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Contamination Design Analysis Approach for Spacelab

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An approach for predicting the induced contaminant environment of the Spacelab vehicle is presented. This approach employs state-of-the-art computer modeling techniques in conjunction with selected materials testing and systems level contamination analysis. Contamination control criteria, as established by the Spacelab payload user community, is used as the basis for the evaluation. Procedures for the verification of the accuracy of the analytical tools utilized in this evaluation are briefly summarized. The current technical assessment of the contamination problems anticipated during the Spacelab program is discussed and recommendations for contamination abatement designs and operational procedures are presented.

Introduction

MUCH has been written in recent years on the subject of the Space Transportation System (STS) Space Shuttle Orbiter induced contaminant environment and its ultimate impacts upon scientific instrumentation and sensitive systems flown as payloads within the Orbiter payload bay.[1-3] Equally as important is the induced environment of the Spacelab vehicle being designed and developed as a prime reusable Shuttle payload. Spacelab contamination will be additive to the environment of the Shuttle Orbiter and must be considered as a primary design parameter in its development. Proper contamination control of the Spacelab vehicle is potentially even more critical than for the Shuttle Orbiter due to its inherent close proximity to scientific instrumentation within the payload bay. This area of concern was recognized early in the Spacelab program and the need was identified for rigorous contamination modeling and analysis studies to predict the Spacelab induced contaminant environment, determine its compliance with program contamination control criteria, and establish recommended contamination abatement procedures and on-orbit operations.

The contamination control criteria for the STS/Spacelab were established by the scientific user community to document the limits and guidelines for spacecraft designers to consider in their final products. Included in the criteria are limitations on: 1) the total number of contaminant molecules along a scientific instrument line-of-sight; 2) the number of particles appearing within a scientific instrument's field-of-view; 3) the background brightness induced by scattering or emission of radiant energy by the contaminant environment; 4) the return flux of contaminant molecules to a sensitive surface resulting from collisions with the ambient atmosphere; and 5) the level of contaminant deposition and/or the resulting absorption of radiant energy on a sensitive surface. The interpretation of these criteria as translated into the ultimate Spacelab design through use of state-of-the-art analytical tools and procedures is the major purpose of this evaluation.

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Spacelab Modeling and Analysis

Major Model Parametric Considerations

A primary design goal for the various Spacelab configurations is to insure that the operation of Spacelab/Orbiter systems and the mission objectives of scientific instruments are not compromised by the induced molecular and particulate contaminant environment emanating from the Spacelab carrier. To accomplish this, a rigorous computer modeling and analysis study has been conducted to establish the predicted on-orbit contaminant environment levels under variable orbital operating conditions. This study served as the basis for developing Spacelab contamination related design and operational requirements necessary to meet the maximum allowable induced environment levels or criteria as set forth in Ref. 4, Vol. X. These criteria, presented later herein, have been accepted for application as a design goal for Spacelab.

The primary analytical tool utilized in this study was the Shuttle/Payload Contamination Evaluation Program (SPACE) which was developed to mathematically synthesize the contaminant sources, susceptible surfaces, and transport mechanisms; and to establish the predicted induced contaminant environments of the Spacelab carriers modeled. The general modeling considerations and approaches employed are discussed in Ref. 5. In the subsections that follow, brief descriptions of the current modeled Spacelab configurations, contaminant sources, major SPACE program input parameters and assumptions are presented.

The accuracy of the SPACE computer program has been previously verified in part by flight data obtained from sensors and instruments flown on Skylab, the Atmospheric

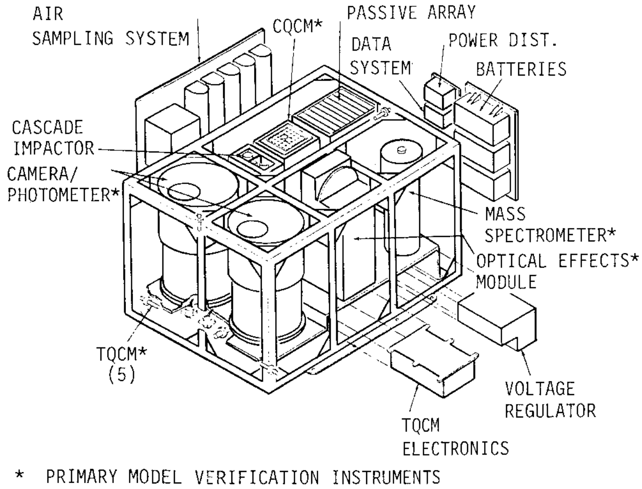

Fig. 1 Induced environment contamination monitor configuration.

Explorer Satellite and the National Oceanographic and Atmospheric Administration/Infrared Television Observation Satellite programs.[6] The Induced Environment Contamination Monitor (IECM) to be flown as Verification Flight Instrumentation (VFI) on the first two STS/Spacelab missions will provide an ideal opportunity for additional SPACE program verification through induced environment modeling as discussed herein and subsequent comparison with acquired flight data. The current IECM instrument complement and configuration is illustrated in Fig. 1. The IECM consists of a variety of scientific instrumentation ranging from thermoelectric and cryogenic quartz crystal microbalances (TQCM's and CQCM's) to mass spectrometers and photometers. The instrumentation mix has been selected to verify that the JSC 07700[4] requirements are satisfied and to establish a baseline environment data base for "typical" STS/Spacelab missions.

The IECM will be flown on the early Shuttle Orbital Flight Test (OFT) flights in addition to the Spacelab VFI missions and will, therefore, establish contamination levels under a variety of operating conditions. The SPACE program will be exercised with input parameters consistent with the IECM instrument configurations, temperatures, etc., and the OFT and Spacelab mission parameters as shown in Fig. 2. SPACE program validation will be accomplished by predicting contamination levels for parameters consistent with applicable IECM measurements. The model will predict molecular number/mass column densities, return flux, and deposition levels. These parameters will then be used to compute background spectral intensity, optical surface degradation, and line-of-sight absorption through separate subprograms/analyses. In the verification process not only will the Spacelab carrier be modeled, but the STS Orbiter will require consideration as well. By comparison of data obtained during the early non-Spacelab OFT missions and the subsequent Spacelab missions, contributions chargeable to Spacelab can be determined and correlated with SPACE program predictions. Once the verification process has been completed and necessary adjustments have been made to the SPACE program code, the accuracy of the model as a basic design, development, and mission planning analytical tool will have been demonstrated.

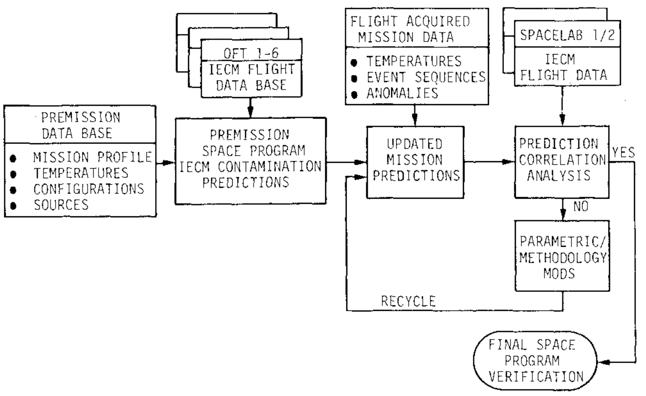

Fig. 2 SPACE program verification approach.

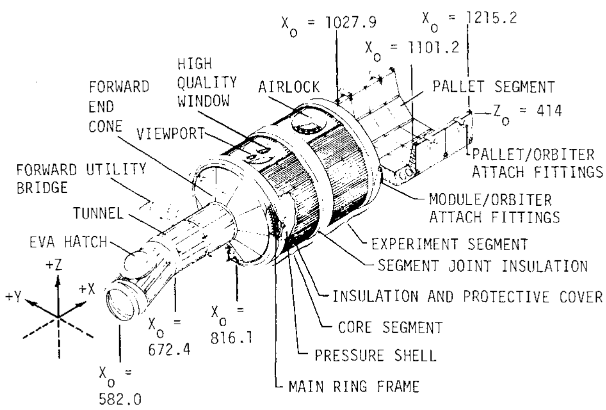

Fig. 3 Baseline long module/one pallet Spacelab configuration.

Modeled Spacelab Configurations

The current SPACE program includes three unique Spacelab configurations deemed representative of the assorted module and pallet hardware combinations that will be utilized throughout the Spacelab program. The modeled Spacelab configurations include: 1) the long module/one pallet (LMOP), 2) the short module/three pallet (SMTP), and 3) the five pallet (FIVP). Geometrical data utilized in establishing the necessary model input parameters for these configurations were obtained from Ref. 7. Figure 3 illustrates the basic LMOP configuration elements utilized in the geometrical modeling. Note that the axis system and station numbers (X_0, Y_0, Z_0) presented are consistent with those of the Shuttle Orbiter coordinate system. The primary purpose for developing the geometrical configurations is to establish the spatial relationship between all Spacelab contaminant

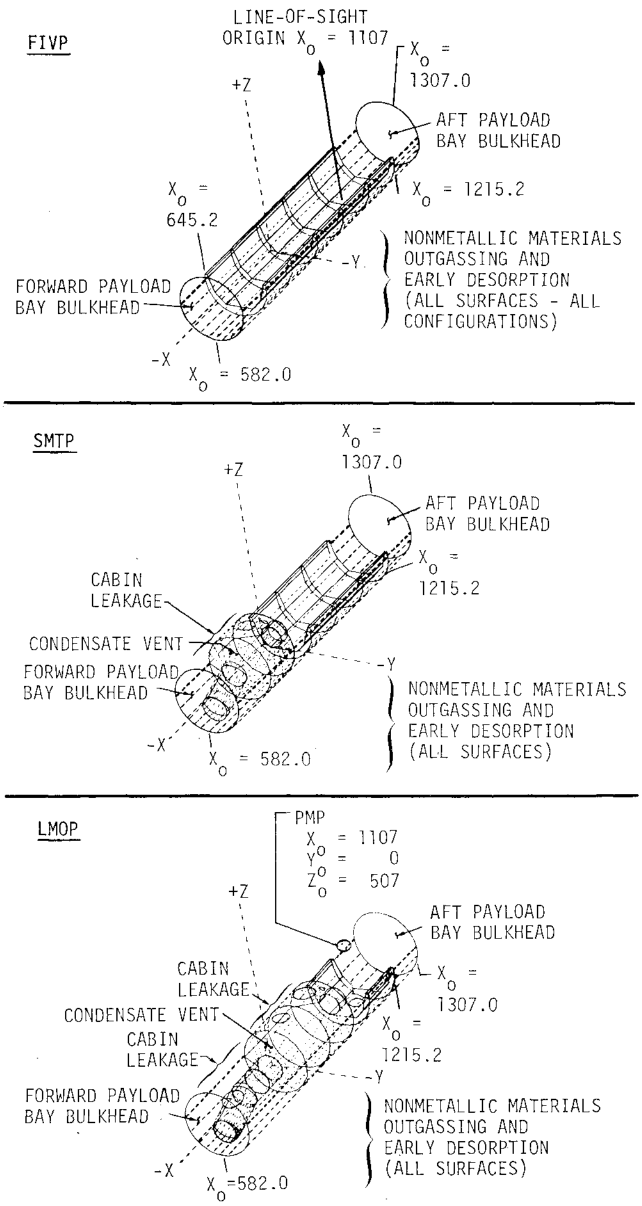

Fig. 4 Modeled Spacelab configurations and contaminant sources.

sources and surfaces in the form of mass transport factors (MTF). The MTF represents the percentage of mass leaving a Lambertian source or surface capable of reaching another point or surface based upon geometry and surface shadowing between sources and receivers. When input to the SPACE program, the MTF formulates the mechanism for describing the Spacelab induced contaminant environment.

The three modeled Spacelab configurations were segmented nodally and displayed graphically by the computer as depicted in Fig. 4. The nodal breakdown of each configuration is used as the prime reference system between the configuration and contaminant source parametric data such as the materials mass loss characteristics and surface temperature profiles. A modified Thermal Radiation Analysis System (TRASYS-II)[8] computer code was utilized to establish the necessary geometrical relationship input data to the SPACE program.

In order to establish consistency between the three modeled configurations, they were each located within the Orbiter payload bay envelope between $X_0 = 582.0$ and $X_0 = 1215.2$ as depicted in Fig. 4. Hardware locations within the bay will vary depending upon physical interface considerations, but the envelope utilized establishes a consistent reference for analytical comparisons. The payload bay surfaces (representative of the Orbiter payload by liner) shown in Fig. 4 are included in the model for surface shadowing characteristics but are not considered to contribute to the Spacelab induced environment.

The SPACE program evaluates the contaminant transport directly between a source and a receiving surface as well as the physics of the contaminant cloud in the near vicinity of the Spacelab. The major items included therein are the phenomena of the column density or "thickness" of the induced environment through which a payload must view and the return flux (or backscatter) of released contaminant molecules to a surface of interest resulting from molecular collisions with the ambient atmosphere or with other contaminant molecules (self-scattering). To evaluate these phenomena, seventeen lines-of-sight for each Spacelab configuration have been geometrically modeled. Along each of these lines-of-sight which originate at $X_0 = 1107$, $Y_0 = 0$, and $Z_0 = 507$ (Fig. 4), a series of "pseudo surfaces" were input to the model as point contaminant receivers. The point of origin is consistent with the Prime Measuring Point (PMP) for contamination control criteria evaluation. Note that the modeled lines-of-sight uniformly encompass a 120-deg conical viewing volume around the $+Z$ axis above the Spacelab configurations as illustrated in Fig. 5 for the SMTP.

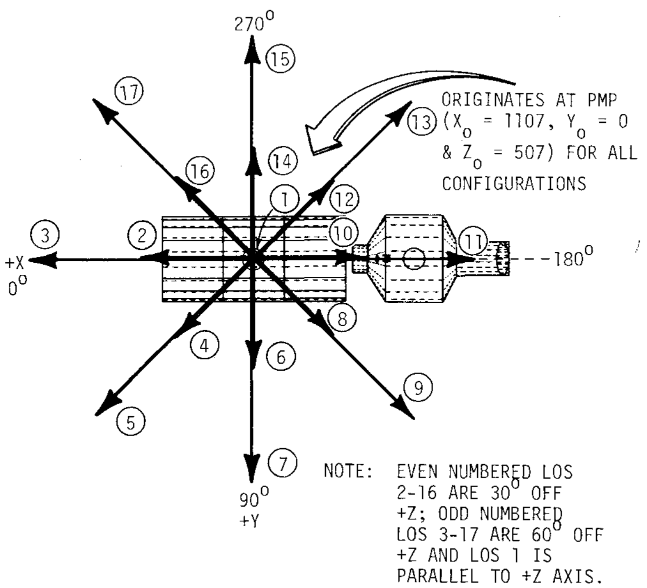

Fig. 5 Modeled Spacelab lines-of-sight.

Spacelab Contaminant Sources

The modeled Spacelab carrier configurations currently have four major indentified contaminant sources. These include: 1) external nonmetallic materials outgassing (i.e., the long-term mass loss of the material upon exposure to space vacuum), 2) early desorption from external surfaces (i.e., the initial high mass loss of adsorbed and absorbed volatiles, gases, and liquids), 3) cabin atmosphere leakage from pressurized tunnel and module segments, and 4) the Spacelab Condensate Vent (SCV). Figure 4 should be consulted for the locations of the modeled contaminant sources for each of the three Spacelab configurations.

These sources were treated as closed-form mathematical expressions, which physically approximate the contaminant emission processes involved. A parametric summary of the methodology and assumptions utilized in the modeling of these sources and the primary considerations involved in determining the major expressions and relationships are presented in the following paragraphs. It was determined through the modeling activities that the major contaminant transport mechanism of concern to Spacelab and its payloads was the phenomena of return flux through ambient interaction, since most Spacelab/payload sensitive surfaces do not possess direct lines-of-sight to the contaminant sources.

Outgassing

Nonmetallic materials outgassing was modeled as a continuous Lambertian contaminant source with an emission rate that is a direct function of surface temperature and time of exposure to the vacuum of space. The design of the external Spacelab thermal control system has apparently been finalized and isothermal total mass loss/volatile condensible material (TML/VCM) test data on the chosen nonmetallic materials has been developed. The current Spacelab passive thermal control system design incorporates Chemglaze II A-276 white paint as the thermal control coating for all internal and external pallet surfaces and multilayer insulation (MLI) as the thermal blanket for the module and tunnel sections of Spacelab.

Thermal vacuum test data on these materials are contained in Refs. 9 and 10, respectively. Figure 6 depicts the variation of Chemglaze and MLI TML rates and outgassing rates as a

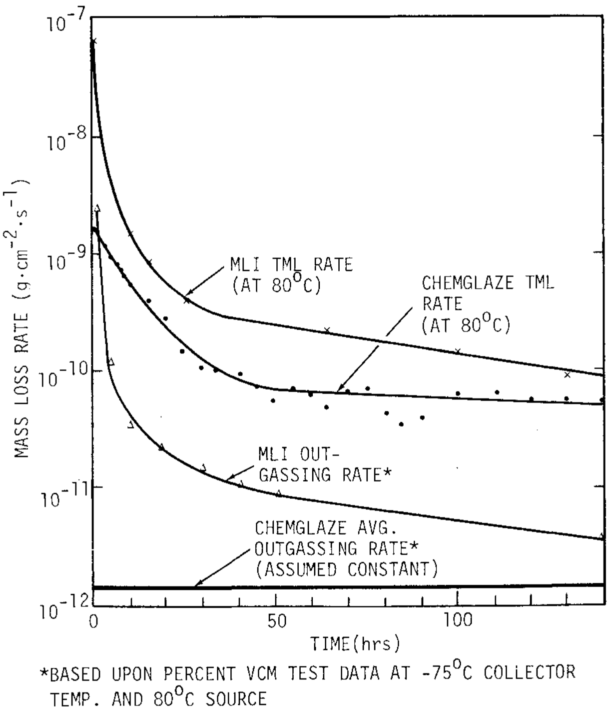

Fig. 6 MLI and Chemglaze II mass loss variation with time.

function of vacuum exposure time at a sample test temperature of 80°C. Outgassing rates for these materials were determined from deposition data in percent VCM for a −75°C Quartz Crystal Microbalance (QCM) deposition monitor by assuming that the sticking coefficient of the large molecular weight outgassing species was unity at that temperature. Chemglaze II percent VCM[9] results were obtained only at the end of the entire 165-h test; therefore, only the average outgassing rate could be determined. In contrast, data on the MLI[10] were presented in terms of percent $VCM \cdot s^{-1}$ and the MLI outgassing decay curve could be established. The outgassing data in Fig. 6 are for a first flight Spacelab vehicle. For any subsequent Spacelab missions (assuming no major refurbishment is required), the outgassing decay curves will essentially pick up in the time history point at the end of the previous mission.

The derived average outgassing rates at 125°C (OGR_{125}) were $1.33 \times 10^{-11} g \cdot cm^{-2} \cdot s^{-1}$ for Chemglaze II and $1.29 \times 10^{-9} g \cdot cm^{-2} \cdot s^{-1}$ for the module MLI. Outgassing rates are input to the SPACE program at the 125°C reference temperature and are then adjusted internal to SPACE for individual nodal surface temperatures. This temperature dependence can be described analytically as

$$OGR_T = OGR_{125} \cdot \exp[(T-125)/K] \qquad (1)$$

where

T = source temperature (°C)
K = material characteristic constant (approximately 20 for Chemglaze and 11 for MLI)

By utilizing the percent VCM data at different QCM temperatures, the outgassing component sticking coefficient variation with temperature was approximated for the MLI and Chemglaze II coatings. Again, by assuming that the sticking coefficient approaches unity at −75°C, sticking coefficients at other temperatures are simply the ratios of the percent VCM at temperature T_c divided by the percent VCM at −75°C. Figure 7 presents the sticking coefficient variation with collector temperature T_c for MLI and Chemglaze II samples held at $T_s = 80°C$. Superimposed on Fig. 7 is the Skylab-derived sticking coefficient relationship used in previous analyses for comparison.

Early Desorption

A similar approach was utilized in modeling the phenomena of early desorption; however, in contrast to outgassing, the early desorption rate tends to decay more rapidly upon initial exposure to space vacuum. In addition, early desorption mass loss characteristics will be repeatable from mission to mission since this source results primarily from absorbed and adsorbed atmospheric gases and liquids. The test data depicted in Fig. 6 were again used to establish the required SPACE program input parameters. Early desorption rates were determined by taking the difference between the TML rate and the outgassing rate as a function of time for each material. Primary constituents of early desorption and their mole fractions include: water (0.57), nitrogen (0.23), carbon dioxide (0.12), and oxygen (0.08). The results presented herein are based upon the early desorption rates at 10 h into the mass loss decay curve. The 10-h point was selected to obtain worst-case predictions for payloads at the point in a typical mission when activation of susceptible instruments might be expected to commence. Early desorption rates at 100°C (EDR_{100}) were determined to be $1.29 \times 10^{-9}\ g \cdot cm^{-2} \cdot s^{-1}$ for Chemglaze II and $4.43 \times 10^{-9} g \cdot cm^{-2} \cdot s^{-1}$ for MLI at 10 hours. Early desorption temperature dependence was modeled as

$$EDR_T = EDR_{100} \cdot \exp\left[\frac{E}{R}\left(\frac{1}{373} - \frac{1}{T}\right)\right] \qquad (2)$$

where

T = source temperature (K)
E = source activation energy (7500 $cal \cdot mole^{-1}$ assumed)

Cabin Atmosphere Leakage

The module and tunnel segments of the LMOP and SMTP Spacelab configurations are pressurized to 14.7 psia with a nominal mix of oxygen and nitrogen. Leakage from these segments will occur through cracks, seams and structural penetrations at a maximum rate of 1.35 kg per day.[7] The mole fractions of the emitted molecular constitutents will be approximately 0.758 nitrogen, 0.219 oxygen, 0.007 carbon dioxide, and 0.016 water. This leakage is modeled as a continuous steady-state Lambertian source assuming uniform emission from the external surfaces of the pressurized Spacelab segments.

Spacelab Condensate Vent

The SCV, located on the upper forward cone of the Spacelab module, is a controllable overboard liquid dump system which emits condensed water and trace cabin atmospheric contaminants at a nominal flow rate of 4.5 $kg \cdot min^{-1}$. The SCV is scheduled for only one operation of 7- to 17-min duration for each seven days on-orbit; therefore, timelining of the SCV for contamination avoidance should not be difficult. The nozzle design of the SCV is similar to that of the Skylab contingency condensate vent employing a double-tapered exit orifice 2.45 mm in diameter and a heater system to inhibit nozzle freeze-up.

The SCV will produce copius amounts of water/ice particles and water vapor (approximately 15% by weight) during

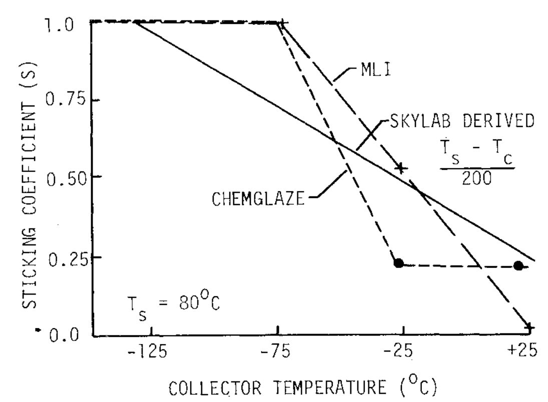

Fig. 7 MLI and Chemglaze II sticking coefficient relationships.

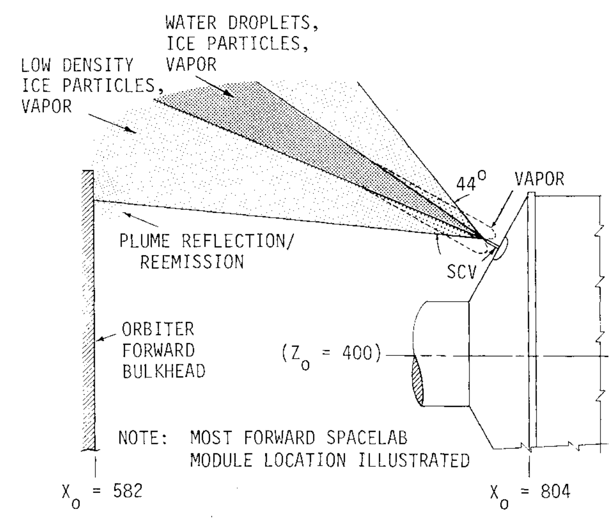

Fig. 8 Spacelab condensate vent plume definition.

operation. The primary contamination concern other than proper timelining is the potential frost layer/snowcone buildup on Orbiter and Spacelab structural surfaces resulting from SCV plume impingement. This would result in an additional unpredictable contaminant source which would be impossible to control. Small vacuum chamber test data on the SCV[11] illustrated in Fig. 8 indicate that plume impingement on the Orbiter payload bay forward bulkhead has been minimized but not totally eliminated for the forwardmost Spacelab module positions within the bay (i.e., worst-case location). The main core and lower density region of the SCV plume will be confined to approximately a 22-deg conical half angle; however, the overexpanded vapor region of the plume distribution as pictured may have been restricted by the confines of the small (0.4-m-diameter) vacuum chamber employed in the test. This may present some condensation problems; therefore, as a precaution, it would be advisable to allow the payload bay area to heat soak under solar exposure during venting operations.

Environment Evaluation

The set of contamination control criteria applicable to the Spacelab vehicle is depicted in Table 1. It was initially formulated by the STS payload user community and is documented in Ref. 4. These criteria establish the on-orbit induced environment level constraints which are not obviously correlatable with basic Spacelab design parameters. The necessary translation between criteria and design has been accomplished through use of the SPACE program in conjunction with supplemental systems analysis. Because of the dependence of the current model format upon the contamination control criteria, it is important to note the additional assumptions and interpretations that are required to make the abbreviated criteria statements more applicable and useful in the design and development studies. These interpretations, presented in Table 1, demonstrate the reasoning behind the modeling decisions and approaches employed and reflect the supplemental inputs to Ref. 4 established by the cognizant scientific community to standardize the contamination evaluations.

The induced environment predictions presented herein for the Spacelab configurations have been formatted to be compatible with the baseline contamination control criteria[4] as interpreted by the scientific user community. These predictions were in turn utilized to determine the ability of the various Spacelab configurations to meet the existing criteria and to establish Spacelab design and development requirements to insure that each major Spacelab contaminant source would comply with the five criteria statements. In the ensuing subsections, predictions for each of the major Spacelab sources are presented, along with an evaluation of compliance with the criteria and the corresponding design/operations impact assessment.

Molecular Number Column Density (NCD)

The primary concern of the NCD (or contaminant cloud thickness) parameter is its propensity to scatter, emit, or absorb radiant energy, thus interfering with the data acquisition ability of sensitive optical experiments. The corresponding contaminant pressures in the proximity of high-voltage power systems can also induce such phenomena as corona arc-over damage and multipacting of transmitting systems. To evaluate this, 17 fixed lines-of-sight for each Spacelab configuration are currently in the SPACE program for which NCD predictions have been made. These lines-of-sight (illustrated in Fig. 5) encompass the 120-deg conical viewing volume stipulated in Table 1. NCD predictions for the continuous Spacelab surface sources are presented in Table 2 for the three modeled configurations. Nonmetallic surface material NCD predictions are based upon the maximum hot case Spacelab thermal profile and the Spacelab materials test data previously discussed. The predicted NCD levels for outgassing and leakage will remain relatively constant throughout a Spacelab mission; however, the early desorption NCD levels will decrease rapidly as the early desorption rate decays with time of vacuum exposure. The primary contamination threats from early desorption will, therefore, be limited to the initial on-orbit phases of a given mission.

The modeled sources which are of concern in meeting the NCD criteria include the SCV, early desorption, and the leakage of cabin atmosphere. No control is required for materials outgassing as stated by this criteria since this source is considered to contain no water constitutents (i.e., the Spacelab outgassing sources meet the NCD criteria).

The SCV exceeds the NCD criteria by over three orders of magnitude during its operation and must be timelined around the operation of those payloads deemed susceptible to water column densities greater than 10^{12} molecules$\cdot$cm^{-2} in order that the intent of the criteria be met. Since this overboard dump is currently planned to occur only once each seven days on-orbit, interference with payload operations should be minimal if properly timelined.

In the evaluation of the leakage contaminant source, the worst-case line-of-sight prediction within 60 deg of the $+Z$ axis is for the LMOP line-of-sight 11 where the total NCD$=4.46\times10^{12}$ molecules$\cdot$cm^{-2} of which 7.14×10^{10}

Table 1 Contamination control criteria applicable to Spacelab

Criteria no.	JSC 00700 Criteria	User community interpretation
1	Control induced water vapor NCD to 10^{12} molecules$\cdot$cm^{-2}	Along any vector within 60 deg of $+Z$ axis originating at the PMP
2	Control return flux to 10^{12} molecules $\cdot$cm$^{-2}\cdot$s^{-1}	Total flux on an unshielded surface (2π-sr acceptance) oriented in the $+Z$ direction at the PMP under worst-case conditions
3	Control to 1% the absorption of uv, visible, and ir radiation by condensibles on optical surfaces	Optical system objective with dielectric surface at 300 K located at the PMP, oriented along $+Z$ axis, acceptance angle of 0.1 sr for a 7-day mission under random ambient drag vector orientation
4	Control 5μ size particles in an instrument field-of-view to one event per orbit	1.5×10^{-5}- sr field-of-view within 5 km of spacecraft
5	Control continuous emissions or scattering to not exceed 20th magnitude$\cdot$s^{-2} in the uv	Equivalent to 10^{-12} B_O at a wavelength of 360 nm (B_O = solar brightness)

Table 2 Molecular number column density predictions

	Number column density, molecules·cm $^{-2}$							
	Outgassing			Early desorption			Leakage	
Line-of-sight	LMOP	SMTP	FIVP	LMOP	SMTP	FIVP	LMOP	SMTP
1	1.9E8[a]	2.8E8	1.3E8	3.7E12	1.8E12	2.1E11	2.6E12	1.4E12
2	1.6E8	2.4E8	1.2E8	3.0E12	1.5E12	1.9E11	2.2E12	1.1E12
3	1.6E8	2.2E8	1.1E8	2.7E12	1.4E12	1.7E11	1.9E12	9.9E11
4&16	1.7E8	2.5E8	1.3E8	3.3E12	1.6E12	2.0E11	2.3E12	1.2E12
5&17	1.6E10	1.5E9	1.2E8	3.4E12	1.5E12	1.8E11	2.1E12	1.0E12
6&14	1.3E9	5.2E8	1.3E8	3.9E12	1.8E12	2.1E11	2.6E12	1.4E12
7&15	3.4E10	3.9E9	1.2E8	5.1E12	2.0E12	1.8E11	2.6E12	1.3E12
8&12	7.2E8	6.6E8	1.4E8	4.8E12	2.3E12	2.2E11	3.1E12	1.7E12
9&13	3.7E10	7.4E9	1.5E8	7.5E12	3.4E12	2.3E11	3.7E12	2.2E12
10	1.1E9	9.6E8	1.5E8	5.1E12	2.6E12	2.3E11	3.3E12	1.9E12
11	1.1E10	2.7E9	1.7E8	8.4E12	4.4E12	2.7E11	4.5E12	3.3E12

[a] $1.9E8 = 1.9 \times 10^8$.

molecules·cm $^{-2}$ is water vapor (see Table 2). This value is well within the criteria limits and, therefore, leakage is in compliance.

The final contaminant source, early desorption, demonstrates a maximum total NCD of 8.4×10^{12} molecules·cm $^{-2}$ for the LMOP line-of-sight 11 at 10 h into a mission. This equates to a 4.1×10^{12} molecules·cm $^{-2}$ NCD for water vapor which exceeds the criteria limit. In order to meet the intent of the NCD criteria for early desorption, it will be necessary for the external Spacelab surfaces to demonstrate an average early desorption rate (EDR) of less than 2.1×10^{-8} g·cm $^{-2}$·s $^{-1}$ at 100°C. This can be accomplished through selection of external materials having an EDR less than this value, through decreasing the total area of coverage of high early desorbing materials, or by delaying data acquisition by susceptible instruments until the NCD levels for water vapor have decayed to less than 10^{12} molecules·cm $^{-2}$. Based upon the Spacelab materials test data shown in Fig. 6, the required delay time could be as high as 24 h. This is highly dependent upon the thermal history of surfaces during that period; however, it is assumed than an average delay time of 24 h will bring the early description NCD levels into compliance with the criteria.

Molecular Return Flux

For most Spacelab payloads, the primary contaminant transport mechanism to sensitive surfaces will be the return flux resulting from molecular collisions with the ambient atmosphere flux. Direct line-of-sight and self-scattering return flux transport were evaluated and deemed negligible under the major Spacelab source conditions. All major Spacelab sources were evaluated for maximum return flux levels as presented in Table 1. The worst-case orbital altitudes were considered for each modeled source, and a medium solar activity was assumed. The orbital altitude and solar activity establish the density of the ambient atmosphere, which directly influences the return flux predictions. Analysis has shown that return flux reaches a peak near 200 km for low molecular weight sources (early desorption and leakage) while at the 200-km altitude the mean free paths of the higher molecular weight outgassing molecules are so small (no more than a few tens of centimeters) that emitted molecules are unable to travel far enough into the ambient "wind" to be scattered back to the PMP. The maximum return flux altitude for outgassing is, therefore, near 250 km where the mean free paths are of sufficient length. The resulting predictions are presented in Table 3.

The main threat of molecular return flux is its ability to accommodate or stick to surfaces upon which it impinges, thus absorbing radiant energy which scientific instruments are attempting to detect or modifying the thermal characteristics of surfaces to which it adheres. The constituents of early desorption, cabin leakage, and SCV return flux will demonstrate negligible dwell times on all surfaces other than those that are cryogenic. In contrast, outgassing species can condense on surfaces with temperatures of 25°C or warmer.

The molecular return flux levels experienced during SCV operation significantly exceed the stated criteria limits (i.e., 1.4×10^{17} molecules·cm $^{-2}$·s $^{-1}$). Sensitive surfaces should be protected from return flux by utilizing operable covers, if practical, while SCV dumps are in progress. Return flux could also be minimized through vehicle attitude selection which is not conducive to return flux during SCV operation. Ideally, such an attitude would place the ambient drag vector continually in the Spacelab $+Z$ direction, thus reducing return flux to the PMP to almost zero.

The worst-case Spacelab configuration for both outgassing and early desorption return flux is the LMOP during the maximum temperature profile attitude (see Table 3). The outgassing return flux prediction for the Spacelab LMOP under maximum ambient drag vector orientation is 8.7×10^{11} molecules·cm $^{-2}$·s $^{-1}$ at 250-km altitude. Spacelab outgassing therefore meets the criteria.

Utilizing a similar approach for early desorption, it was determined that the maximum LMOP return flux rate would be 5.0×10^{14} molecules·cm $^{-2}$·s $^{-1}$ based upon the 200-km altitude predictions. To meet the return flux criteria for early desorption, the EDR would have to be less than 9.22×10^{-11} g·cm $^{-2}$·s $^{-1}$ at 100°C assuming that all external Spacelab surfaces contribute. As it was in the case for early desorption compliance with the NCD criteria, the intent of the return flux criteria can be met for susceptible payloads if the exposure of their sensitive surfaces is delayed until such time that the early desorption return flux rate has decayed through vacuum exposure to an acceptable level (approximately 35 h). If practical, susceptible surfaces should provide their own protective devices such as operable covers and the maximum ram vehicle attitudes should be avoided during the early high mass loss period. Selection of orbital altitudes above approximately 600 km would also reduce the return flux to an acceptable level.

Table 3 Return flux predictions

	Maximum return flux (2π-sr surface), molecules·cm $^{-2}$·s $^{-1}$		
Configuration	Outgassing at 250 km	Early desorption at 200 km	Leakage at 200 km
LMOP	8.7×10^{11}	5.0×10^{14}	4.1×10^{14}
SMTP	1.6×10^{11}	2.4×10^{14}	2.1×10^{14}
FIVP	1.4×10^{10}	2.4×10^{13}	...

Table 4 Spacelab materials outgassing deposition predictions

Configuration	Deposition (0.1-sr surface, 250 km, 27°C) Rate, molecules · $cm^{-2} \cdot s^{-1}$	Accumulative (7 day mission), molecules · cm^{-2}	Å
LMOP	8.61×10^{7}	1.26×10^{13}	0.21
SMTP	1.69×10^{8}	2.47×10^{13}	0.41
FIVP	1.33×10^{8}	1.94×10^{13}	0.32

Meeting the intent of the return flux criteria for cabin atmosphere leakage may be more difficult to achieve due to its continuous, uncontrollable characteristics. Predictions for the worst-case Spacelab leakage configuration, LMOP, indicate a return flux of 4.1×10^{14} molecules · $cm^{-2} \cdot s^{-1}$ at 200-km altitude, which exceeds the criteria. Decreasing the allowable design leak rate of the Spacelab vehicles could be extremely costly to the program, and such an approach is somewhat impractical in that only 3.29 g · day^{-1} could be allowed to leak to insure criteria compliance. Realistically, leakage return flux should not impact any exposed surfaces other than possibly such cryogenic systems as the LHe Infrared Telescope which will have an acceptance angle much less than 2π steradian (sr) (closer to 0.1 sr). However, as stated, the return flux criteria is exceeded. The levels for leakage return flux can be decreased by utilizing previously suggested methods of surface protection, attitude and orbital altitude selection (above 600 km), or in some cases by providing an inert gas purge system.[12]

Absorption Due to Condensible Deposition

The deposition of molecular contaminants upon sensitive spacecraft surfaces may alter the optical or thermal properties of those surfaces and degrade system performance or acquired scientific data. The level of experienced deposition will be a function of contaminant flux, molecular species, and the temperature profile of the surface of interest. SPACE program deposition predictions for the major Spacelab sources as based upon the assumptions set forth in Table 1, are presented in Table 4. This evaluation indicates that the only modeled contaminant source presenting a concern for absorption by condensibles under the stated assumptions is the outgassing of Spacelab external nonmetallic materials. This is the only identified source that will accumulate in measurable quantities on a surface at 300 K (27°C). Sticking coefficient data employed in the modeling was based upon the TML/VCM data presented in Fig. 7.

To analyze the phenomena of outgassing deposition effects, a systematic approach was utilized based upon flight acquired absorption coefficient data[13] to translate deposition thickness into percent absorption of radiant energy. The results of this evaluation indicate that the maximum absorption due to condensibles will be induced by the SMTP Spacelab configuration. By assuming that the sensitive surface would be a reflective optic detecting at 1500 Å wavelength (the most sensitive to thin film absorption), the maximum absorption due to outgassing deposition would be 0.16% under the conditions evaluated. This is well within the criteria limits and consequently the Spacelab design as modeled is in compliance. It is important to note, however, that condensible deposition may still be of concern for payloads with different configurations and temperature profiles from those assumed.

Induced Particulate Environment

In determining the induced particulate environment of a manned spacecraft such as the Spacelab carrier, known defined particulate sources like the SCV can be parametrically analyzed in a closed mathematical form by knowing the primary vent system characteristics (based upon existing system test data or detailed stream tube vent plume and freezing analysis) and integrating these into an appropriate particle trajectory analysis program. This was conducted for the SCV,[14] and the acquired results indicate that this criteria statement can be exceeded during and for up to a minimum time increment of 17 min after SCV operation. Under this condition, the intent of the criteria can be met through timelining of the SCV overboard dump around operations of payloads that have been determined susceptible to particles in their field-of-view. Current planning is for the SCV to be operated only once per each seven days on-orbit; therefore, noninterference timelining should create minimal problems.

In contrast to well-defined controllable particulate sources such as the SCV, intermittent particulate sources (i.e., random particle emission) present a more difficult analytical problem. Actual flight observations of past orbiting systems are currently used in most instances as the primary data base for random particle evaluation. The applicability of such flight data to a different space vehicle such as Spacelab is questionable. Previous analysis of this phenomena has been based primarily upon particle tracks observed on the Skylab ATM S052 While Light Coronagraph film frames.[15] This data presented the number of detectable random events (particles) per time period (approximately 4.8 particles · $sr^{-1} \cdot s^{-1}$) as well as information about velocity and size ranges for the field-of-view and sensitivity of the S052 instrument. It excluded such known particulate producing events as overboard liquid vents. Diffraction scattering theory analysis indicates the sizes to be greater than 6 μ in diameter, which is near the size level of 5 μ quoted in Table 1. This would equate to an implied random particulate observation rate of 0.389 particles per orbit within a 1.5×10^{-5}-sr field-of-view. Adjusting this for the approximate surface area ratio between Spacelab and Skylab reduces this rate to 0.06 particles per orbit, which implies compliance with the criteria. However, for the S052 telescope, having a hyperfocal length of 850 m, particles out to the 5-km criteria limit were not detectable.

Using such a method has some logical basis, but is questionable at best. Qualitative assessments utilizing the S052 data can still be made, but when quoting or referencing the data, all assumptions and limitations must be clearly stated to insure proper interpretation of the results. One important implication that might be drawn from the S052 analysis is that the current contamination control criteria for particles may be difficult for the Spacelab carrier as well as the Shuttle Orbiter to meet. Materials selection control as well as ground contamination control should, therefore, be equivalent to or better than those used on Skylab.

Background Brightness

Background brightness induced by the scattering or emission of radiant energy can result from the presence of either contaminant particles or molecules within the field-of-view of a sensitive optical instrument. For the major modeled Spacelab molecular contaminant sources, the primary phenomena of concern in this regard is the scattering of solar energy from the irradiated contaminant molecules. Since this criteria statement actually involves a contaminant effect rather than a specific contaminant level such as NCD, it is first necessary to express the criteria statement in terms that are compatible with the SPACE program predictions to determine compliance with the criteria. This can be accomplished for molecular sources utilizing the expression

$$H_{\text{total}} = \phi \cdot H_0 \frac{8\pi^4 \rho^6}{\lambda^4} \left(\frac{n^2 - 1}{n^2 + 2}\right)^2 (1 + \cos^2\theta) \cdot \text{NCD} \qquad (3)$$

where

ϕ = surface of interest solid angle, sr
H_0 = source irradiance, w · $cm^{-2} \cdot \mu^{-1}$

ρ = molecular radius, cm
n = complex index of refraction
θ = scattering angle, deg
λ = wavelength, cm

This expression in conjunction with the proper parametric input data establishes the maximum allowable NCD to just meet the background brightness criteria statement. For the Spacelab contaminant source of outgassing where ρ is assumed to be 3.75 Å (3.75×10^{-8} cm), the resulting maximum allowable NCD for a 90-deg scattering angle would be 1.1×10^{16} molecules·cm^{-2}. This is over 3×10^{5} times higher than the maximum predicted outgassing NCD levels for the Spacelab configurations and equates to an allowable Spacelab outgassing rate of approximately 3.4×10^{-4} g·cm^{-2}·s^{-1} at 100°C.

Utilizing a similar approach for the Spacelab contaminant sources of early desorption and cabin atmosphere leakage (both having a molecular radius of 1.65 Å yields a maximum allowable NCD of 2.6×10^{18} molecules·cm^{-2}. This value compared to the maximum predicted NCD for early desorption and for leakage indicates complete compliance of these sources with the background brightness criteria.

Although approximately 15% of the vent effluents from the SCV will be emitted in the form of water molecules, the greater concern of this source with regard to the background brightness criteria will be the scattering and emission from the generated ice particles. Due to its potential production of many particles in the submicron region where the scattering level can be significant, exceeding this criteria during vent operations is highly probable. For this reason, the SCV overboard dumps should be timelined to avoid interference with sensitive Spacelab payload data acquisition.

Conclusions

A viable approach to spacecraft design contamination analysis employing state-of-the-art computer tools and procedures has been demonstrated. It has indicated that the current Spacelab design is acceptable from a contamination viewpoint if the users of Spacelab are aware of the environment to which they will be exposed and the constraints/precautions necessary to insure that contamination does not compromise their instruments. The conclusions presented herein are based solely upon the Spacelab design and its on-orbit performance. Any user of the STS/Spacelab must also consider the additional contamination sources of the Shuttle Orbiter as well as the ground facility and launch-induced contamination environments.

As a result of the systematic evaluation of the Spacelab-induced contaminant environment, conclusions have been drawn and recommendations for Spacelab/payload design and operational contamination avoidance have been made. The primary conclusion developed from this evaluation is that due to the programmatic requirement that the Spacelab be a highly flexible/diversified vehicle with a multitude of uses and objectives, that a contaminant free environment acceptable to all payloads cannot be provided economically through design alone. The proper approach would, therefore, be to optimize the current design as recommended and institute strict mission timeline and operational planning based upon individual payload mixes and mission objectives. Such planning will dictate allowable orbital altitudes, attitudes, vent timelines, and exposure times for a particular mission to minimize potential contaminant impacts.

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