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Reduction of Flight Hardware Outgassing After Integration Under a Less Stringent Requirement

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1. ABSTRACT

In preparation for the Hubble Space Telescope (HST) Second Servicing Mission, hardware which was assembled a decade earlier was refurbished and cleaned to meet a requirement more than an order of magnitude cleaner than the original requirement. The Fine Guidance Sensor (FGS) Radial Bay Module is located in close proximity to the HST science instruments; therefore the contamination sensitivity of the Second Servicing Mission science instruments necessitated the establishment of new FGS contamination requirements. These new requirements are based on a critical optics temperature of -88° C; the original FGS outgassing requirements were based on protecting the HST primary mirror, which has an average temperature of +10° C. A contamination reduction plan was devised, implemented, and refined, resulting in partial deintegration of the FGS, the use of molecular adsorbers, and the use of a bakeout temperature within 1° C of the maximum survival temperature of the hardware. Final contamination measurements are within 3% of the predicted levels and meet the Second Servicing Mission contamination requirements.

Key words: adsorber, bakeout, FGS, HST, outgassing

2. BACKGROUND

The Hubble Space Telescope (HST), an orbiting observatory, contains three Fine Guidance Sensors (FGSs) and five Scientific Instruments (SIs) (Figure 1). During the Second Servicing Mission extra-vehicular activities (EVAs), astronauts will replace one of the FGSs. The Space Telescope Imaging Spectrograph (STIS), which will be installed, and the Wide Field Planetary Camera 2 (WFPC-2), which was installed during the First Servicing Mission, both require high throughput in the ultraviolet range. The contamination budget for WFPC-2 is the most stringent, allowing 1% throughput reduction per month (reversible) on the -88° C CCD window[1].

The FGS light entrance aperture is open to the space shared by all science instrument apertures and pick-off mirrors (the Hub area). The FGS core is a graphite epoxy optics bench attached to an aluminum electronics shelf called the Dome. The optics bench is surrounded by a heater shroud which is covered with Multi-Layer Insulation (MLI). The outer shell of the FGS is fiberglass covered by MLI blankets. Figure 2 is a cut-away depiction of the FGS.

The FGS which will be installed during the Second Servicing Mission was the first FGS built, and was in some ways a prototype. At the time of the build, the first generation instrument requirements had not been established; therefore, the FGS outgassing requirement was based on the impact on the HST primary mirror. The FGS was baked out until the deposition was less than 1 Hz/hr on a Quartz Crystal Microbalance (QCM) held at +10° C. Using lessons learned from the integration of this first FGS, the next three were constructed with more stringent materials requirements. Under Marshall Space Flight Center guidance, FGS #4 was then reworked to become an identical, flight spare FGS.

As new generations of more sensitive SIs were developed, the HST contamination requirements became more stringent. Modeling of the HST Hub area showed that a new FGS could be a significant source of contamination to the SIs. Although the FGS has vents in the Dome area, less than 1% of the outgassing flux through these vents reaches the Hub area of the HST. Current FGS requirements are therefore referenced to the front aperture. The spare FGS outgassing was found to be 3.4×10^{-7} g/s on a -88° C QCM. Because science data following the First Servicing Mission proved that the contamination levels of the installed instruments were acceptable, the decision was made to clean up the spare FGS to the level of a First Servicing Mission SI. The FGS requirement was set to 2.08×10^{-8} g/s measured with a QCM at -65° C (due to chamber

constraints, the coldest QCM temperature available during a previous SI certification was -65° C). This requirement was contingent upon similarity of the outgassed species from the FGS and the First Servicing Mission instrument.

3. CONTAMINATION REDUCTION PLAN

A contamination reduction plan was essential to bring the FGS within the Second Servicing Mission requirements. Analysis of the outgassing rate of the FGS at its bakeout temperature indicated that more than six months of bakeout would be required to meet the outgassing requirement[2]. The two most significant factors contributing to the duration of the bakeout were the temperature limit (+29° C) and the tortuous path for molecules to escape from the interior of the FGS. An alternate solution was devised: since the FGS would be partially disassembled for modification, individual components would be deintegrated and baked out at higher temperatures. Each of the components would have its outgassing rate measured before and after bakeout, allowing determination of the total reduction in outgassing for the FGS.

If the outgassing rate of the FGS was not sufficiently reduced by the component bakeouts, molecular adsorbers could be installed to further reduce the outgassing rate. An interior model of the FGS, using molecular transport kinetics modeling, would be used to determine the optimal locations of the adsorbers. Molecular transport kinetics uses an iterative diffuse reflection algorithm to determine the mass accumulation on a surface over time. Surface temperatures, sorption characteristics, and contaminant properties are used to determine the residence time at each node of the model. This model, with the addition of nodes representing the test configuration, would be used to correlate QCM readings during certification with the outgassing flux from the FGS vents and aperture.

Bakeout of the FGS optical bench was reserved for a last resort because moving the partially disassembled Bench, with its critically aligned optics, would risk damaging the hardware.

After the electronics boxes were deintegrated from the FGS and baked out, it became apparent that the electronics boxes did not account for enough of the contamination to bring the FGS within its requirement, and that the adsorbers, due to restrictions on their locations, could not make up the difference. The remaining portion of the FGS would have to be baked out. To permit bakeout at the highest safe temperature, real time analysis would be used to evaluate bakeout progress; if the analysis indicated that the bakeout goals would not be met in the available time, the hardware temperature would slowly be raised to the maximum survival temperature of the FGS. Once the bakeout criteria were met, the FGS would be reintegrated and certified as a system.

4. BASELINE MEASUREMENT

The outgassing rate of the FGS was measured in a chamber set-up consisting of a support fixture called the Star Selector Test Stand (SSTS) and a heater shroud enclosed within a cold shroud. Openings in the heater and cold shrouds were closed out with MLI or tape except for the desired vents. Three QCMs were positioned to view the FGS front aperture, and one was positioned to view the rear vents. Prior to measurement at 21° C, the FGS was baked out at 29° C to eliminate surface contaminants. The outgassing rate of the FGS, as calculated by modeling the test configuration, is shown in Table 1. Because the decay constant was not measurable over the short duration of the bakeout, data from previous spacecraft were used to estimate the time required to bake out the FGS to the Second Servicing Mission requirement.

5. COMPONENT BAKEOUT

Contamination reduction began with measurement and bakeout of FGS components. The FGS was separated into two sections, the Dome and the Bench. Most of the electronics are mounted on the Dome; two Remote Units (RUs) and one Sensor Electronics Assembly (SEA) were deintegrated from the Dome. The Bench was disassembled in layers; first the top and side blankets and exostructure panels, then the interior blankets and heater panels, and finally the Image Dissector Camera Assembly (IDCA) and Electronics (IDCE). Also removed was the Stray Light Tube Assembly (SLTA), which channeled light into the IDCA. The IDCA, IDCE, and SLTA were no longer necessary for FGS operation and were refitted

to mount molecular adsorbers. Whenever possible, cables were left mated and in place to minimize the need for new staking compounds.

The outgassing of the individual components was determined on a total grams per second basis by using a test box[3]. The hardware was placed into an isothermal box with two controlled vents. One vent was completely occluded by a QCM, and the other was open to the vacuum chamber, which had cold shrouds to eliminate chamber backscattering. Assuming that the QCM sticking coefficient is unity, the total outgassing may be calculated from the relationship:

$$OGR = \Delta f \, \sigma \, (A_{QCM}+A_{vent})(1/3600) \qquad \textbf{EQ 1}$$

Where the outgassing rate (OGR) is in grams per second, Δf is the QCM reading in Hz/hr, σ is QCM sensitivity in $g/cm^2/Hz$, A_{QCM} and A_{vent} are QCM crystal and test box vent areas measured in cm^2, and the final factor converts hours to seconds. Measurement was performed on the as received parts and after bakeout of the parts. These measurements allowed prediction of the outgassing rate of the reassembled FGS. The exception was the blanket bakeout; due to the large size and number of the blankets, a test box was not used.

The outgassing rates of the individual components, as surveyed at 21°C after deintegration from the FGS and after bakeout, are shown in Table 2. When the dome and bench outgassing rates are summed with the component rates, the total is more than 100% of the measured rate during the FGS bakeout. This is attributed to the improved vent paths for molecular contamination when the parts are deintegrated. Forty-five percent of the baseline outgassing was attributable to the deintegrated hardware. Although the post bakeout outgassing rates for the components were lowered by as much as two orders of magnitude, the remaining contamination sources in the FGS Bench and Dome were sufficient to prevent the FGS from meeting the Second Servicing Mission requirement. The rates in g/s are shown in Table 3.

6. ADSORBER IMPLEMENTATION

To reduce the FGS outgassing beyond what was accomplished through component bakeout, molecular adsorber installation was planned. Molecular adsorbers are ceramic materials with a very large surface area to volume ratio, this ratio being achieved through a microscopic pore structure. For this application, an adsorber material with previous flight qualification[4], Linde 13x, was used. The adsorber is bonded to a corderite honeycomb substrate to increase the presented surface area. These substrates are mounted on posts which have been bonded or bolted onto the flight hardware.

Several constraints had to be met prior to installation of the adsorbers into the FGS: particle generation, mechanical strength, stray light, and molecular retention were evaluated. A black adsorber was developed to minimize reflection of stray light. Through vibration of the adsorbers at high loads, loose particles remaining from the coating process were dislodged and removed. This process also served to verify the adsorbers' ability to withstand launch loads. Molecular retention was tested for caprolactam (a small hydrocarbon) and palmitic acid (a large hydrocarbon). For both materials the sticking coefficient was near the ideal maximum, with a linear reduction in sticking coefficient as mass was adsorbed. Capacity of the adsorbers was similar for both species, averaging 120 mg per adsorber assembly.

The IDCA, IDCE, and SLTA, because they were no longer needed for FGS operations, were modified to provide mounting sites for molecular adsorbers. The optics and electronics in these items were removed prior to bakeout and certification. Separately certified were the studs and mounting plates for the adsorbers. Some exostructure panels and the pickoff mirror cover rails also had adsorber mounting studs bonded to them; these studs were installed after panel bakeout and certification. Hysol EA 934 epoxy and EC 2216 were used for staking and bonding because of their low outgassing rate. A total of 49 adsorbers were mounted inside the FGS.

7. BENCH BAKEOUT

The component bakeouts eliminated approximately 45% of the FGS outgassing; however, the Second Servicing Mission requirement is 4% of the FGS inital outgassing rate. Therefore, despite risks to the hardware, the Bench and Dome were

baked out. The vacuum facilities at the contractor site could not support the bakeout of the disassembled FGS, so the Bench and Dome were shipped to Goddard Space Flight Center (GSFC).

The partially disassembled FGS required protection for shipment to GSFC. Heater panels were tied down and an aluminum superstructure was fabricated and attached to the Bench to provide rigidity during transportation. To minimize contamination, and to eliminate the need for baking out the aluminum ribs, they were left uncoated and were cleaned with acetone and isopropyl alcohol prior to installation on the FGS. Installation was accomplished using clean stainless steel bolts and nuts. The inner two bags were Capran 980, and the outer bag was polyethylene. A nitrogen purge was supplied to the innermost bag during shipment (by environmentally controlled, air ride van) to GSFC. The Dome was triple bagged and shipped with the Bench. Because the Dome is an easily cleanable aluminum structure, the additional protection of a purge was not required.

Bakeout of the Bench occurred in a 25 foot diameter, 60 ft tall vacuum chamber. To measure the total outgassing of the Bench it was necessary to create a test box large enough to enclose the Bench and associated. This fixture consisted of four cryopanels (controllable hot and cold), two heater panels, an aluminum frame, and aluminized mylar tape and sheet material. As shown in Figure 3, the fixture without aluminized mylar sheet material forms a box which is open at the top and bottom of each side. These openings were used for personnel access to the hardware during the installation and removal of the Bench. After the Bench was in place, the openings were sealed, leaving only a single 32 square inch vent. Three QCMs and a coldfinger were placed in the fixture. To permit active cooling of the Photomultiplier Tubes (PMTs), a cold plate was suspended from the fixture frame. This plate was attached to the PMT thermal strap, and the PMTs and cold plate were wrapped in aluminized mylar. Because the view from the "box" vent to the rest of the chamber was blocked by a scavenger plate, it was possible to simultaneously bake out the Dome in a separate test box.

To minimize schedule impact, the Bench was baked out at the highest acceptable temperature, acceptable being defined by the trade off between schedule risk and hardware risk. At the beginning of the bakeout, the relationship between the outgassing rate at the bakeout temperature (29.5° C) and the certification temperature (25° C) was noted. Having established a goal for the certification, it was possible to estimate how close to certification the Bench was by monitoring the outgassing rate at 29.5° C. The outgassing data was analyzed to determine the decay constant, and predictions of the time required to reach certification were made. Ideal outgassing behaves according to an exponential decay process, with the outgassing rate given by:

$$OGR_t = (OGR_{initial})e^{-t/\tau} \qquad \textbf{EQ 2}$$

The outgassing rate (OGR) is usually given in grams per second, t is time, and τ is the decay constant (in the same units as t). With a single outgassing specie, the decay constant does not change with time; therefore, plotting the natural log of the outgassing rate against time will result in a straight line with a slope of $-\tau$. The Bench data is shown in Figure 4. Because the outgassing sources contained a mixture of species, the decay constant varied as species were depleted at different rates. To provide a more accurate prediction of the bakeout duration, the QCMs were set to a sequence of temperatures 10° apart ranging from +10° C to -70° C. This data was used to isolate similar species and determine a composite decay curve of the form:

$$OGR = Ae^{-t/\tau A} + Be^{-t/\tau B} + \ldots Je^{-t/\tau J} \qquad \textbf{EQ 3}$$

Because the cold data was taken first, the heavier components, which decayed quickly initially, were under-represented in the composite equation. Further errors were introduced because solving the equation requires simultaneous information from each specie category; with three QCMs it was necessary to extrapolate some of the curves to have "data" for the multiple temperatures simultaneously. The decay constants for each temperature range are shown in Table 4. The difficulty in piecing together the individual decay rates can be seen from Figure 5. Each temperature was held for a short time relative to the bakeout duration, resulting in long projections of noisy data. As can be seen in Figure 4, the composite curve which was generated does not show the rapid initial decay caused by depletion of heavy species. The tail end of the curve, possibly due to errors introduced by extrapolation, indicates more rapid outgassing decay than observed. The decay constant was also computed for a composite of all materials condensing on the -88° C QCM. This composite decay constant varies over time, but becomes more stable as the number of contributing species dwindles. After 200 hours the composite decay constant was

stabilizing around 321 hours - a number which would result in the bakeout criteria being met several weeks past the latest acceptable end date.

When it became apparent that the Bench would not meet certification in the time allotted, the FGS temperature was slowly raised above the safe limit. On August 12 the temperature was raised 2° C and the decay constant was remeasured. On August 16 the temperature was raised 1° C, to 32.5° C. The effect of these small temperature increases can be seen in Figure 4. The PMT's were being maintained at 30° C by active cooling, but in the event of a cooling failure, the PMT's could have exceeded the failure temperature of 32° C. In addition to the risk to the PMTs, the temperature gradients being developed by active cooling of the PMTs had the potential to change the alignment of the optical bench. Near the end of the bakeout, the temperature was lowered to 25° C to verify the relationship between the outgassing rate at 32.5° C and the outgassing rate at 25° C. The bakeout was concluded on time, with the Bench meeting the certification goals.

8. PREDICTION OF FGS CLEANLINESS

The Bench and Dome outgassing numbers shown in Table 3 include the background due to difficulties in obtaining a post-test measurement. Note that the contribution from the Dome area to the front aperture outgassing is essentially 0%. This is due to internal seals which were installed to isolate the optics bench from the rest of the electronics. It is expected that the actual end of test outgassing rate for the Bench was 10-15% lower than the numbers shown; however, post-test chamber difficulties prevented accurate measurement of the background. The adsorber analysis indicated that outgassing would be reduced 40% initially, with a lifetime average of 15 to 20%. With the molecular adsorbers reducing the aperture outgassing rate by 40%, the total outgassing rate of the reassembled FGS was calculated to be 1.65×10^{-8} g/s with the FGS at 25°C, measured on a -65° C QCM. Even using the mission average efficiency, and discounting the on-orbit reduction in outgassing over time, the certification criteria of 2.08×10^{-8} g/s would be met.

9. FINAL CLEANLINESS MEASUREMENT

The FGS outgassing certification occurred in the same test set-up as the initial outgassing measurement: the FGS was enclosed by a heater shroud within a cold shroud. A 48 hour bakeout phase at 29° C was conducted to remove any surface contaminants which had accumulated during reassembly and thermal vacuum cycling. The FGS temperature was reduced to 25° C for the certification phase. On a -65° C QCM, the FGS front aperture outgassing rate was 1.61×10^{-8} g/s, and the aft vent rate was 1.0×10^{-8} g/s. The FGS was then dropped to 21° C and measured on a -88° C QCM. The front aperture outgassing rate was 1.1×10^{-8} g/s. The certification outgassing rate was within 3% of the prediction, and was well within the requirement. The fact that the measured rate was slightly lower than the prediction is attributable to the inclusion of the background in the Bench outgassing rate.

10. LESSONS LEARNED

Monitoring Bakeout Progress

Increasingly shorter integration schedules and more complex instruments are causing compression of bakeout schedules. At the instrument or spacecraft level, temperatures may be limited by hardware safety constraints. In a typical bakeout, 10° C margin is provided between the maximum bakeout temperature and the survival temperature of the hardware. Being able to predict the time at which the hardware will certify allows the project to manage the risk of reducing the temperature margin or delaying the schedule. The apparent decay constant using a QCM at one temperature will change as the ratio of outgassed species changes; therefore, measurements should be made a several temperatures and a multi-species decay equation used. The use of multiple QCMs allows simultaneous measurement at different temperatures; however, when outgassing cannot be measured simultaneously at all desired temperatures, the warmer QCM temperatures should be measured first. **For time critical bakeouts, use multiple QCMs at different temperatures to gather decay constant information; this information can be used to predict the time required to reach certification.**

Outgassing Measurement

When component outgassing rates are being measured for use in predicting higher assembly outgassing rates, it is desirable to know the total outgassing of the item. Measurement of total outgassing from a complex item, such as an instrument, requires one of two methods. The vacuum chamber, including the shrouds, pumps and vacuum lines can be modeled so that a QCM reading can be related to total outgassing. If the chamber is not isothermal, the QCM data will not be linearly related to the outgassing rate. Alternatively, the hardware can be placed inside an isothermal enclosure with a known vent area, and a simple relationship between QCM reading and total outgassing can be established. **When multiple QCM temperatures are being used, or few QCMs are available, placing hardware inside a test enclosure simplifies measurement of total outgassing rate.**

Use of Molecular Adsorbers

The best strategy for reducing contamination levels within a spacecraft are materials selection, component bakeouts and venting strategies. Many integration steps inevitably add contaminant sources after component bakeout, and structural considerations limit the extent to which baffling and venting can be implemented. Molecular adsorbers act as virtual vents which slowly lose efficiency as the active sites are filled. The effectiveness of the adsorbers depends upon placement within the spacecraft; modeling is therefore required to determine optimal locations. **When properly located, molecular adsorbers can significantly reduce contaminant emission from within an enclosure.**

11. CONCLUSION

It is possible to retroactively implement more stringent contamination requirements upon an instrument or spacecraft. Many portions may be easily deintegrated for high temperature bakeout, and the remainder may be baked out close to its maximum temperature by using temperature control zones and real time analysis of the bakeout progress. The addition of molecular adsorbers wherever feasible will also reduce contamination levels. The HST spare Fine Guidance Sensor outgassing rate was reduced by more than an order of magnitude using these methods.

12. ACKNOWLEDGEMENTS

The authors would like to acknowledge the efforts of the individuals who made the contamination reduction program a success. Particularly valuable was the support of the molecular adsorber team, including Shaun Thomson of GSFC and Doug Hawk of Swales, for their development of the adsorber mounting concept, testing of cleanliness and effectiveness, and providing installation oversight. Also of note are Frank Finnerty, Tony Cappiello, and the rest of the Hughes Danbury Optical Systems personnel who made it possible to violate almost every handling constraint on the FGS without damaging the hardware; Lockheed for providing systems oversight; ManTech for providing integration and cleanroom support through long hours and weekends; and the Jackson and Tull thermal engineers who controlled the temperature of the FGS during Bench bakeout.

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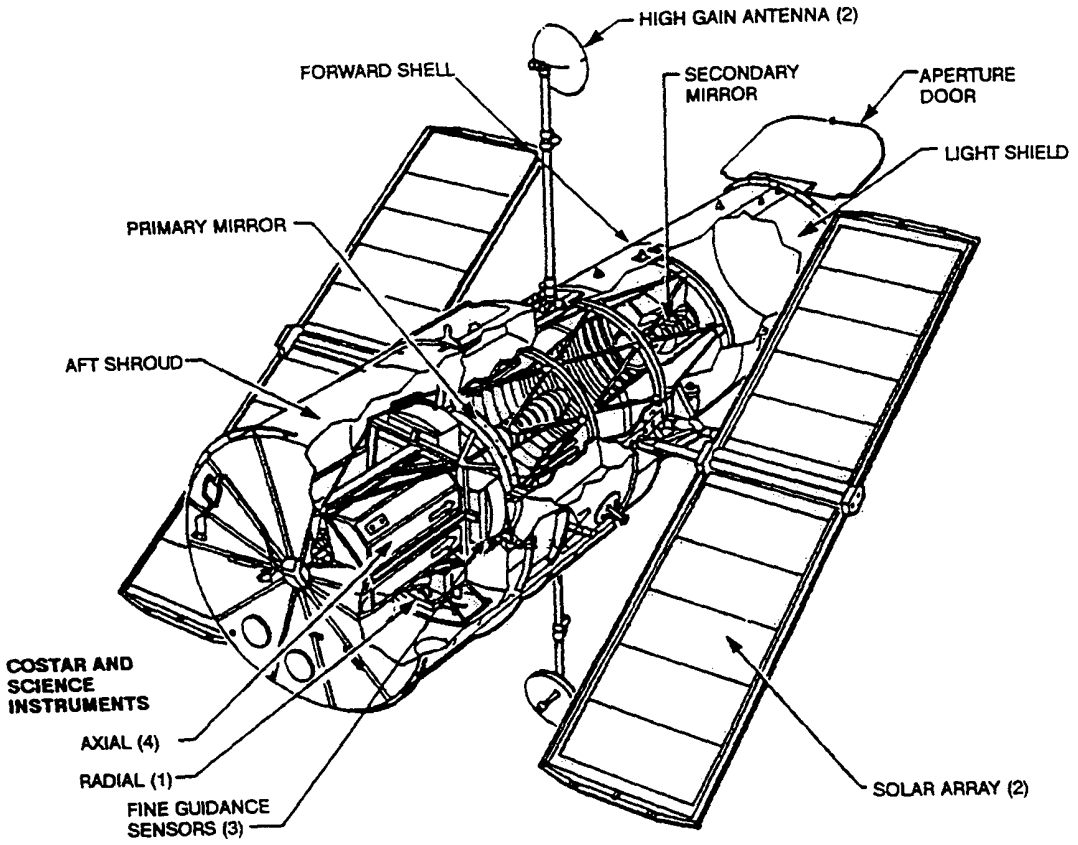

Figure 1: Hubble Space Telescope

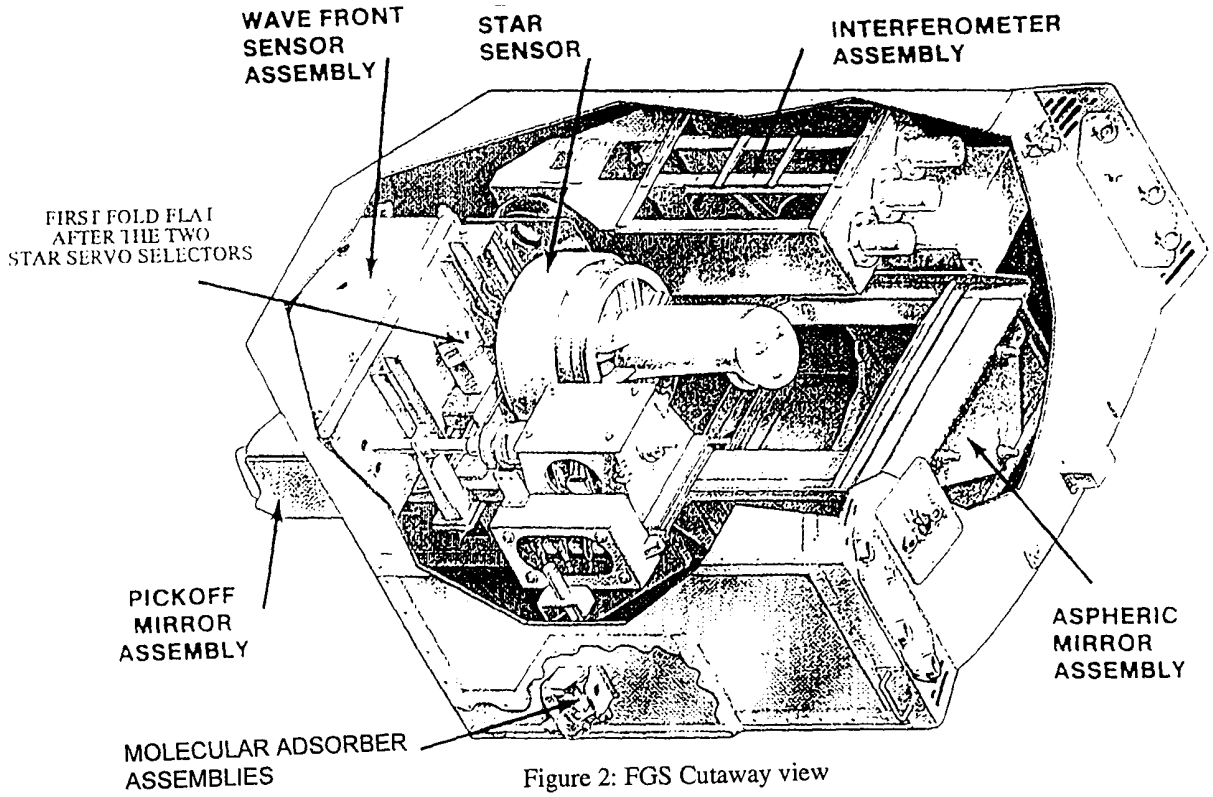

Figure 2: FGS Cutaway view

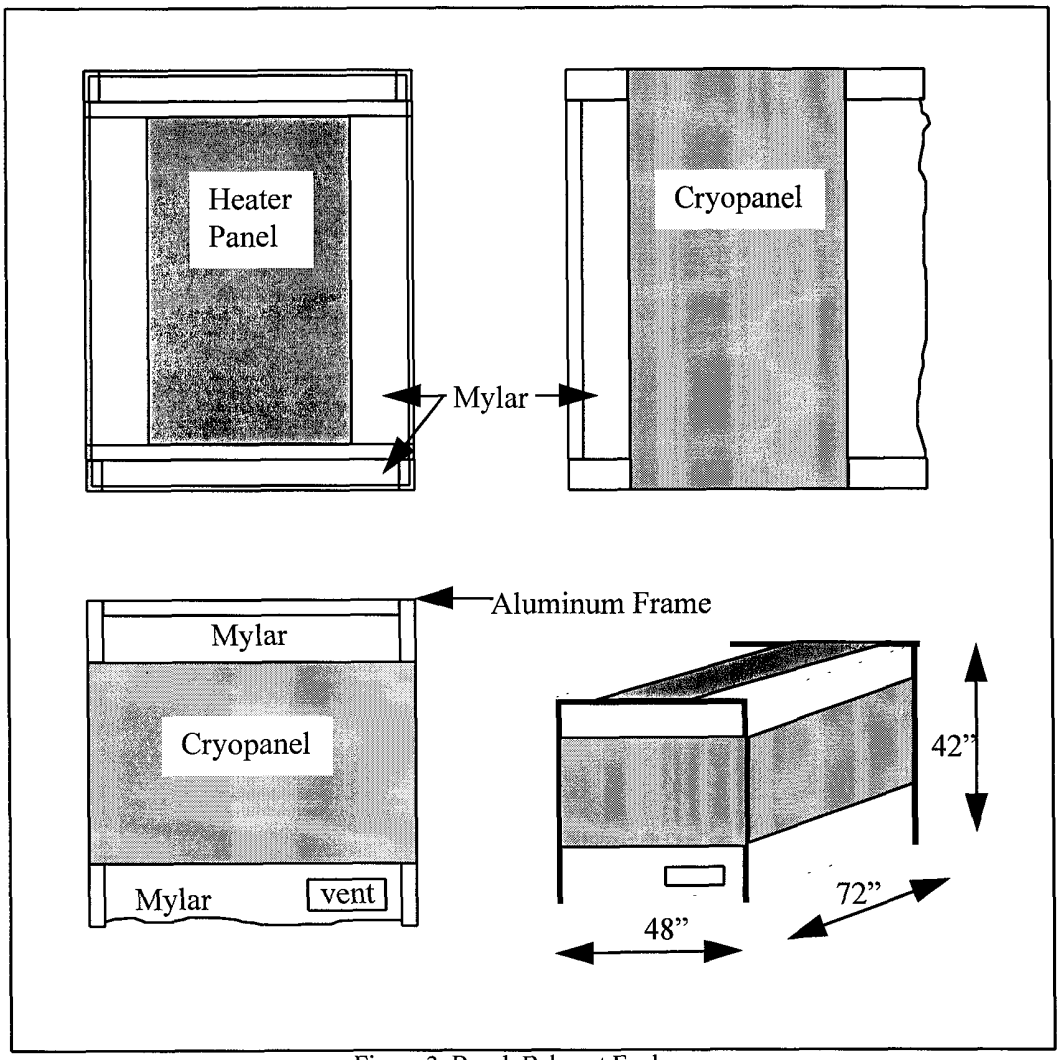

Figure 3: Bench Bakeout Enclosure

Table 1: FGS Baseline Outgassing Rates

QCM Temperature	Aperture Outgassing (g/s)	Aft Vent Outgassing (g/s)
10° C	Negligible	Negligible
-20° C	9.37E-09	3.26E-09
-70° C	4.36E-07	8.47E-08
-88° C	4.85E-07	9.36E-08

Table 2: As Received Component Outgassing Rates

Outgassing Survey of components at 21° C, QCM at -88° C			After Bakeout, % Reduction
Component	Outgassing g/s	% of FGS Total	
Exostructure	3.63E-08	20%	98%
Heater Panels	2.22E-08	12%	95%
IDCA, etc.	9.36E-09	5%	100%
SEA	7.87E-09	4%	98%
RU (2)	7.47E-09	4%	96%
MLI	6.73E-11	0%	99%
MOF	1.88E-10	0%	Not Reflown
Dome	2.68E-09	1%	100%
Bench	1.57E-07	85%	86%
Total	2.43E-07	132%	90%

Table 3: Post Bakeout Component Outgassing Contribution to FGS Front Aperture

Component	Measured (g/s) h/w 25° C, QCM -65° C	Viewfactor to Front	Contribution to Aperture (g/s) h/w 25° C, QCM -65° C
Exostructure	9.82E-10	2%	1.49E-11
Heater Panels	1.60E-09	50%	7.98E-10
IDCA, SLTA	2.46E-12	100%	2.46E-12
SEA	2.25E-10	0%	0.00E+00
RU (2)	4.52E-10	0%	0.00E+00
MLI	2.46E-12	10%	2.46E-13
AME	5.54E-11	100%	5.54E-11
AMA	1.48E-11	100%	1.48E-11
POMC Rails	1.23E-12	100%	1.23E-12
Bench	3.32E-08	80%	2.66E-08
Dome	9.82E-11	0%	0.00E+00
Total	3.67E-08	N/A	2.75E-08

Table 4: Exponential Decay Constants for FGS Outgassing Species

Temperature Range (°C)	-20 and up	-30 to -20	-40 to -30	-50 to -40	-60 to -50	-70 to -60	-88 to -70
τ (hr)	158	208	303	238	196	166	119
Initial Hz/hr	181	206	302	273	330	268	228

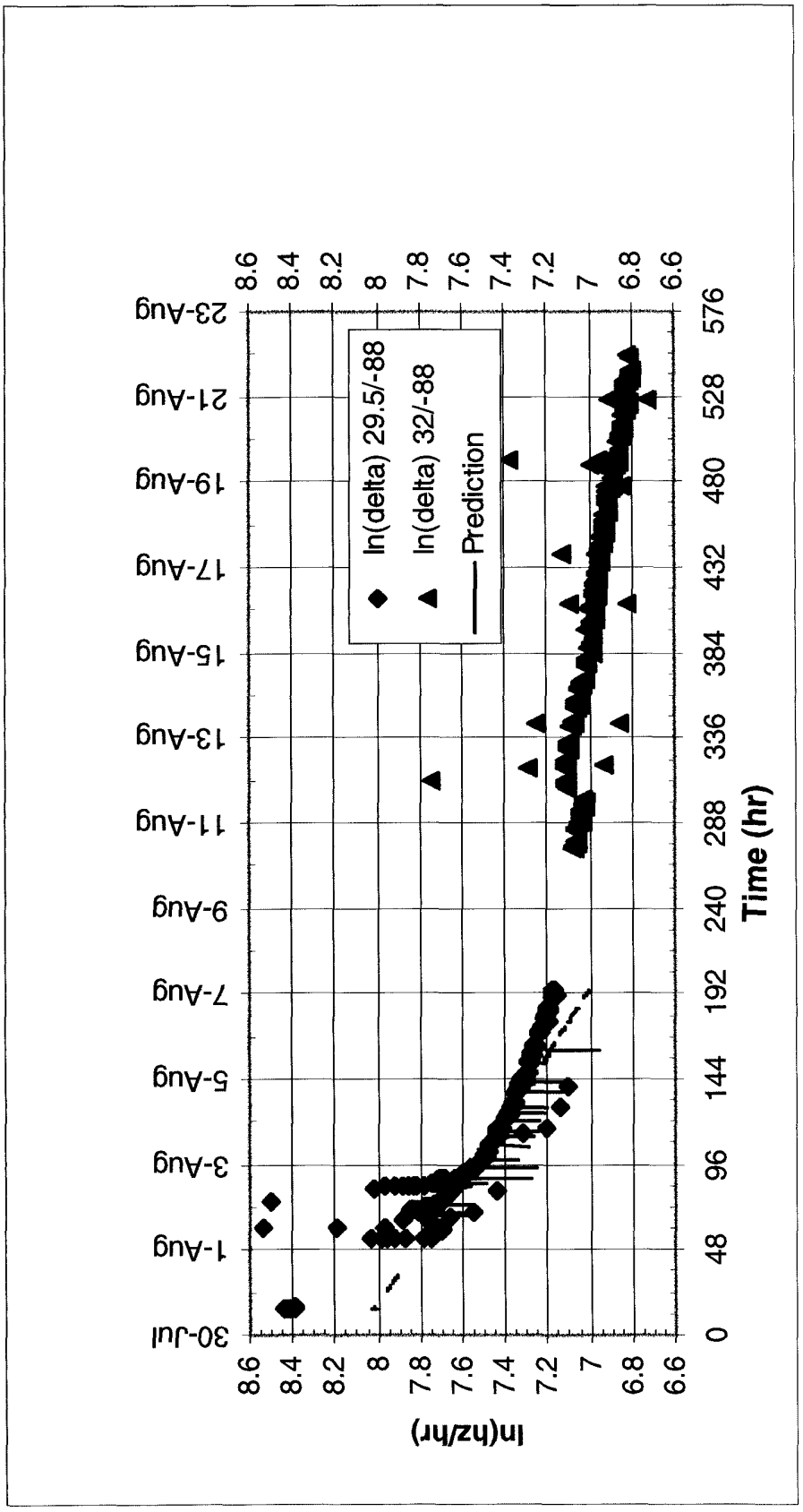

Figure 4: Bench Outgassing Data

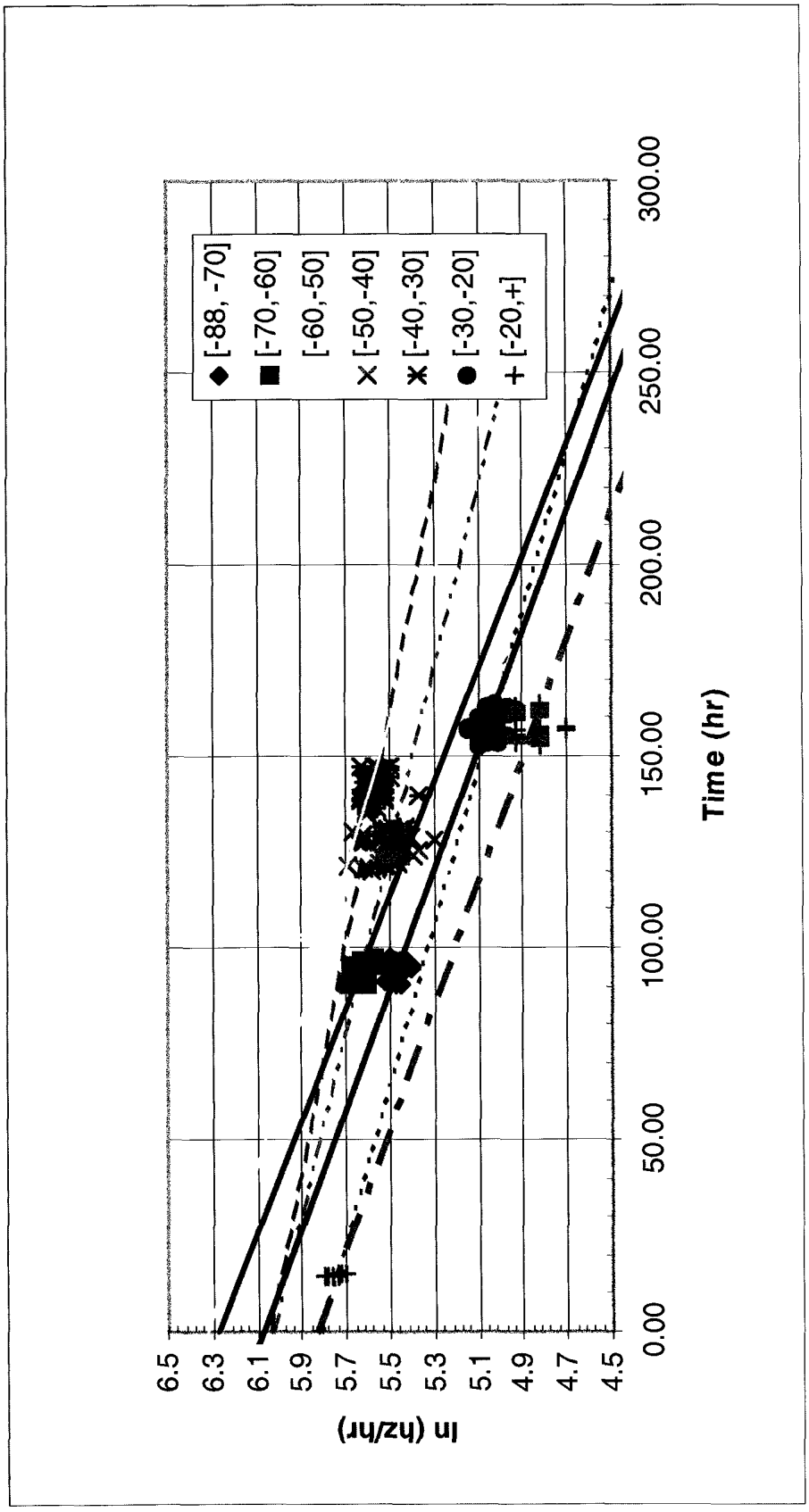

Figure 5: Decay Constant Analysis of Outgassing Data