CONTAMINATION CONTROL PROGRAM FOR THE COSMIC BACKGROUND EXPLORER: AN OVERVIEW

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1. ABSTRACT

Each of the three state-of-the-art instruments flown aboard NASA's Cosmic Background Explorer (COBE) (2) were designed, fabricated, and integrated using unique contamination control procedures to ensure accurate characterization of the diffuse radiation in the universe. The most stringent surface level cleanliness specifications ever attempted by NASA were required by the Diffuse Infrared Background Experiment (DIRBE) which is located inside a liquid helium cooled dewar along with the Far Infrared Absolute Spectrophotometer (FIRAS). The DIRBE instrument required complex stray radiation suppression that defined a cold primary optical baffle system surface cleanliness level of 100A.** The cleanliness levels of the cryogenic FIRAS instrument and the Differential Microwave Radiometers (DMR) which were positioned symmetrically around the dewar were less stringent ranging from level 300A to 500A. To achieve these instrument cleanliness levels, the entire flight spacecraft was maintained at level 500A throughout each phase of development. This paper describes the COBE contamination control program and the difficulties experienced in maintaining the cleanliness quality of personnel and flight hardware throughout instrument assembly, spacecraft integration, flight environmental qualification, and launch site operations.

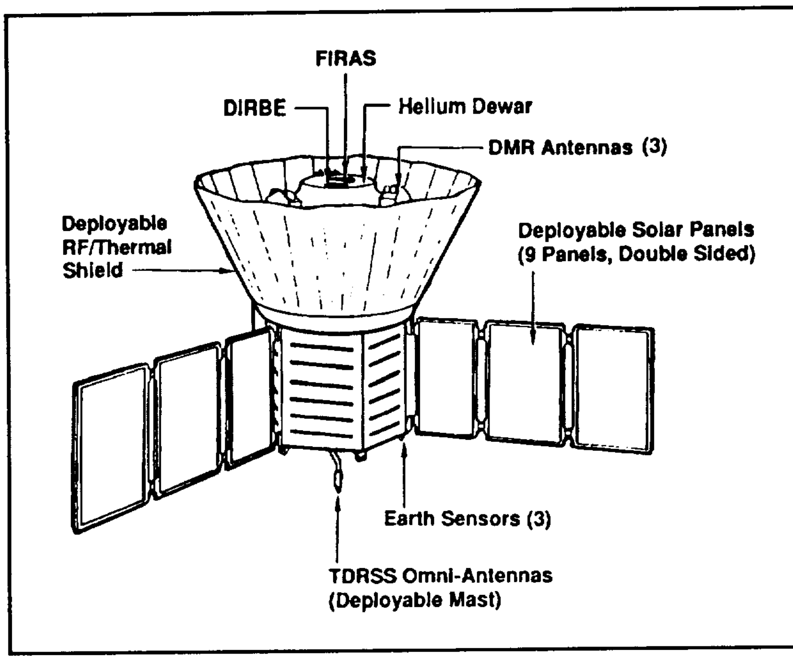


Figure 1. Cosmic Background Explorer

2. INTRODUCTION

The COBE spacecraft was launched on a Delta Rocket into a 559 nautical mile polar orbit on November 17, 1989 to study the dynamics of the origin of the universe. Figure 1 shows a schematic drawing of the spacecraft's deployed on-orbit configuration and relative locations of the DIRBE, FIRAS, and DMR instruments inside the Radio Frequency (RF)/thermal shield. The deployable mechanisms aboard the spacecraft include the omni-antenna, three solar array wings, RF/thermal shield with attached DMR contamination covers, and the dewar aperture cover that protected the FIRAS and DIRBE instruments from particulate and molecular contamination during the first 72 hours of orbital operations.

** Surface Cleanliness Levels and Air Quality Class results are stated according to Federal and Military Standards (References #1 & 3)

Both the FIRAS and DIRBE instruments operate at temperatures below 2 Kelvin inside the dewar. This required innovative contamination control measures to prevent condensation of outgassing materials on critical cold optical components. FIRAS is a modified Michelson interferometer that operates in the wavelength range from 0.1 to 10 mm to determine the spectrum of the cosmic background radiation.(2) It utilizes a polished aluminum input skyhorn to direct cosmic radiation into the optical system. Particulate or molecular contamination in excess of level 300A would decrease off-axis rejection performance of the skyhorn and possibly destroy tiny elements inside the bolometer detectors at the base of the skyhorn.

The DIRBE is located above FIRAS inside the liquid helium dewar and is currently measuring the diffuse galactic radiation in the wavelength range from 1 to 300 microns. The first optical element in this off-axis Gregorian system is a super polished, gold-coated aluminum parabolic mirror that was cleaned and maintained at level 100A to minimize radiation scattering.(5) DIRBE was assembled in a Class 100 vertical flow clean room, and completely sealed with the exception of a 70 micron pore filter positioned in the optical baseplate under the primary mirror. This filter allowed pressure equalization between the two instruments inside the COBE dewar during vacuum pump down procedures.

The final instrument flown aboard COBE was the DMR which has three individual receiver heads positioned symmetrically around the periphery of the dewar to determine whether the cosmic background radiation is equally bright in all directions. The DMR antennas operate at wavelengths of 3.3, 5.7, and 9.6 millimeters respectively to map the entire sky.(2) The internal surfaces of the corrugated horns were protected from particulate contamination at all times to preserve the cleanliness of the horn throats and the switching mechanism that is used to calibrate each receiver on orbit. A particle of 180 microns in length would cause blockage in the horns and interrupt signal throughput.

3. CONTAMINATION CONTROL SPECIFICATIONS

During early design phases, cleanliness specifications for the COBE instruments described above were established to protect critical components such as the DIRBE optics and detectors from unknown contamination. They were based on theoretical instrument performance degradation studies performed early in the project's design phases and contamination data obtained from previous successful satellites such as the Infrared Astronomical Satellite (IRAS). However, this data did not describe the effects of molecular depositions and particulate debris on the performance of the unique COBE instruments. There was also limited data defining the contamination transport mechanisms in a space environment that could coat critical cold optics with molecular layers of contamination from high energy atomic oxygen bombardment or particulate contamination from micrometeriod collisions with the spacecraft. Based the lack of scientific data, the COBE design team defined cleanliness specifications as stringent as possible based on the availability of state-of-the-art cleaning procedures, cleaning facilities, clean room garments, and clean room operating procedures.

COBE flight hardware was cleaned and certified to the design phase specified cleanliness levels at the component level prior to spacecraft integration. Once flight integration started, it became extremely difficult to maintain these cleanliness levels due to fabrication and integration operations that took place after the instrument components were originally cleaned. Additional contamination control analytical data was obtained using flight-like breadboard instruments and experimental techniques such as white light scattering photography, detector Non-Volatile Residue (NVR) analysis, and Bidirectional Reflectance Distribution Function (BRDF) measurements which describe the scattered radiance produced by particulate or molecular contamination on optical surfaces. These analyses showed that the strict cleanliness levels defined during the design phase of the COBE project were only required on critical optical surfaces such as the DIRBE primary mirror and forebaffle, FIRAS sky horn, and DMR corrugated antennas. As a result of this data, new flight hardware was designed to protect critical areas such as the DIRBE input aperture and DMR antennas, and contamination control specifications for less-critical instrument surfaces were relaxed to more achievable levels as shown in Figure 2.

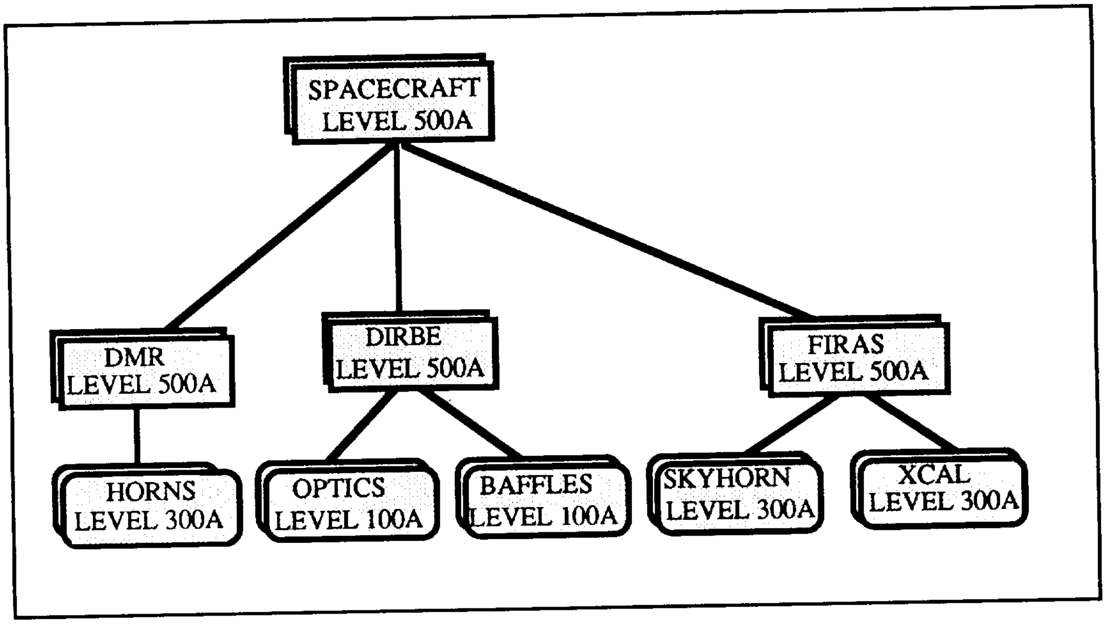


Figure 2. COBE Amended Contamination Control Specifications

4. CONTAMINATION CONTROL FLIGHT HARDWARE

Due to the stringent COBE contamination control specifications, sensitive surfaces of the FIRAS, DIRBE and DMR instruments were protected by deployable contamination control covers during launch and the early orbital outgassing period. A dewar aperture dome was the primary protection device that covered the FIRAS and DIRBE instruments inside the dewar. This dome was installed prior to pumpdown operations and remained attached to the dewar until the spacecraft had orbited the earth for 72 hours. The primary contamination concern during this time period was the possibility of water condensing on the primary optical surfaces of the cold instruments. Outgassing characteristics of the COBE were determined utilizing data obtained from the thermal vacuum qualification test that essentially baked out the entire spacecraft for 3 days then exposed it to both hot and cold orbital simulations. Since the thermal vacuum chamber contributed to the dissipation of water and other volatiles, it was necessary to compare the actual thermal test data to a statistical spacecraft outgassing model based on theoretical flux data. Outgassing data from multi-layered thermal blankets was used to evaluate the outgassing characteristics of the COBE thermal shield and top deck blankets. Once the outgassing model was established, other factors such as the dewar temperature profile, spacecraft orientation on orbit (90 degrees off velocity vector), and redistribution probabilities were factored in to arrive at the 72 hour safe outgassing period.

A secondary DIRBE contamination cover was attached to the inside surface of the dewar aperture cover to protect the primary mirror from contamination generated inside the dewar during spacecraft vibration testing, launch site transportation and launch. An optical scatterometer was mounted to the viewed aluminum surface of the oval DIRBE cover to measure the amount of radiation scattering produced by particles on the gold coated primary mirror. This scatterometer was activated throughout ground testing and just before deployment of the dewar aperture cover to measure the contamination generated during launch. Figure 3 shows the position of the scatterometer and contamination cover inside the dewar aperture cover.

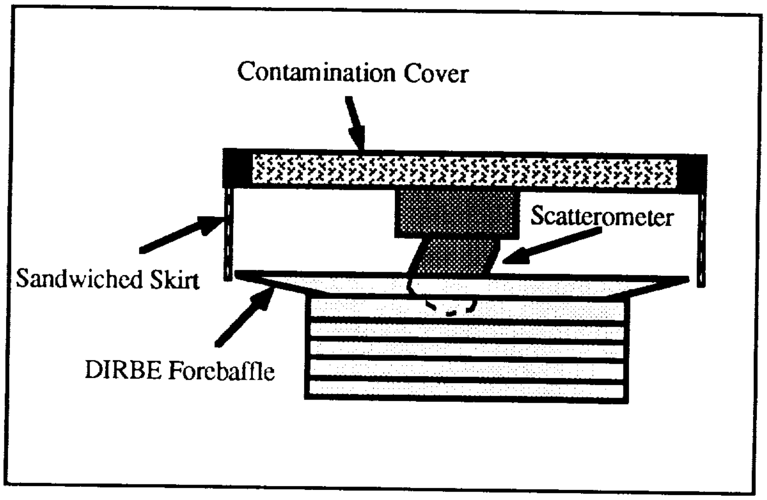


Figure 3. DIRBE Contamination Control Cover Skirt

Additional contamination control covers were also designed to protect the DMR antennas from particulate debris until the covers were deployed with the thermal shield approximately one hour into orbit. Although the Delta Rocket fairing halves were cleaned and verified to Level 500A for the first time in the history of Delta projects, debris generated during launch could dislodge and migrate into the corrugated horns effecting the switching mechanism that allows on-orbit calibration. Therefore, light weight covers were fabricated to protect the horns. Silicon foam was sealed with aluminized kapton and hinged from the stowed thermal shield panels. The covers rested 0.3 inches above each set of DMR horns on a honey comb support plate that contacted each radiometer in the center section through a smooth delrin rail. When the thermal shield deployed, the delrin guide slid across a kapton track that was attached to the center of each radiometer. This provided a relatively particle free interaction between the delrin and kapton. Figure 4 shows the DMR contamination covers in the stowed position. The covers were successfully deployed with the thermal shield and each DMR is functioning as planned.

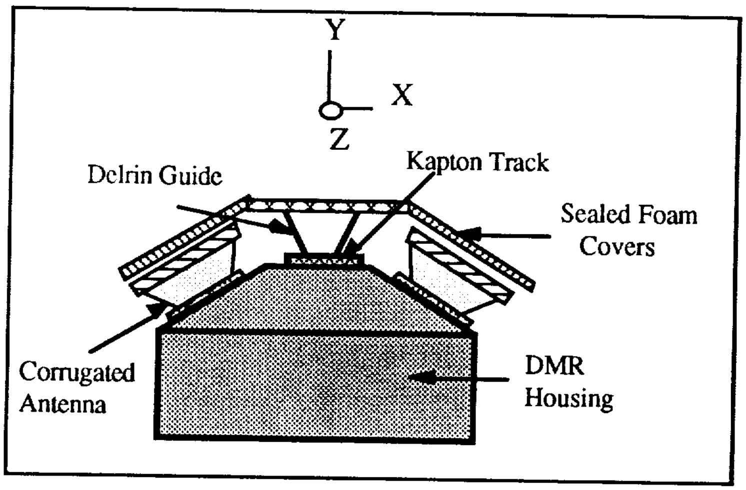


Figure 4. DMR Contamination Control Covers

5. CLEANING and INSPECTION TECHNIQUES

All COBE surface cleanliness levels were maintained throughout fabrication, integration, environmental qualification, and launch operations. These cleanliness levels were achieved through initial component level cleaning in the COBE Precision Cleaning Facility (CPCF) along with routine cleaning of the entire spacecraft. The CPCF is a Class 10,000 vertical laminar flow clean tent equipped with an exhaust bench for chemical cleaning, ultrasonic cleaning station, and contamination inspection stations. During spacecraft integration, a Quadrex Precision Cleaning Unit was installed in the CPCF. It uses a high pressure Freon spray to remove surface contaminants from compatible materials. The CPCF was continuously supported by two contamination control technicians who cleaned and inspected each piece of COBE flight hardware prior to integration to the spacecraft.

Standard cleaning procedures included a combination of thermal bakeouts, solvent rinsing, vacuuming, gaseous nitrogen blasting, vibration testing, and ultrasonic techniques. Each of the COBE flight components were required to undergo a thermal bakeout to reduce potential contamination due to outgassing. The thermal vacuum chambers were equipped with a cold finger and Quartz Crystal Microbalance (QCM) to measure outgassing rates and amounts.

The COBE Contamination Control Group and Quality Assurance (QA) personnel utilized three different inspection techniques to verify the levels of cleanliness of COBE flight hardware. First, the component was visually inspected using a minimum 100 foot-candle intensity White Light and a Long Wave Blacklight (365 nm) to determine the presence of molecular and particular contamination. Second, a tape lift sample was taken and analyzed to provide a statistical estimate of the total number and size distribution of particles per square foot that was present on the sampled item. If the item failed this tape test, it was recleaned according to the steps identified in the cleaning procedure. Third, if molecular contamination levels needed to be verified, a solvent wash was taken and analyzed using infrared and mass spectrometry techniques. By utilizing these contamination inspection techniques, we were assured of launching a COBE spacecraft that met the functional contamination performance requirements.

6. FLIGHT QUALIFICATION CYCLE

The COBE flight environmental qualification cycle was designed to ensure survivability and functional performance of each spacecraft subsystem during launch and orbital operations. Flight hardware was environmentally qualified at the component level as well as the fully integrated spacecraft level. The qualification sequence included thermal vacuum cycling, three axis vibrations, acoustic bombardment, microphonics, electromagnetic capability (EMC), and radio frequency interference (RFI) tests. Special precautions were taken during each test to minimize contamination of the instruments and spacecraft.

During each test, the spacecraft was located in a <Class 10,000 clean room environment and all testing hardware was cleaned per COBE cleaning procedures. For example, the spacecraft was double bagged in a clean antistatic Nylon film during transportation to the vibration, acoustic, thermal vacuum, and RFI chambers. Once inside the thermal vacuum and RFI chambers (both are Class 10,000), the outer bag was removed and the environment was stabilized prior to removal of the inner bag and exposure of the spacecraft. The vibration and acoustic chambers were not clean rooms and the bags remained on the spacecraft throughout testing. The bags were purged with Class 100 air conditioned atmospheric air to maintain thermal specifications on the instrument electronics. The 18X8 feet diameter bags used during the environmental qualification cycle were fabricated and cleaned at GSFC using a bagging fixture designed and built by the COBE Contamination Control Team.

6.1 Component Level Qualification Testing

The critical FIRAS, DIRBE, and DMR components were individually flight qualified prior to integration to the instrument and spacecraft module. Throughout this testing, maintaining the cleanliness level of the DIRBE primary mirror was the major contamination control goal. The DIRBE baffle system as first assembled, was painted with Chemglaze Z-306 black paint filled with microballons to decrease optical scattering. However, these microballons flaked and collected on the primary mirror during both ambient and cryogenic vibrations. To alleviate this problem, the baffle system was stripped of paint and black anodized. After completion of additional ambient and cold temperature vibration tests, tape lift samples from the center of the primary mirror were analyzed using an energy dispersive spectrometer and scanning electron microscope. The tapes showed no evidence of anodized aluminum flakes on the post vibration tape samples. The corresponding cleanliness levels met the Level 100A COBE specification.

Although the anodize surface was adequate for the DIRBE baffle system, FIRAS experienced flaking of it's anodize outer shell portion of the skyhorn during contamination certification. Long (400 microns) strips of anodize material were lifted off the skyhorn by the tape samples used to test flight components for particulate contamination. An anodized test sample was chosen that exhibited similar tape test results and vibrated to the same levels as the anodized DIRBE forebaffle described above.

Upon completion of the vibration testing, the test sample was visually inspected and several tape samples were taken from the clean bag that surrounded the sample. Final materials analysis showed the anodize material was not shedding from the test piece due to vibration. The long strips of anodize material seen on the previous tape tests were definitely not found in the post vibration particle analysis. Therefore, it appears that the only way to cause the anodize material to shed is to physically remove it with tape. The FIRAS skyhorn was qualified and flown with the original anodized outer surface.

6.2 Thermal Vacuum Testing

To simulate thermal environmental conditions imposed on COBE during launch and mission operations, the spacecraft was thermally cycled in a Space Environmental Simulator (SES) at GSFC. During the thermal vacuum portion of the simulation test, spacecraft temperatures averaged 5-10 C above and below the predicted flight temperature extremes. Figure 5 profiles the thermal vacuum chamber average temperature throughout the duration of the test.

The primary contamination control objective for the thermal simulation test was to determine the possibility of the spacecraft self-contaminating its instruments either during launch or on-orbit. Secondary objectives were: 1) bakeout the entire spacecraft during the first three days of hot soak conditions 2) measure the amount of condensed contamination throughout each phase of the test, and 3) determine the chemical makeup of the residue collected on cold surfaces in the chamber. All of this data was combined with a statistical on-orbit outgassing model of the COBE spacecraft to determine an optimum outgassing period prior to dewar aperture cover deployment.

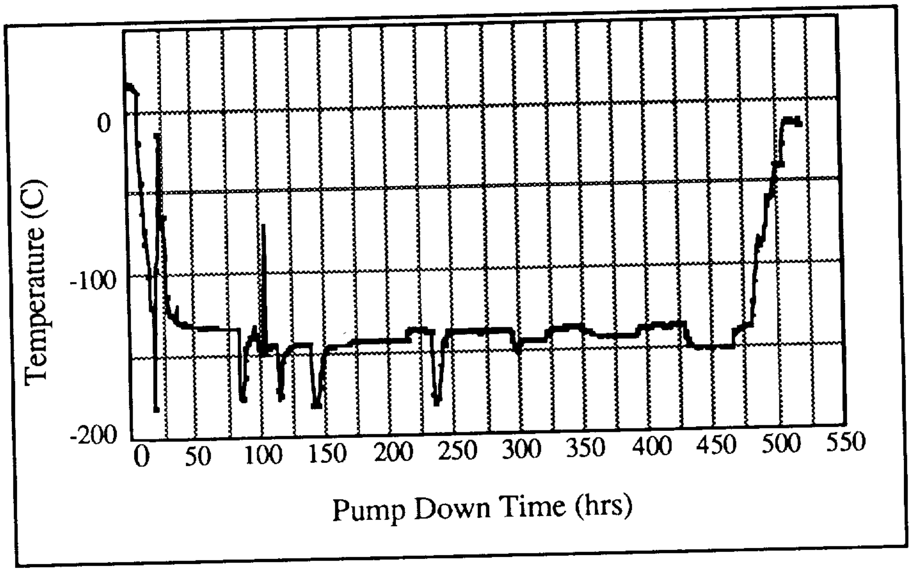


Figure 5. COBE Thermal Vacuum Cycle Temperature Profile

6.2.1 Contamination Monitoring Techniques

Three quartz crystal microbalances (QCM) were spaced symmetrically around the spacecraft and initially cooled with liquid nitrogen to provide a real-time means of measuring the quantity of outgassing contaminants throughout testing. A QCM displays the difference between beat frequencies of two 10Mhz crystals in Hertz which can be analytically converted to a quantitative amount of outgassing from the spacecraft. The QCMs were placed symmetrically around the spacecraft and two feet from the flight hardware.

Along with the QCMs, a residual gas analyzer (RGA) was used to measure the ratio of mass-to-electric charge of gas molecules in the thermal vacuum chamber. The gasses and vapors isolated for the COBE test included water, oxygen, nitrogen, and helium. RGA scans were recorded each eight hour shift, and the data was reduced to profile outgassing rates as a function of chamber pumping time.

In addition to outgassing rates, the quantity and chemical background of condensed material was determined using a cold finger, scavenger plate, and six polished aluminum mirrors. The mirrors were mounted to the DMR support ring to collect condensed residue from the most contamination sensitive portions of the spacecraft. The cold finger and scavenger plate were attached to the chamber and actively cooled with liquid nitrogen so outgassing molecules from the spacecraft would stick to the cold surfaces. The 4 foot diameter aluminum scavenger plate was flooded with nitrogen throughout the duration of the test, whereas, the cold finger was actively cooled for the last eight hours of the test. Upon completion of the thermal cycling test, the mirrors, cold finger, and scavenger plate were rinsed with a solvent, and the residue was analyzed using Infrared and Mass Spectrometry techniques.

6.2.2 Thermal Vacuum Test Results

QCM

Once the QCMs stabilized, temperature and frequency data was recorded hourly to establish trend profiles. The frequency data was further reduced by calculating the difference between two subsequent frequency readings to obtain a delta (Δ) frequency value. A representative graph of the QCM temperature versus Δ frequency profiles is shown in Figure 6. The erratic amplitude spikes occurring throughout the scan are the result of the instability in the QCM temperature controller which occasionally varied by more than 5 C and caused delta readings to vary up to 100 Hz/Hr.

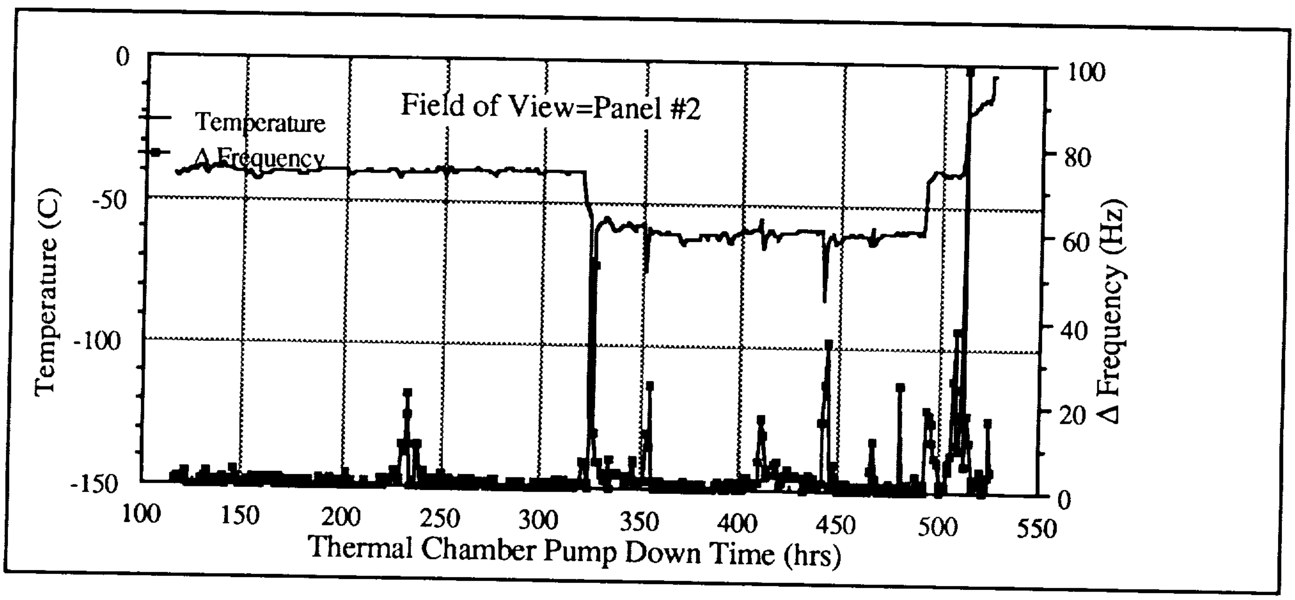


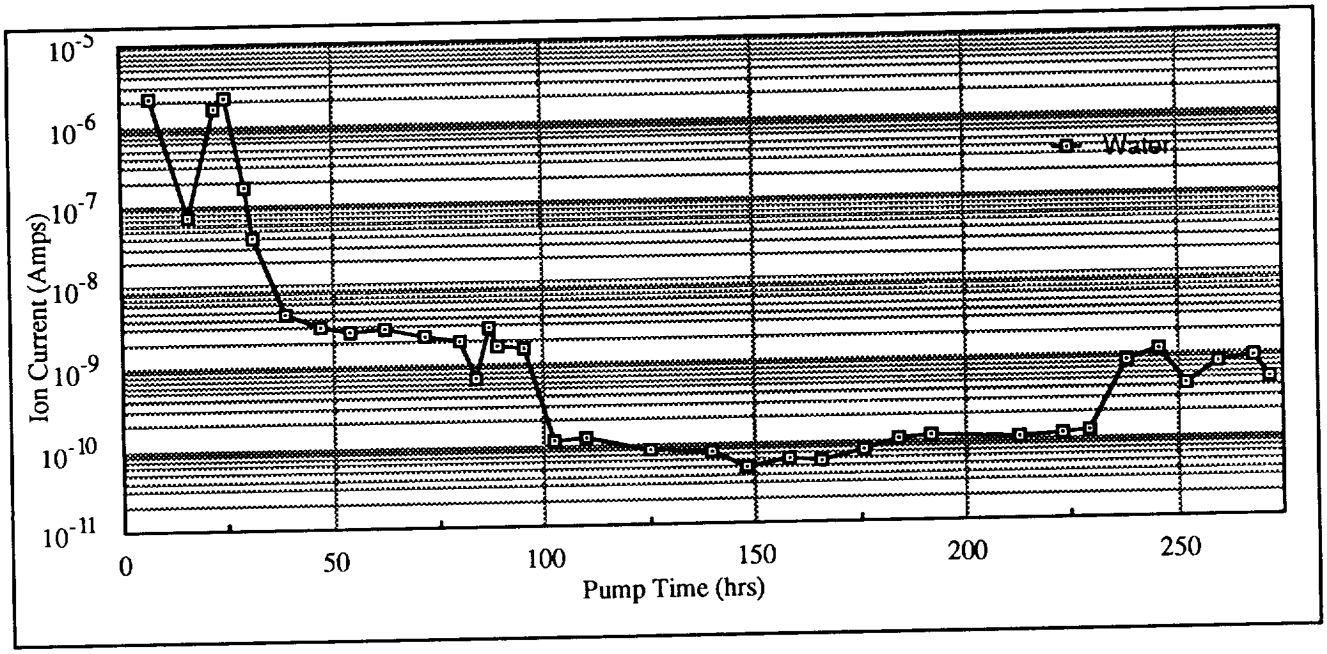
Figure 6. QCM #1 Delta Frequency Profile

Despite lowering the QCM temperature to -60 C, the final Δ frequency results successfully met the specifications outlined in the COBE Contamination Control Plan Phase II which calls for the QCM Δ frequency to be < 200 Hz/Hr, for five consecutive hours.

RGA

The RGA trend data was compiled for water, nitrogen, helium, and oxygen. A representative RGA trend profile for water is shown in Figure 7. The initial spikes on the graph at the end of the first day are the result of a helium leak in the dewar pump lines. The diffusion pumps were turned off, and the chamber was brought back to ambient conditions before the leak was isolated and controlled.

Once the chamber was pumped back down to 10^{-7} TORR, the outgassing rates of helium, oxygen, and nitrogen decreased to the 10^{-9} scale. Water dissipated at a slower rate, stabilizing after 50 hours of hot soak conditions. The temperatures of the spacecraft during this first hot bakeout phase averaged 10 C higher than mission temperature predicts. Thus, outgassing rates should be slower on orbit than seen in the thermal vacuum tests.



Figue 7. RGA Trend Profile for Mass#=18 (Water)

Cold Finger

The cold finger was activated during the last eight hours of the thermal vacuum test, and the residue was rinsed into a petri dish for analysis which showed 1.3 mg of contaminants. This unusually low level of contamination included Caprolactam, Tributyl Tin Chloride, Triallyl Cyanurate, Benzoic Acid, DC 704, and Phthalate Esters. With the exception of DC 704 diffusion pump oil and Phthalate Esters, the other materials that condensed on the cold finger are frequently used in the insulation of electrical harnesses. The most abundant condensed material was Caprolactum which is the anti-static agent in the Richmond Corporation Anti Static (RCAS) 2400 Nylon bagging material. COBE eliminated this contamination source by changing the bagging material that was used after thermal vacuum testing to a mylar type material known as Llumaloy-HSC (Martin Processing). The components that were extracted from the cold finger rinse are acceptable according to the flight levels specified in the COBE Contamination Control Plan Phase II.

Scavenger Plate

Residue from the scavenger plate showed essentially the same chemical characteristics as the contamination rinsed from the cold finger. The amount of residue was 3.3 mg, however it was rinsed from a surface area of 12.5 square feet which is 10 times the area of a cold finger. This residue contained normal chamber and spacecraft materials.

Witness Mirrors

The witness mirrors were strategically placed on the DMR support ring to collect contamination that would condense on the most critical external surfaces of the dewar and DMR instruments. The post test chemical analysis of the witness mirrors showed no detectable organic residue.

6.3 VIBRATION/ACOUSTIC TESTING

The COBE flight spacecraft was also subjected to acoustic testing along with a 3-axis sinusoidal vibration sweep. It was double bagged and purged throughout the duration of the tests because the vibration and acoustic cells were not clean rooms. Primary contamination control objectives were to measure the generated debris and spacecraft self-contamination, analyze the effectiveness of the DMR contamination control covers, and asses the possibility of debris created during the launch reaching sensitive areas around the DMR heads and cryogenic dewar.

Prior to vibration and acoustic testing, machined witness plates containing mylar disks coated with transfer adhesive were mounted to the DMR honeycomb support ring in the same locations as the witness mirrors used during the thermal vacuum tests. The witness plates were designed to gather the contamination generated between the external surfaces of the DMR blanket material and the painted dewar. Upon completion of the tests, the mylar disks were removed and analyzed.

6.3.1 Vibration Test Results

The level of contamination measured on each witness plate met the level 500 COBE mission specification. These results are shown in Table 1 below. The debris seen on the mylar plates was a combination of metal particles and small polyester fibers generated by clean room garments. The fibers are removed during the routine spacecraft cleaning shifts and will not contaminate the spacecraft during launch or in orbit.

There were also many tape lift samples taken at various locations on the spacecraft after it returned to the clean room. A majority of the tape lifts were from the upper deck regions close to the DMR instruments. Aluminum and black anodized particles of various sizes were found on the top portion of MLI attached to the bottom deck. Additional tape samples showed migration of the debris from inside the cowling to the solar arrays and other portions of the bottom deck. The particles were generated by a scrapping interaction between the backside of the cowling and the spacecraft frame during testing. A layer of isolating Nylon material was added between the spacecraft and the painted flight cowling panels to provide a smooth surface that would not shed during launch.

Witness Plate #	Location	Results
1	Left side of the 90 GHz DMR head	Level 500
2	Right side of the 53 GHz DMR head	Level 300
3	Left side of the 31 GHz DMR head	Level 300
4	Right side of the 90 GHz DMR head	Level 500
5	Right side of the 31 GHz DMR head	Level 500
6	Left side of the 53 GHz DMR head	Level 300

* All measured contamination levels on the witness plates meet the functional performance specifications outlined in the COBE System Performance Specifications for a Delta Launch.

TABLE 1. Post-Vibration Contamination Witness Plates Results

7. TRANSPORTATION TO LAUNCH SITE

A unique COBE transporter trailer was built to control the temperature, pressure, humidity, and cleanliness of the environment that surrounds the spacecraft while protecting it from induced vibrations and stresses. The filtration system used in the transporter enabled the pressure to stabilize at equilibrium inside the clean container during both takeoff and landing of the C-5 transport plane that carried the spacecraft from Andrews AFB in Maryland to Vandenburg AFB in California. This transporter is shown schematically in Figure 8.

Prior to mounting the spacecraft to the transporter, large Llumaloy-HSC bags were fabricated and fitted with 70 micron pore filters mounted symmetrically around the center and top of the bags. These bags were fabricated at GSFC because the estimates from various contractors around the U.S. were extremely high and they could not meet the required delivery schedule. The final acceptance testing of the bags consisted of particle counts, rinse samples (to test for non-volatile residue) and tape lift samples. The particle counts and tape lift samples inside the bag were all <level 500, and the rinse sample residue was < 1mg/sq. ft. which is the COBE molecular contamination specification.

Once the bags were completed, they were sealed around the spacecraft and it was mounted vertically to the transporter using an engineering model of the 6019 Delta adapter ring. A breathable air purge line equiped with a desiccant and 2 micron particulate filter was inserted into the inner bag to provide positive pressure between the inner bags and the air inside the outer hard shell which was insulated and isolated from the skid base. A thick outer bag equiped with three HEPA filters was then placed around the double bagged spacecraft and supported by a cage to add further weather protection. The outer bag was a two piece design with zippers to provide sudden decompression relief. The HEPA filters protected the spacecraft from the incoming air supplied by the HVAC system which consisted of dual air conditioners and heaters and was powered by a diesel generator. The design supply air flow rate was 800 cubic feet/minute (cfm) with a fresh air flow rate of 100 cfm which provided two air changes per minute inside the outer hard box. The HEPA filter system and the outer bag ensured a < Class 1000 environment around the spacecraft throughout transportation.

Contamination measurements were taken once the spacecraft was unbagged at VAFB to verify surface cleanliness levels. During the application of tape samples and solvent wiping, technicians noticed moisture on the bottom deck multi-layered-insulation (MLI) under the vent lines from the helium dewar. Although the humidity was controlled by the transporter, the venting of helium caused moisture to condense onto the vent tube next to the spacecraft which increased the humidity inside the inner bags. A thin layer of contamination was also noticed on the top deck thermal shield standoffs, MLI, and aluminum panels. Extensive analysis showed that the contamination was Caprolactum which is the monomer that the RCAS 2400 clean bags were made from. Caprolactum becomes a contaminant at room temperature when an acceptor substrate such as silicon based paint or potting material is present and the relative humidity is around 50% or more.

The presence of caprolactam was realized early in the integration phase of the spacecraft and the solution called for a complete thermal bakeout prior to TV/TB testing because the rate of volatilization is diffusion controlled and recondensation can occur on cold surfaces such as the thermal shield. An effort was made to remove the Caprolactam from the spacecraft through thermal vacuum testing, but apparently, some still remained absorbed to the polyurethanes (paint, potting, conformal coating and staking material). The moisture (condensation) attracted the Caprolactam from the vapor phase, since it is hygroscopic. All of these facts were verified using IR and mass spectral analysis in the laboratories. The Caprolactam was removed with absolute (200proof) ethyl alcohol and the spacecraft showed no further signs of contamination due to the transporter environment.

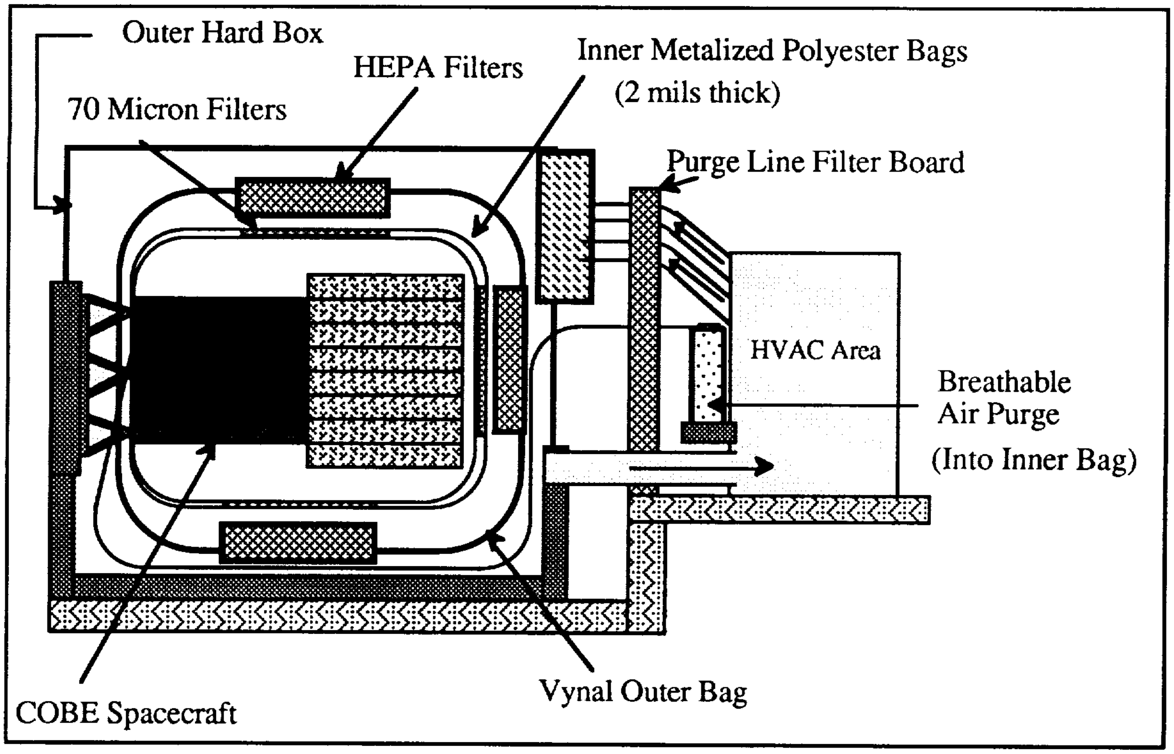


Figure 8. COBE Launch Site Transporter Clean Environmentally Controlled System

8. DELTA FAIRING CLEANING PROCEDURE

The Delta rocket fairing halves were submitted to the same contamination levels and inspection techniques as the external surfaces of spacecraft because the spacecraft was not adequately protected from contamination generated during fairing installation and launch.

The COBE/Delta fairing "super cleaning" task began with an initial inspection of the building 1610 white room (VAFB) (Class 10,000 at best) and both fairing halves by representatives from McDonnell Douglas, Kennedy Space Center, and GSFC. During this inspection, all parties noticed loose sections of silicon sealant that was used to seal gaps between machined aluminum flanges and the fairing skin in the upper nose cone. By sealing these areas, the debris between the flanges and fairing skin is trapped which eliminates the possibility of metal particles redistributing on the spacecraft during launch. This section was the most critical portion of the fairing because it was directly above the COBE dewar and DMR instruments during launch. Therefore, materials experts from McDonnell Douglas were summoned to VAFB to inspect the silicon adhesion. The material was physically stripped from the fairing, and new silicon was applied with emphasis on proper surface cleaning and preparation.

Once the new silicon had cured for seven days, it adhered strongly to the aluminum fairing skin and the super cleaning procedures continued. These procedures which were developed by the COBE project combined high pressure freon spraying with tedious vacuuming and wiping techniques to achieve the final cleanliness level of 500A. This level was ultimately reached despite inefficient equipment and facilities and the fairings were double bagged for transportation and storage on the gantry.

The final cleanliness levels of the fairings were verified by visual inspection under both UV and white light. Thirteen tape lift samples were taken to document the effectiveness of the newly developed super cleaning techniques. These levels were comparable to the external cleanliness level of 500A on the COBE spacecraft.

9. LAUNCH SITE OPERATIONS

Once the spacecraft arrived at the launch site, it was positioned in a horizontal laminar flow clean tent that ranged between Class 100 and 1000 depending upon the amount of activity and number of personnel workingin the area. Cleaning stations and a garment changing area was built adjacent to the large opening of the tent and a curtain that covered 60% of the opening was added to increase the airflow velocity to 300 feet/second in the change room and 150 feet/second in the clean tent. This tent proved to be a stable environment that maintained the cleanliness of the spacecraft throughout final launch integration prior to transporting to the gantry.

The gantry was a Class 100,000 facility located on the shores of the Pacific ocean. We were extremely concerned about maintaining the cleanliness levels on the spacecraft during Delta rocket mating and fairing installation. Several unique measures were incorporated into the standard procedures to maintain the cleanliness of the spacecraft in such a dirty environment. First, the gantry was cleaned a several times by the McDonnell Douglas technicians, however, the resulting air class levels were still unsatisfactory for our spacecraft. Further cleaning by our technicians lowered the contamination levels from around Class 300,000 to 10,000 as shown in Figure 9. Second, the spacecraft was double bagged and purged with Grade C gaseous nitrogen during transportation to the gantry, then the purge was changed to conditioned air provided by a portable A/C unit that was positioned on level five of the gantry until the fairings were installed. Third, the clean bags and purging hoses remained on the spacecraft until just before the fairings were installed to protect the spacecraft as long as possible. Finally, a "shower" cap was installed on the spacecraft to protect the exposed DMR instruments and cryogenic dewar until just before the second half of the fairing was installed.

Once the spacecraft was securely inside the fairing, a HEPA filtered A/C hose was connected which was certified to Class 100 and provided positive air flow (100 cfm) through each stage of the Delta rocket. The air flow inside the fairing was routinely sampled for 20 minute time periods to measure the air quality around the exposed spacecraft. A sample of the data is shown in Figure 10. Although the gantry environment was dirty, the air quality data showed a clean environment inside the fairings and gave us confidence that the strict cleanliness specifications outlined earlier were met.

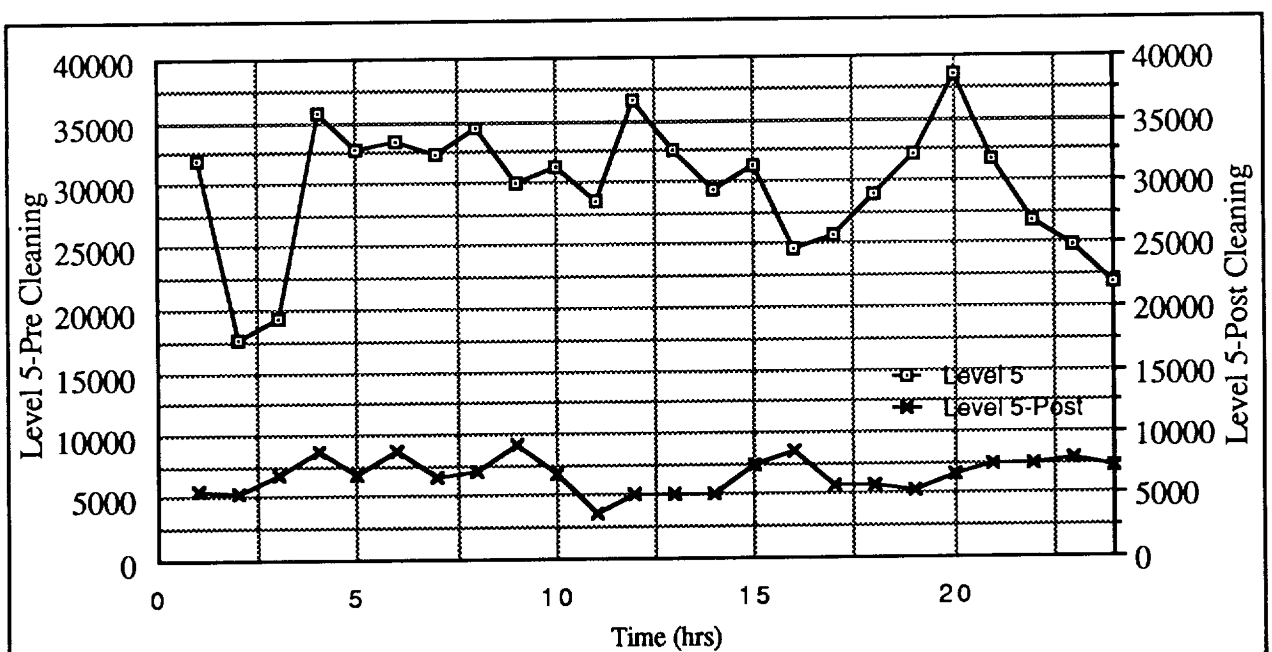


Figure 9. Delta Gantry-Level 5 Cleanliness Certification Particle Counts

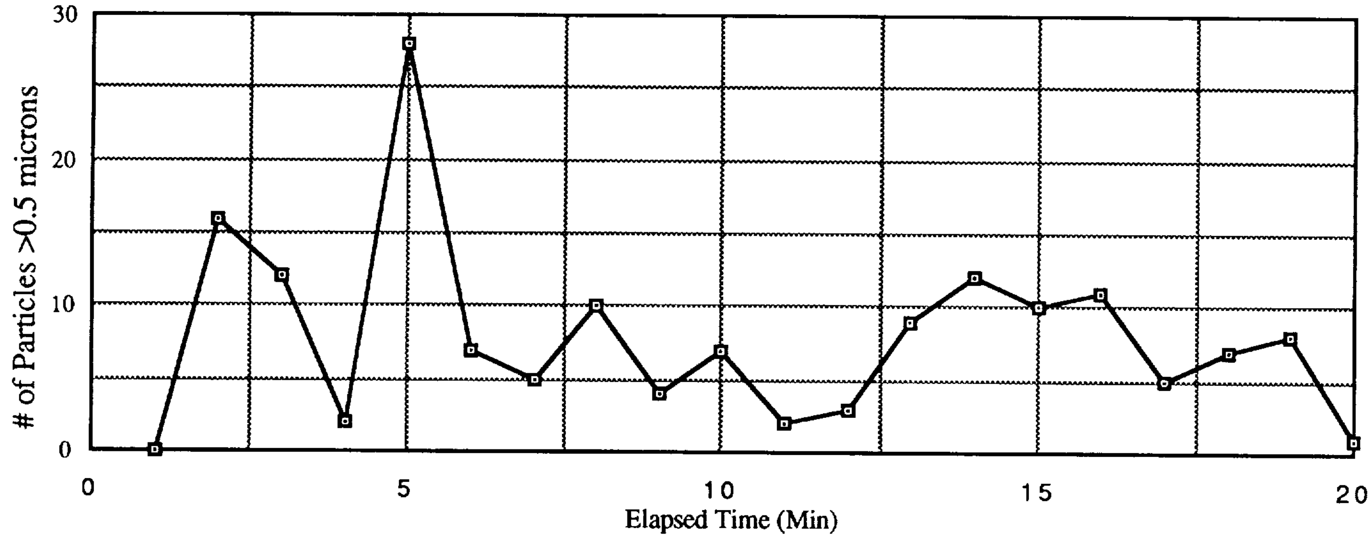


Figure 10. Delta Fairing Cleanliness Certification Particle Certification

10. FINAL CONTAMINATION RESULTS

The final contamination levels of all flight hardware were verified at different times throughout spacecraft integration, launch site operations, and Delta fairing installation. These verifications consisted of visual inspections, tape test readings, and solvent wipe analysis. All contamination verification occurred at the last possible time that we had access to the flight hardware. For example the FIRAS and DIRBE flight contamination verification was completed during integration into the cryogenic dewar, whereas, the DMR instrument and thermal shield readings were taken on the gantry-fifteen minutes prior to fairing installation. A representative sample of the tape lift data taken just prior to launch is shown in Table 2. All measured contamination levels from the flight instruments and spacecraft met or were below the required levels as stated in the COBE Contamination Control Plan.

11. CONCLUSION

The stringent cleanliness specifications required by the FIRAS, DIRBE, and DMR instruments were initially met and maintained by implementing strict clean room operational procedures, routine cleaning and inspections of flight hardware, and unique environmental control systems that protected the spacecraft from contamination during transportation and launch operations. Flight instrumentation was initially cleaned and certified to specified levels at the component level prior to instrument integration. These cleanliness levels were amended during integration because new flight hardware was designed to protect contamination sensitive instrument components, and additional analytical data was obtained that justified relaxing the specifications to more achievable levels.

These levels were maintained throughout environmental qualification, transportation to the launch site, and launch operations by protecting contamination sensitive hardware, performing routine cleaning of the spacecraft, and controlling daily operations of support personnel in the clean rooms (which proved to be most effective means of maintaining a clean spacecraft). The spacecraft was located in a Class 10,000 clean room environment which consisted of either a clean room, purged double bagged assembly, HEPA filtered transporter or purged Delta fairings. The GSFC Contamination Control Team was consistently developing new cleaning, inspection, and contamination monitoring techniques that are now being used by other clean satellites such as EUVE and ROSAT. Private companies such as McDonnell Douglas have also benefited from the COBE contamination control program by incorporating our clean room operation and hardware cleaning and

Location	Result
Panel 2-Black Painted Surface of Transponder Electronics Box	Level 300
Panel 2-MLI Surface of the Battery Wall	Level 300
Panel 2-Bottom Deck MLI Surface next to the Batteries	Level 300
Cowling Panel #1-Bare Aluminum Surface	Level 500
Cowling Panel #1-2-Bare Aluminum Surface	Level 300
Panel 1-Bottom Deck MLI	Level 200
Panel 1-Black Painted Surface of the PSE Electronics Box	Level 500
Panel 1-Black Painted Surface of the SCU Electronics Box	Level 300
Panel 3-Black Painted Surface of DMR IPDU Electronics Box	Level 300
Panel 3-Black Painted Surface of FIRAS IPDU Electronics Box	Level 300
Panel 3-Bottom Deck MLI	Level 500
Payload Attach Fitting Surface on the Delta Second Stage	Level 300
Shunt Panel Surface	Level 500
Sun Sensor MLI Surface	Level 300
DMR 90 GHz CC Covers	Level 300
DMR 31 GHz CC Covers	Level 300
DMR 53 GHz CC Covers	Level 300
Omni Antenna Aluminum Surface	Level 500
Kapton MLI Surface of the Thermal RF Shield	Level 500
Silver Teflon Surface of the Thermal RF Shield	Level 300
Solar Array Aluminum Surface S/N 05	Level 500
Dewar Sun Shade Painted Surface	Level 500
Solar Array Aluminum SurfaceS/N 08	Level 300
Earth Scanner MLI Surface	Level 300
Delta Fairing Iso Grid Surface	Level 750
Delta Fairing MLI Surface	Level 500

TABLE 2. Final Flight Tape Lift Sample Results

inspection techniques such as the fairing cleaning procedures into their launch preparation documents for future contamination sensitive spacecraft. The COBE contamination control program briefly outlined in this paper can be applied to future "clean" spacecraft projects to obtain stringent cleanliness levels that until now have been unachievable.

Early observations from COBE show the instruments are operating nominally and optical scattering principally caused by particulate and molecular contamination is an order of magnitude smaller than originally budgeted with the spacecraft's contamination specifications. Although we do not have an active means of measuring on-orbit contamination, scientific data suggests that the FIRAS, DIRBE, and DMR instruments have not suffered any performance degradation due to presence of particulate or molecular contamination.

12. RECOMMENDATIONS

1. Contamination sensitive projects should develop a detailed cause and effect contamination analysis during the design study phase, and establish the Contamination Control Team early in the hardware phase to reduce innefficiencies and logistical problems.

2. The Contamination Control Team must design, build and operate efficient flight hardware cleaning and inspection facilities. A little creativity can go along way in designing cost efficient facilities.

3. A materials study and early orbital outgassing model of the spacecraft should be developed during the design phase to determine realistic contamination control specifications.

4. Real-time contamination monitoring devices should be mounted next to sensitive hardware to measure on-orbit outgassing rates. COBE was baselined with flight QCMs that were supposed to operate at 4 Kelvin, however, the technology was not developed and the instrumentation was removed.

5. The Contamination Control Team must isolate super clean operations from the standard clean room environment with the use of clean tents, separate change areas, and GSE cleaning stations.

6. Contamination sensitive hardware must be protected at all times throughout each phase of spacecraft development and launch---Do not rely on the cleanliness of the surrounding environment.

7. Learn from COBE!! We have generated a wealth of contamination control data that should be utilized by future projects to prevent them from making similar mistakes.

13. REFERENCES

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SESSION VIII

NEW APPROACHES