# CONTAMINATION CONTROL FOR THE CASSINI IMAGING SCIENCE SUBSYSTEM

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## BIOGRAPHY

After receiving a B.S. in Physics from U.C.L.A. in 1986, and working 4 years in the field of Microgravity Research, Glenn Aveni became part of the Contamination Control Team at JPL. Since then he has performed molecular contamination analyses of such camera systems, besides ISS, as the Wide Field Planetary Camera II (WF/PC II) for the Hubble Space Telescope (HST), the Multi-Angle Imaging Spectro-Radiometer (MISR) on the Earth Observing System (EOS) platform and the Miniature Integrated Camera and Spectrometer (MICAS) on the New Millennium Program / Deep Space 1 (NMP/DS-1) spacecraft.

## ABSTRACT

The contamination control activity performed for the Cassini Imaging Science Subsystem (ISS) consisted of an overall system analysis for susceptibility to molecular and particulate contamination at the sensor's most sensitive wavelengths. This analysis considered the system functional requirements, the expected sources of contaminants, the expected effects of those contaminants, and the transport of those contaminants to the sensors. The derived requirements and a plan to meet them during assembly, test, and storage of the instrument were documented in the Contamination Handling Requirements (procedure). The final phase of the contamination control activity was to monitor the hardware (record data and implement cleaning procedures) during assembly and thermal vacuum testing prior to delivery to Assembly, Test and Launch Operations (ATLO).

## KEY WORDS

Cassini, ISS, Contamination Control, Molecular, Particulate, Susceptibility, Signal Throughput Degradation, UV Sensitive, Transport Factors, Flux, Fluence, Control Plan, MCIF, TQCMs, NVR, PCL.

## CAMERA SYSTEM OVERVIEW

The Imaging Science Subsystem (ISS) is a dual camera system to be flown on the Remote Sensing Pallet of the Cassini spacecraft (S/C). The narrow view-angle camera (NAC) is of Cassegrain/ Ritchey-Chretien construction consisting of a primary and a secondary mirror with an open front aperture (no cover) and a range of wavelength sensitivity from 2000Å (UV spectrum) to 11,000Å (IR spectrum). The optical train of the wide view-angle camera (WAC) consists of a refracting lens assembly with a range from 3800Å continuing into the IR. Although their range of sensitivity differs, both cameras share the same filter and sensor technologies. The shortest wavelength for each system is the most sensitive to signal throughput degradation. These are the drivers for determining system contamination requirements (i.e. allowable percent degradation due to molecular and particulate contamination affecting a signal of 2000Å wavelength for the NAC and 3000Å for the WAC; 3800Å is the requirement for the WAC, however readily available absorptance data extends only to 3000Å).

## ANALYSIS APPROACH

During the design phase of ISS, a preliminary assessment was made by the Optical and Systems Engineering teams, concerning the System Functional Requirements, determining that up to a relative four percent degradation to throughput at the most sensitive wavelength (2000Å; due to molecular and particulate contamination) would be acceptable to the system[1]. Unfortunately, the contamination analysis could not be based on a preliminary value (although this value later became the requirement). Therefore, the susceptibility of the system to contamination was evaluated by an estimation of the source contamination during assembly, test and flight, in the form of signal throughput degradation that may occur throughout mission life.

The design drawings created early in the project included a preliminary list of the materials that were to be used for the hardware. Structures, composites, epoxies, paints and primers, electronic components, cabling wires and harnesses, etc., were all assessed as to how much of a contamination source (at their in-flight temperatures) they may be during flight. The majority of the molecular outgassing source data was taken from earlier materials tests performed in the Molecular Contamination Investigation Facility (MCIF) at JPL, for the Wide Field Planetary Camera II (WF/PC II; also UV sensitive) system flown on the Hubble Space Telescope (HST). Recommendations for material substitution and fabrication processes along with verification of material acceptability were also made based on the MCIF data.

The outgassing source data for ISS (from the WF/PC II materials tests) was converted from material vacuum collection data taken with Quartz Crystal Microbalances (QCMs) set at collection temperatures similar to the sensitive surface temperatures (-100°C, - 20°C) of ISS. QCMs measure molecular contamination flux (mass per unit area time) in units of Hz/hr where a 15 MHz crystal has a sensitivity of 1.56 $ng/cm^2Hz$. Suspicious materials listed on the parts list that had not been previously tested, underwent their own MCIF tests with data taken at specific temperatures for the material's use. Knowledge of the geometry of the MCIF vacuum chamber set-up with relation of the source material to the QCMs allowed the collection rates to be converted into material source rates at specific collection and source temperatures. The normalized data was scaled from the mass or exposed surface area of test sample to that actually being used.

Input from Thermal Engineering[2] for the worst-case system temperatures during flight (cold for collectors and hot for sources) was critical in determining at what collection temperatures the sensitive surfaces would accumulate (collect and re-emit) molecular contamination and also at what source temperatures the molecular sources would outgas. The most sensitive collection surfaces for ISS are the front windows of the CCDs (-90°C; with a re-emission rate, k, of $4.9 \times 10^{-11}\ s^{-1}$ for a "worst-case" hydrocarbon molecule), and the field flattener (FF)/corrector assemblies (-20°C; $k = 2.1 \times 10^{-6}\ s^{-1}$) located in the radiation shields surrounding the CCD housings. The other parts of the optical trains, the mirrors of the NAC and the lenses of the WAC, will be kept near +20°C during flight, and are assumed to have high enough re-emission rates ($9.5 \times 10^{-5}\ s^{-1}$) so as not to be considered sensitive surfaces to molecular contaminants. Like the warm optics, the sources of molecular contamination will also be at +20°C. Thus source data at this temperature was utilized for contaminant flux. Subassembly orientation of the hardware determines the flow path of molecular contaminants from their sources (both internal and external) to the sensitive surfaces; lenses, mirrors, windows and thermal surfaces. These paths consist of vents, open apertures, optical baffles, and mated surfaces. Some suggested design considerations were implemented to reduce the conductive path between critical surfaces and to get the molecular contaminants out of the system: venting of the electronics volume behind the CCD package in order to isolate the contaminants from the CCD volume and directing the vent of the CCD volume away from possible contamination sources of the shutter housing. Separation by blanketing was another method used to isolate contamination from volumes containing sensitive surfaces.

The molecular transport paths were calculated by simplifying the hardware geometry to fit formulas for pre-existing plane or solid configurations[3]. Since most paths are a series of small slits, tubes, and holes, a method is used which incorporates the length and size of the path to give an effective opening area for conductance[4]. These effective areas are combined in such a way as to give a geometrical transport factor for contaminant mass, $F_{TC}$, of the contaminant to the collecting surface. The relation is as follows:

$$F_{TC} = (A_{eff} \bullet A_c)/[(A_x + A_{eff})(A_v + A_c + A_{eff})] \qquad (1)$$

where $A_{eff}$ is the conductance to the collecting surface, $A_c$ is the area of the collecting surface (for the FF, $A_c = 4.9\ cm^2$ and for the CCD, $A_c = 9.6\ cm^2$). $A_x$ is the conductance in parallel with $A_{eff}$ not leading to the collecting surface, and $A_v$ is the conductance in series with $A_{eff}$ collecting material in parallel with $A_c$ or just venting it away. A diagram is shown in Figure 1.

No computer modeling was performed for this project, i.e. all analyses were performed by hand-calculations. Some examples of transport factor reduction are: conduction through the CCD vent tube to the CCD window $F_{TC} = 1.4 \times 10^{-3}$, conduction through the external aperture of the NAC to the Field Flattener $F_{TC} = 1.6 \times 10^{-4}$.

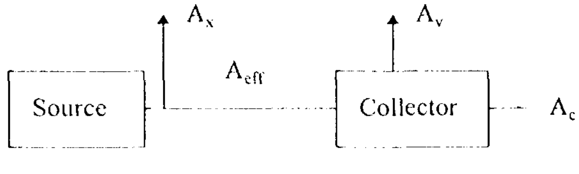


**Fig. 1 Molecular Conductance Diagram**

Once the material outgassing rates, transport factors from each source to each sensitive surface, and the sticking coefficients relating to the re-emission rates for each sensitive surface were calculated, they were combined to derive the total fluence, $\Psi$ (mass per unit area), of molecular contamination that would collect over the life of the mission. The total collection fluence per sensitive surface was calculated from the relation,

$$\Psi = (\varphi_s/k)(A_q/A_c)F_{TC}(1-e^{-kt}) \qquad (2)$$

where $\varphi_s$ is the source flux, $A_q$ is the test source collection area and $A_c$ is the actual source collection area. From this collected fluence the percent degradation in signal throughput at the specific wavelength of concern was plotted versus time[5].

The percent of signal transmission, T, are related to the contaminant mass fluence by the formula

$$T = 10^{-\alpha\Psi} \qquad (3)$$

(related to contaminant thickness[6] by density $\rho = 1$ g/cm$^3$). The derived degradation is based on a contaminant absorptivity, $\alpha$, of $1.1 \times 10^5$ cm$^2$/g (base 10) at a wavelength of 2000Å (most sensitive wavelength) for the NAC and of $2.1 \times 10^4$ cm$^2$/g at a wavelength of 3000Å for the WAC[7]. After agreement on an allowable four percent degradation was made, this value was suballocated between the three main contamination sources; molecular contamination from inside the ISS subassemblies, 2.7%, molecular contamination from the external space environment including the S/C and Launch Vehicle, 1.3%, and particulate contamination from all sources, 1%.

The derived total allowable molecular contamination values, from both internal and external sources, collecting on the sensitive surfaces were 120 ng/cm$^2$ for the NAC and 620 ng/cm$^2$ for the WAC through end of life (EOL) of the mission. Considering the transport to sensitive surfaces from the external environment implies that 266 $\mu$g/cm$^2$ of molecular contamination at the NAC aperture will consume the 1.3% external environment degradation requirement, while the front lens of the WAC can withstand 13751 $\mu$g/cm$^2$. Estimates of S/C and Launch Vehicle environments were made and confirmed not to exceed these requirements[8]. The total obscuration of the signal throughput due to particulate contamination of one percent through EOL is equivalent to a particle cleanliness level PCL 640 (MIL-STD-1246). Suitable cleanliness levels for verification during pre-launch phases were also established.

## CONTROL PROCEDURES

The Cassini ISS Handling Requirements document[9] is the summary of all analyses and reports written about contamination for ISS. It covers the description of the instrument, contamination goals to be met, results of the analyses and the practice of meeting the goals.

Estimates of material outgassing (MCIF data) and molecular collection, weighed against the allowable signal degradation, determined the on-ground material bakeout (time and temperature) and in-flight decontamination (period and duration) schedules. Instead of requiring each component or subassembly to undergo outgassing verification (QCM monitoring and measurement) the Project decided, since previous familiarity of the materials existed, that the molecular contaminants could be diffused from the hardware materials by being vacuum baked over predetermined times at elevated temperatures to achieve the desired results. Specific subassembly bakeouts are listed in Table 1. The "Estimated Percent Cleanliness After 48 Hours" column was a device created for the Project in case it ran up against budgetary/scheduling conflicts and is not based on true engineering data.

Table 2 is included here to show the guidelines used for the bakeout of specific materials that make up the subassemblies. It must be noted that these bakeout times and temperatures represent the need to reduce the outgassing source rates for a UV sensitive instrument by one order of magnitude (after volatile depletion).

Prior to assembly, all metallic and solvent compatible parts were precision cleaned to PCL 300A (Level A is equivalent to 1 $\mu$g/cm$^2$ NVR) while all optical components were cleaned to PCL 150(A/10).
To keep the Non-Volatile Residue (NVR) and particulate levels on the hardware low during assembly and testing, environmental precautions were taken. Room cleanliness levels were measured frequently, and bagging and purge techniques were employed.

During assembly and test the particle levels were maintained at PCL 300A internal to the systems and PCL 400A on external surfaces. Through launch (last particulate redistribution) the surfaces are estimated to degrade to PCL 640. Optics were assembled on Class 100 clean benches while the rest of the assembly process was performed in verified Class 10,000 clean rooms controlled to 22°C ± 5°C with 30% to 50% RH. This cleanliness class requires specific personnel procedures to be maintained at all times. All support equipment was to be kept at VC-2 cleanliness levels.[10]

**TABLE 1.**
**SUBASSEMBLY BAKEOUTS**

| Subassembly/Component | Allowable Bakeout Temperatures (°C) | Recommended Bakeout Time (Hrs) | Estimated Percent Cleanliness After 48 Hrs |
|---|---|---|---|
| Filter Wheel Assembly:<br>Metal Parts<br>Stators w/ Toluene | <br>100<br>70 | <br>96<br>300 | <br>75<br>10 |
| Hood | 70 | 120 | 40 |
| Internal Subassembly Wiring/Connectors | 95 | 170 | 40 |
| Lubricated Fasteners | 90 | 96 | 85 |
| MLI | 95 | 96 | 75 |
| Optical Assemblies | 70 | 96 | 65 |
| Radiation Shield | 70 | 120 | 60 |
| Sensor Head Electronics (after conformal coat) | 70 | 120 | 40 |
| Sensor Head Subassembly | 50 | 120 | 40 |
| Shutter Housing | 100 | 96 | 75 |
| Shutter Mechanism with Electronics Board | 70 | 120 | 40 |
| Temperature Transducer and Heater Assemblies | 90 | 96 | 75 |
| Thermal Radiators (after Assembly/Paint | 125 | 120 | 70 |

During the course of assembly and test a cleaning schedule was mandated. This is shown in Table 3.

Transportation and storage of hardware was also controlled. A system purge with Grade B bottled dry nitrogen (dew point -73.4°C STP) at a rate of 3.5 $ft^3$/hr was part of the procedure for entering and exiting hazardous environments. Monitoring the hardware during assembly and test consisted of taking tape lifts and Freon Sample Wipes of the hardware and exposing Low-Volatile Residue (LVR) and Particle Plates to the assembly and test environments. Prior to thermal vacuum (T/V) testing, the vacuum chamber (7 foot diameter by 15 feet long) was chemically washed and baked out at +105°C for 7 days. After the bakeout the molecular background was measured with a -20°C QCM to have a collection flux of 78 ng/$cm^2$hr with the chamber walls at +20°C[11].

During T/V testing, the LVR Plate and the Particle Plate were augmented by Witness Mirrors and a QCM. The LVR Plates showed collection of Aliphatic Hydrocarbons, Esters and trace Silicone, usually on the order of 100 ng/$cm^2$ (A/10). The Particle Plates collected levels on the order of PCL 300. The reflectivity of the Witness Mirrors showed negligible change. An incident did occur during T/V where the external environment requirements were exceeded. This was documented[12] and clean-up procedures were implemented.

**TABLE 2.**
**MATERIAL BAKEOUTS**

| Material | Allowable Bakeout Temperatures (°C) | Recommended Bakeout Time (Hrs) | Estimated Percent Cleanliness After 48 Hrs |
|---|---|---|---|
| Aeroglaze Coated Parts | 115 | 96 | 75 |
| Cat-A-Lac Coated Parts | 65 | 120 | 40 |
| EA 2216 B/A | 70 | 96 | 70 |
| EA 9394 | 120 | 96 | 75 |
| Eccobond 55/9 | 120 | 96 | 60 |
| Flex Epoxy (Epon 828, Epon 871,AEP,Cabosil) | 120 | 96 | 60 |
| Hincom/NS43G (50/50) | 125 | 120 | 40 |
| HT 424 Adhesive | 150 | 96 | 75 |
| Martin Optical Black Anodized Parts | 80 | 72 | 80 |
| RTV 566 A/B | 115 | 96 | 80 |
| Solithane 113/C113-300 | 90 | 96 | 50 |
| Stycast 2850 ST-24LV | 65 | 150 | 40 |

The QCM measured real time molecular contamination collection (always following 10°C colder than the front optics) to indicate the amount the front apertures were ingesting. At the beginning of the test the chamber background was measured to determine the condition of the environment prior to cooling the instrument. Prior to backfilling the chamber at the end of each test, a verification was performed by warming the QCMs, to determine how much of the molecular contamination that had collected, remained on the warmed optical surfaces. Each verification indicated a collection rate (at the aperture) of no more than 90 ng/cm$^2$hr, an amount believed to remain on the optics indefinitely.

Finally, during flight, there exists a decontamination procedure by which the ISS focal planes and radiators may be warmed (or kept warm) to +20C. The worst case procedure (least effort) requires turning on the heaters for roughly 20 hours every 6 months. The other extreme is to keep the heaters warm throughout the flight, only disabling them during in-flight operation.

## CONCLUSIONS

A contamination analysis of the system was made in order to meet the ISS system functional requirements, and the procedures necessary to meet the derived requirements were executed. However, the difficulty of this type of exercise is shown by the fact that there exists no means by which to verify compliance with requirements during flight, except by the action of receiving a satisfactory signal at the most sensitive wavelengths. The instrument was delivered to the spacecraft meeting the PCL 400A exterior requirement and is now the responsibility of the Cassini Contamination Control program.

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