF-PCR (26 days) $\rho = 6.7 \times 10^2$/cm² Level 200 to 500
		16 days exposure in PCR $\rho = 5 \times 10^2$/cm² Level 300 to 750
		Samples exposed from first access OPF to last access PCR $\rho = 2.7 \times 10^3$/cm² Level 500 to 750

TABLE 4.- STS-2 to STS-4 SUMMARY RESULTS - CASCADE IMPACTOR

Measurement	Requirements	Mission	Results, μg/m^3	
			Ascent	Descent
>5-μm size particles	<375 μg/m^3 (assuming d = 25 μm, ρ = 2 g/cm^3)	STS-2	~30	~10
		STS-3	~10	~10
		STS-4	Non-functional	~20
1- to 5-μm size particles	<100 μg/m^3 (assuming d = 5 μm, ρ = 2 g/cm^3)	STS-2	~500	~250
		STS-3	<10	<10
		STS-4	~400	~10
0.3- to 1-μm size particles	<10 μg/m^3 (assuming d = 1 μm, ρ = 2 g/cm^3)	STS-2	~250	~125
		STS-3	<10	<10
		STS-4	≈150	Non-functional

TABLE 5.- INDUCED ENVIRONMENT CONTAMINATION MONITOR - AIR SAMPLER RESULTS: CONTAMINANT TOTALS FOR REPRESENTATIVE ASCENT AND DESCENT PHASES

Location	Species	Levels expected, spec.	Detection method (a)	Observed
Ascent	Volatile hydrocarbons[b]	Unknown, no spec.	A	~50 ppm by weight, ~10 ppm by volume[b]
Ascent	Reactive HCl	Unknown, no spec.	B	None detected to 1 ppm sensitivity
Descent	Reactives NO, NO_2, NH_3	Unknown, no spec.	C	None detected to 1 ppm sensitivity
Descent	Volatile hydrocarbons[b]	Unknown, no spec.	A	~20 ppm by weight, ~4 ppm by volume[b]

[a]A - concentration on adsorbent; postflight gas chromatograph/mass spectrometer (GC/MS) analysis.

B - reaction with silver oxide/hydroxide surfaces; postflight analyses by electron spectroscopy for chemical analysis (ESCA).

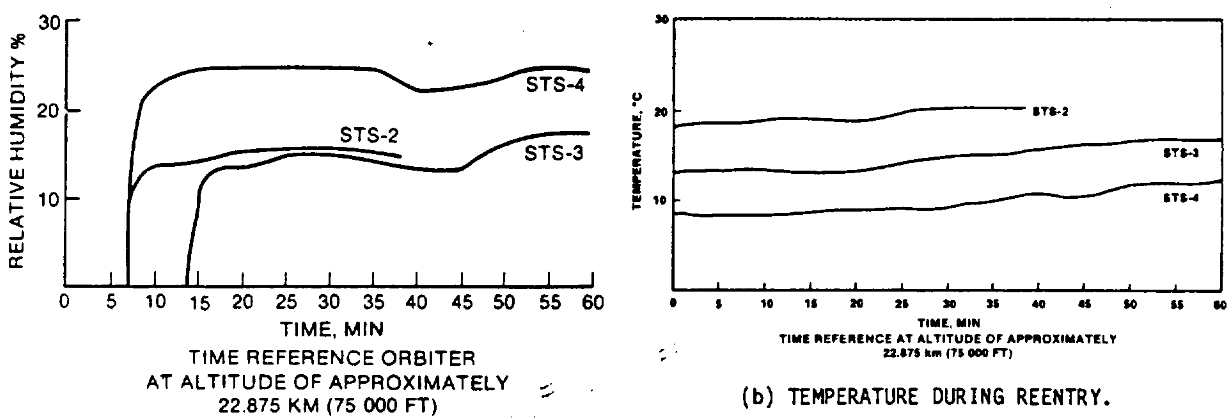
C - reaction with ruthenium trichloride surfaces; postflight analyses by ESCA.

[b]Covers C_9 to C_{24} range and uses ~C_{12} as average molecular weight to obtain ppm by volume.

TABLE 6.- AIR SAMPLER RESULTS: CONTAMINANT TOTALS FOR REPRESENTATIVE STS GROUND, ASCENT, AND DESCENT PHASES

Mission phase	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 adsorbent; postflight GC/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.



(a) RELATIVE HUMIDITY DURING DESCENT.

(b) TEMPERATURE DURING REENTRY.

FIGURE 2.- IECM MEASUREMENTS ON STS-2 TO STS-4.

Table 8 gives a summary of -z-axis mass deposition at a sensor temperature of 30° C, also extrapolated to 30 days for STS-3 and STS-4. (STS-2 -z-axis TQCM sensor was inoperative.) Only for a short period of time on STS-3 did the deposition rate exceed 1×10^{-5} g/cm²/30 days. Further, table 9 gives a similar summary for an average of all five TQCM sensors (±x, ±y, -z directions). These data indicate that mass depositions on surfaces with direct views to the Orbiter should not be significant. The CQCM (-z-axis) sensors, with temperatures ranging between -101° and 35° C, indicated even less total mass accumulation during the missions, ranging from 3.5×10^{-6} g/cm²/30 days on STS-2 to negative values on STS-4. The OEM optical samples showed 1 to 2 percent increased transmittance trends, and the mass spectrometer indicated insignificant return flux for masses greater than 50 amu.

The TQCM, the CQCM, and the mass spectrometer were used to monitor the STS-3 PRCS engine test (L2U test). The accumulation on the QCM's dissipated with 1/e time constant of about 15 minutes at 30° C sensor temperature. The mass spectrometer measured pressures to its limit of about 5×10^{-5}

TABLE 7.- H_2O RETURN FLUX AND CALCULATED COLUMN DENSITIES

Mission	Return flux, particles/cm^2-sr-s		Column density, particles/cm^2	
	Maximum[a]	Final	Maximum	Final
STS-2[b]	1.5×10^{14}	1.8×10^{13}	2.0×10^{13}	2.7×10^{12}
STS-3	9.8×10^{11}	2.6×10^{11}	1.5×10^{11}	4.0×10^{10}
STS-4	2.1×10^{14}	6.6×10^{12}	3.2×10^{13}	1.0×10^{12}

[a]Except for PRCS firings and payload bay door closings.
[b]The STS-2 values are considered upper limits.

TABLE 8.- DATA FROM -Z-AXIS TQCM MASS DEPOSITION SENSORS AT 30° C EXTRAPOLATED TO 30-DAY MISSION

MET, hr	Mission	Measured value, ng cm^{-2} hr^{-1}	Value extrapolated to 30-day mission, gm cm^{-2}/30 days
003.8	STS-3	<0	<0
016.6	STS-4	5.7	4.1×10^{-6}
021.9	STS-3	14.6	1.0×10^{-5}
034.9	STS-4	3.2	2.3×10^{-6}
040.0	STS-3	1.0	7.2×10^{-7}
058.0	STS-3	0	0
076.0	STS-3	<0	<0
084.7	STS-4	.4	2.9×10^{-7}
102.9	STS-4	4.2	3.0×10^{-6}
112.5	STS-3	14.8	1.1×10^{-5}
121.4	STS-4	4.2	3.0×10^{-6}
125.7	STS-3	<0	<0
139.5	STS-4	7.6	5.5×10^{-6}
157.9	STS-4	<0	<0

TABLE 9.- DATA FROM ALL TQCM SENSORS AT 30° C EXTRAPOLATED TO 30-DAY MISSION

MET, hr	Mission	Measured value, ng cm^{-2} hr^{-1}	Value extrapolated to 30-day mission, g cm^{-2}/30 days
2.1	STS-2	<0	<0
3.8	STS-3	<0	<0
13.8	STS-2	20	1.4×10^{-5}
16.6	STS-4	<0	<0
21.9	STS-3	5	3.6×10^{-6}
25.4	STS-2	7.7	5.5×10^{-6}
34.9	STS-4	1.8	1.3×10^{-6}
38.2	STS-3	4.6	3.3×10^{-6}
40.0	STS-3	23	1.7×10^{-5}
50.0	STS-2	22.6	1.6×10^{-5}
58.3	STS-3	9.7	7.0×10^{-6}
76.3	STS-3	7.9	5.7×10^{-6}
84.7	STS-4	<0	<0
94.4	STS-4	35.3	2.5×10^{-5}
102.9	STS-4	2.5	1.8×10^{-6}
112.5	STS-3	11.1	8.0×10^{-6}
121.4	STS-4	3.8	2.7×10^{-6}
125.7	STS-3	<0	<0
139.5	STS-4	2.7	1.9×10^{-6}
157.9	STS-4	<0	<0

torr during door closings. Partial pressures of carbon dioxide, also a concern for infrared observations, were insignificant.

The STS-4 contamination mapping with the IECM using the remote manipulator system (RMS) results indicate qualitative agreement of direct molecular flux and return flux outgassing levels of high molecular weight (>50 amu) too small to be quantified, and cabin leakage was not detectable. A Freon 21 leak in the FES/cooling system loop was clearly detected.

More detailed IECM results are given in references 4 and 5. The camera/photometer stereopair provided 0.24-steradian (32°) field-of-view film records of contaminant particles as small as 25 micrometers illuminated by the Sun against a dark sky or Earth background, and background brightness levels during these periods as well as levels during orbital nighttimes. A summary of particles detected during the first 48 hours of the missions is given in figure 3, excluding water dumps. Only the first 48 hours are shown because of the short mission time of STS-2 and camera failure at 50 hours mission elapsed time (MET) on STS-3. On STS-4, continued low levels of particles are shown beyond 48 hours. The particle population goal is less than one 5-micrometer particle/orbit in a 1.5 × 10^{-5}-steradian field of view. After about 15 hours MET, the number of >25-micrometer particles observed is about 0.03/orbit in a 1.5 × 10^{-5}-steradian field of view, sufficiently small to make it unlikely that the goal would be exceeded significantly by smaller particles. During water dumps, the particulate count is very high, again as expected and excluded by the goal definition (>100/frame), and the scattered light from the particles limits the photometer-controlled exposure to 1 second. When the water dumps are terminated, the particle count decays rapidly with a time constant 1/e of 5 minutes as shown in figure 4. Particle count increases have not been seen with operation of the FES.

Sky background brightness after about 15 hours MET and during the absence of water dumps consistently shows no difference during orbital nighttimes and daytimes, indicative of no contribution from molecular or particulate scattering, which is a requirement goal. Stars as faint as $m_v = 10$ are consistently seen during these day and night observations; the exposures were terminated by integrated starlight in both cases. No evidence has been found of light that can be attributed to the glow phenomenon.

ENVIRONMENT INTERACTIONS

The OEM and PSA samples show no discernible optical or physical effects on such optical materials and coatings as lithium fluoride, calcium difluoride, magnesium difluoride (MgF_2), barium difluoride,

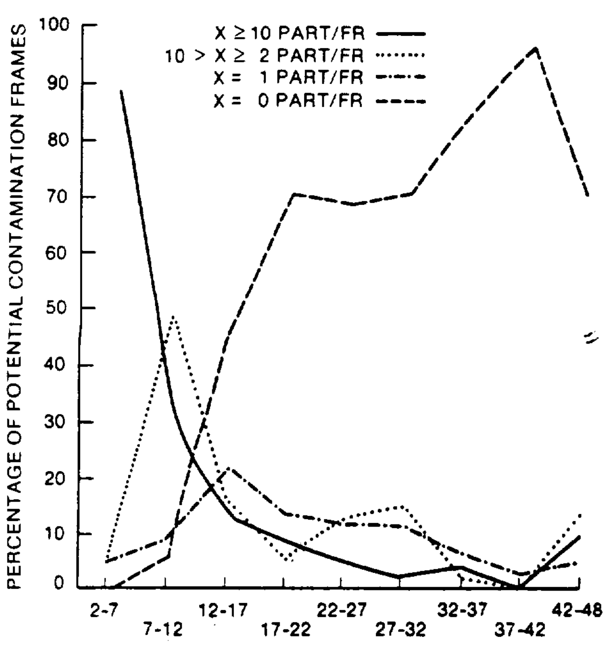


FIGURE 3.- PARTICLE DENSITY ON FRAMES.

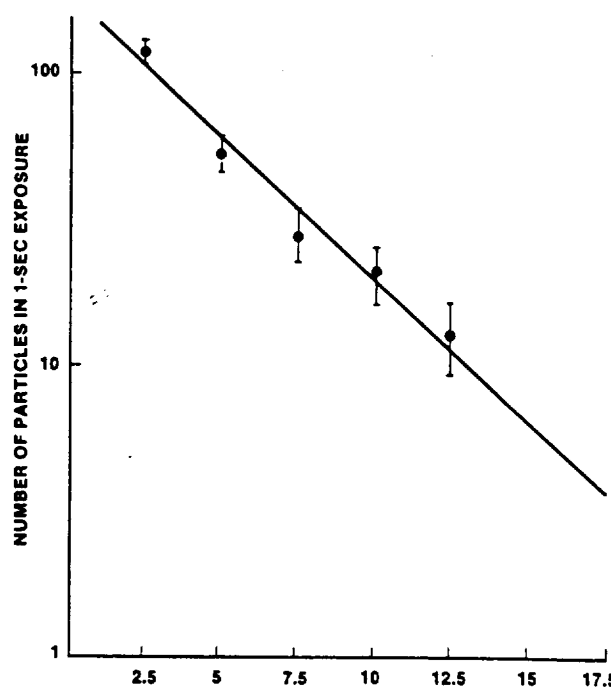


FIGURE 4.- PARTICLE COUNT DECAY AFTER WATER DUMP TERMINATION.

sapphire, crystalline quartz, fused silica, gold, platinum, MgF_2 over aluminum, and pyrex. Some coatings, however, apparently formed oxide resulting from the exposure to oxygen atoms. Thin films of osmium (15 nanometers) on fused silica flown on STS-3 and STS-4 were removed, presumably, by the formation of osmium tetroxide, which has a vapor pressure of 760 torr at 25° C. A vacuum-deposited 300-nanometer carbon film and a 255-nanometer silver film, both on quartz, were added to STS-4. The carbon film was removed and the silver film was converted to a transparent blue-green film, determined to be Ag_2O (ref. 6).

Silver-plated nuts on the PSA and the fixed part of the REM for the PDP showed apparent heavy oxidation, even though located such that a direct view to space was never possible. Osmium films deposited over a flash coating of nickel were flown on STS-5. The samples were positioned to have both direct and indirect view to space. The results indicate that most, if not all, of the osmium was removed (ref. 7).

Leger (refs. 8 and 9) has reported weight loss of various organic materials exposed to atomic oxygen. Mass measurements on Kapton surfaces showed losses of as much as 4 to 5 micrometers thickness on STS-3. Other film samples and Orbiter organic paints showed effects such as mass loss and loss of binder, leaving pigment-rich surfaces. The S13G silicone-based paint on the IECM, however, did not degrade physically or optically during the mission.

OPEN ISSUES

Several of the requirements and goals listed in table 1 could not be completely verified using IECM data. One example not completely verified is the particle environment during the on-orbit phase of flight since the IECM camera particle size detection limit is 25 micrometers and the goal addresses particle size down to 5 micrometers. Verification of this requirement will require data generated by a cryogenically cooled infrared telescope. Such a device is planned for flight on the Spacelab II mission, and plans have already been made to examine data generated by this system for contamination effects. Data from other near-term payloads will also be examined and used to provide a complete definition of the environment and acceptable operational techniques for hopefully all types of payloads.

One aspect of the Shuttle system which was not covered by the use of the IECM was contamination of the upper stages. Measurements now being planned should provide the necessary data.

The complete approach for control of contamination during ground turnaround is still being developed. 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 which developed during preparations for launch of the Tracking and Data Relay Satellite A (TDRS A) on STS-6. With the emphasis generated by this event and some additional test data, detailed contamination control procedures which will be acceptable to all can be developed.

CONCLUSIONS

The Space Shuttle contamination control program has been completed with the measurements of the environment made during the orbital flight test program using the IECM. Performance of the Shuttle system has been assessed by comparing the measured environment with the contamination requirements and goals developed by the two contamination working groups. This comparison shows that, in general, where measurements were performed, contamination requirements and goals have been met. Molecular contamination, in terms both of gaseous and condensable species, is below the requirement levels and should be adequate for all payloads with minimal need for covers or other forms of protection. Particle release rates during quiescent periods appear to be within the requirements established based on cryogenic infrared telescope needs. Further measurements are required to fully verify this requirement for particles smaller than 25 micrometers. Except for surface glow effects first observed and photographed on STS-3, light background levels in the visible spectral region are within required levels. Verification of this requirement for the infrared and utraviolet spectral regions will have to await further elements by near-term payloads. Light emitted by the primary and vernier reaction control system jets during firings may require changes from standard operational techniques for certain contamination-sensitive payloads.

Ground contamination control needs additional definition of procedures to be used for payload integration and ground facility operation. Part of the higher than expected particle content in the payload bay during ascent may be due to a lack of implementation of adequate control during ground turnaround for the early Shuttle missions. This situation should improve with continued emphasis and the development of a significant experience base.

The approach used for the development of the contamination control program was very effective in developing a system with excellent performance and in defining 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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