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Outgassing of INSAT 3D Spacecraft during Thermal Vacuum Performance Test

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***Abstract*— Thermoelectric Quartz Crystal Microbalance (TQCM) is used to measure the contamination mass flux in thermo-vacuum chamber. When mass flux intercepts the crystal and condenses on it at a specific temperature the thickness of the quartz crystal changes. This results in a change of the resonance frequency of the crystal. Therefore a change in frequency of the crystal per unit time is a direct measure of the contamination flux per unit time arriving at the crystal. This makes it useful to study the outgassing flux from spacecrafts during Thermal Vacuum Performance (TVP) Test. As the ambient environment created during TVP test is likely to be the same as experienced by an on-orbit spacecraft, TQCM data modeling is useful to predict on-orbit contamination of spacecrafts due to self outgassing. We study the behavior of TQCM data in different phases of TVP test of INSAT 3D spacecraft. We found that satellite outgassing is approximately eleven times more during 'Long Hot Soak' as compared to 'Long Cold Soak'. Also TQCM frequency change in consecutive hours of tests is less than 1 Hz/hr. This figure supports excellent cleanliness of INSAT 3D spacecraft in context of contamination outgassing. We suggest that such data study is useful to quantify the outgassing behavior of Indian Satellites during their on-orbit operations.**

***Index Terms*—** INSAT 3D, Outgassing, TQCM, TVP Test

I. INTRODUCTION

Diffusion and desorption through the bulk volume and from surface of a material under high vacuum is termed as outgassing [1]. The phenomena of outgassing from materials in vacuum limit the choice of materials availabilities in spacecrafts [2], [3]. Due to spacecraft outgassing in orbit, spacecraft itself becomes a source of contamination [4]. Such self generated contamination creates a cloud of unwanted molecules and dust particles around the spacecraft [4], [5] which degrade the performance of sensitive optical components, scientific and imaging payloads, optical solar reflector, thermal surfaces and solar cells [6]. Therefore an international standard has been established for choice of material for the spacecrafts on the basis of maximum limit of outgassing [2]. In order to monitor outgassing from the spacecrafts, Thermoelectric Quartz Crystal Microbalance (TQCM) is used in space simulation chamber during Thermo-Vacuum Performance (TVP) Test of spacecrafts. When mass fluxes intercept the crystals and condense on it at a specific temperature the thickness of the quartz crystal changes. This results in a change of the resonance frequency of the crystal. Therefore a change in frequency of the crystal per unit time is taken to be direct measure of the contamination flux per unit time arriving at the crystal [7]. For this reason Quartz Crystal Microbalance (QCM) acts as a mass sensor [8], [9] to measure tiny amount of deposited mass. TQCM has been helpful to draw important conclusions of outgassing behavior of spacecrafts during space simulation tests [10] - [12]. QCM also has flown in many missions to measure the on-orbit contamination of spacecrafts [13] - [16].

Outgassing from substances strongly depend upon the temperature and surrounding environment [4]. To a first order it can be considered that under high vacuum outgassing from a surface is less sensitive of vacuum [4]. Outgassing rate with time depend upon nature of gas evolved, material as well as the processes (diffusion, desorption) involved. Time dependence of outgassing can be exponential (e^{-t}), square root ($t^{-1/2}$) or linear (t^{-1}) depending on whether it is first order surface desorption, diffusive processes or metal outgassing [1, 4]. In much of the cases these dependency of time do not hold due to complicated molecular phenomena involved. From the knowledge of outgassing behavior a self contamination model of an orbiting spacecraft can be developed [4], [5], [17].

II. OUTGASSING MEASUREMENT FROM QCM

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When used for outgassing measurement TQCM indicates the net mass on the crystal [7]. This net mass over a unit time is the difference of rate of outgassing flux depositing on the crystal and the rate of total evaporation of deposited mass flux from the crystal. The mass change on the crystal is related to frequency shift Δf as [7]

$$\dot{m}_s\,(T_s) = \left(\frac{A_c}{A_s\sigma\Gamma}\right)\left(C_m\frac{\Delta f}{\Delta t} + \dot{m}_c\,(T_c, d, f_c)\right) \qquad (1)$$

where σ is the sticking coefficient of outgassed molecule on the crystal. Γ is the fraction of molecules that leaves the spacecraft and arrive at crystal. A is area where the subscript 'c' and 's' stands for the crystal and spacecraft. C_m is crystal mass sensitivity constant. $\dot{m}_s$ is outgassing mass flux rate per unit area of spacecraft at temperature T_s. $\dot{m}_c$ is the evaporation rate from crystal per unit area which depends upon crystal temperature T_c, thickness of deposited mass flux d and the crystal frequency f_c . Crystal frequency decides the acceleration experienced by a deposited particle over the crystal surface. This acceleration is around million times 'g' [8] where g is acceleration due to gravity. Such high acceleration on crystal surface creates an oscillating force over the particle. If this force is more than the adhesive force between the particle and crystal, particle can be expelled out of the crystal. The acceleration across the crystal surface follows a Gaussian like distribution [8]. Due to such acceleration field and molecular phenomena involved (at nano gram scale) the evaporation rate depends upon the surface coverage and thickness of contamination layer over the crystal. Reevaporation rate may not be uniform. Work carried out in [7] reports two different reevaporation rates for thin and thick films over QCM crystal. It is said that a uniform reevaporation rate may be obtained by a relatively thick layer over the crystal [7].

There has been attempt to model the outgassing from spacecraft by the knowledge of frequency change observed by a TQCM (or combination of TQCMs) [12]. QCM has been flown in many space missions to directly measure the on-orbit outgassing. During space simulation test the environment experienced by the spacecraft is likely to be the same as in the orbit except that spacecraft is stationary. It is for this reason an upper bound of frequency change (Δf) of TQCM is used to characterize the cleanliness level of the spacecrafts during space simulation test even though knowledge of $\dot{m}_c$ is quite unknown [10]. However it is necessary to maintain crystal temperature constant during a set of observations. It is because that crystal resonance frequency as well as reevaporation rates are sensitively depends over crystal temperature. Accordingly by studying frequency response of crystal at different temperature outgassing of different species of contamination can be known as different species condense at different temperatures [18].

III. COMPREHENSIVE ASSEMBLY AND TEST THERMO VACUUM CHAMBER (CATVAC)

CATVAC thermo-vacuum facility is used for performing thermal vacuum performance test (TVP test) on spacecrafts. The vacuum chamber is made of SS 304 L with horizontal configuration and measuring 10m in length and 6.5m diameter. It consists of blister type bubbled shrouds laid throughout chamber and the front and rear dishes. These shrouds are used for creating and maintaining a simulated space thermal environment using either liquid nitrogen or gaseous nitrogen as the media. The vacuum system of the facility consists of a battery of evacuation pumps. These include two sets each of rotary vacuum pump with roots pump. High vacuum system comprises three magnetically levitated turbo-molecular pumps with pumping capacity of 2000 LPS each and four cryogenic pumps with pumping capacity of 60000 LPS each. The system is augmented with a liquid nitrogen operated cold trap called as *Meissner* trap to

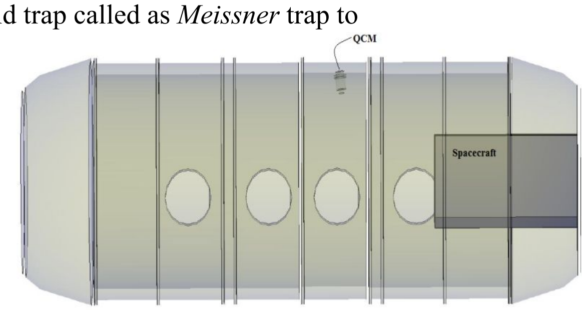

Fig. 1 Schematic diagram of thermo vacuum chamber with Spacecraft and location of QCM (not drawn to scale).

reduce the effective pump down time. The vacuum system can evacuate the chamber to 10^{-6} mbar [19].

The thermal shrouds inside the chamber are divided into 14 different sections each of which can be controlled independently by a configured control system and instrumentation network operating in closed-loop. The thermal system can operate the shrouds from -100^0C to 100^0C using gaseous nitrogen (GN_2) and at -190^0C using liquid nitrogen (LN_2). All vacuum pumps, thermal system control and chamber motion systems are operated over programmable logic controllers with respective instrumentation and attached human machine interfaces. The thermal control system is PID controlled for control of the shroud temperatures at desired set-point. The contamination monitoring system of the chamber includes *Thermoelectric Quartz Crystal Microbalance (TQCM)* sensor located as shown in Fig. 1. Residual Gas Analyzer (RGA) is used for monitoring partial pressures of different gases present in the rarefied chamber volume.

IV. OUTGASSING MEASUREMENT OF INSAT 3D SPACECRAFT

TVP test of INSAT 3D was carried out in Comprehensive Assembly and Test Thermo-Vacuum Chamber (CATVAC), ISITE of ISRO in two phases [20], [21] . An MK10 15 MHz TQCM was used to measure outgassing flux from spacecraft under high vacuum in first phase of the test. For crystal operating at 15 MHz frequency the mass sensitivity of the crystal is [18]

$$\Delta m / A = 1.96 \times 10^{-9} \, (gm/cm^2) \times \Delta f \, (in \ Hz) \qquad (2)$$

where Δm is the mass deposition of outgassing contaminant on area A of the crystal and Δf is equivalent change of crystal frequency. The density of spacecraft contamination is believed to be in the range of 0.8-1.5 gm/cm^3 [16]. For calculation purpose its average value is taken as unity. Hence in this case when Δm is converted to thickness 't' (in A unit) for the given MK10 15 MHz TQCM one gets [18]

$$t\,(A) = 0.197\,(A/Hz) \times f\,(Hz) \qquad (3)$$

Or equivalently,

$$\Delta f\,(Hz) = 5.085\,(Hz/A) \times \Delta t\,(A) \qquad (4)$$

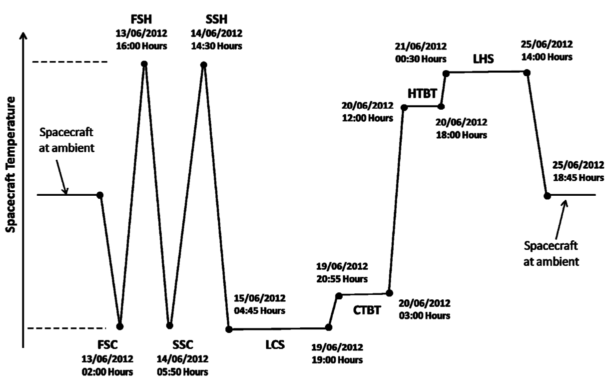

Fig. 2 TVP test profile of INSAT 3D spacecraft. FSC and SSC signify 'first short cold' and 'second short cold' respectively. Similarly FSH and SSH signify 'first short hot' and 'second short hot' respectively. TBT stands for 'thermal balance test', C and H means cold and hot. LCS and LHS mean 'long cold soak' and 'long hot soak' respectively.

Equation (4) tells that for 1 A thickness change on TQCM crystal, the frequency change is approximately 5 Hz.

TVP tests comprise of two short cold, two short hot, long cold soak, thermal balance test and long hot soak as shown in Fig. 2 [20]. Chamber temperature was maintained at -100^o C while average chamber vacuum was around 3×10^{-6} mbar. TQCM was switched on when chamber temperature reached -100^{o}C . TQCM crystal temperature was maintained at -40^{o}C for entire duration of test. The duration of TVP test (in first phase) was around 20115 minutes (335.25 hours ≈14 days) [20, 22]. During different phases of the test, temperature of satellite systems are changed for the performance verifications. This changes the outgassing behavior of spacecraft (due to changes in temperature). For a number of reasons a mathematical modeling for outgassing-time (or outgassing-temperature) for a spacecraft like object is much difficult to establish [23]. Therefore in this paper we investigate the 'behavior of spacecraft outgassing' based on available TQCM data. TQCM data was recorded in every two minutes interval and their variations in different phases of the test were analyzed. Subsequent sections mention in detail the response of TQCM frequency for various test phases of INSAT 3D.

A. TQCM response during First Short Cold

Low ambient temperature (-100^{o}C) of chamber radiatively cools the spacecraft. In initial tests some of the spacecraft elements are allowed to reach upto -20 ^{o}C for a relatively short time [20]. This is known as 'First Short Cold' (FSC). FSC was attained around 415 minutes (≈ 6.9 hours) after chamber attained -100^o C. Plot of TQCM frequency with time for this duration is shown in Fig. 3. From the time dependency

of outgassing it is believed that much of the spacecraft outgassing happen in first few hours after being exposed to space environment. It is known that outgassing sensitively depends upon the temperature. During 'FSC transition period' spacecraft temperature is not constant.

From the behavior of crystal frequency-time (f-t) plot three region can be identified (see Fig. 3). Region I (which we mark up to 130 minutes (≈ 2.17 hours) shows a comparatively fast decrease in frequency and a much complicate behavior with time. In Region II (that lasts upto around 350 minutes ≈5.83 hours), f-t profile is exponential while in Region III it is comparatively linear. Region III extends upto 680 minutes. It is clear that on exposing spacecraft in vacuum surface desorption will happen earlier than diffusive process. The reason being that in diffusive process molecules diffuses from the bulk of material and then desorbs from surface to ambient

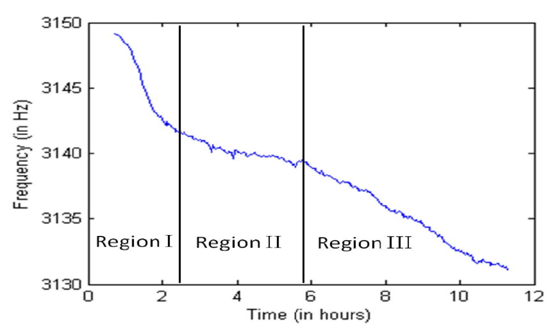

Fig. 3 Plot of crystal frequency with time during FSC.

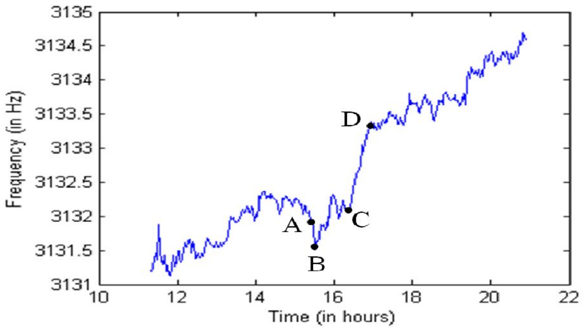

Fig. 4 Plot of crystal frequency with time during First Short Hot transition.

environment. Therefore we conclude that Region II shows an excess surface desorption of outgassed molecules while Region III shows the region of comparative low surface desorption than diffusive outgassed molecules from spacecraft and metal outgassing.

B. TQCM response during First Short Hot transition

After completion of tests in FSC, the next phase of the TVP test is 'First Short Hot' (FSH). During FSH some of the spacecraft elements temperatures are raised (for a comparatively short period) as per the mission requirements for checking health performance for various components at their extreme operational temperature. At this stage some of the spacecrafts elements are raised upto around 45^o C [20]. FSH is reached at t=1255 minutes (≈ 20.9 hours). f-t plot during FSH transition is shown in Fig. 4. Two regions are noticeable. A→B shows a steep dive in outgassing reading while region C→D shows a steep rise. Region A→B lasts for two minutes and coincide with the timing of two minutes temporary shutdown of CATVAC operations (due to power failure). During this time IR cage lamps which are used for heating of spacecraft elements were off. This resulted in a sudden radiative cooling of spacecraft which reduced the outgassing. As a result of shut down cooling of thermal shrouds stops and thermal control units (TCU) take its own dynamic time to restore the temperature with a finite ramp rate. The steep rise in region C→D is due to temperature rise (from -100^o C) of thermal shrouds (TCU-9) near to which TQCM is located. At point C, TCU-9 thermal shroud temperature is -86.6^o C.

C. TQCM response between two Short Hot

On completing the tests on FSH, transition starts for 'Second Short Cold' (SSC). After SSC reached, the next phase of the test is 'Second Short Hot' (SSH). Spacecraft's elements temperatures are changed as per the tests requirements [20]. At around t = 2025 minutes (≈33.75 hours), SSC was declared and transition to SSH start. SSH was declared at around t ≈ 2605 minutes (≈ 43.42 hours). Crystal frequency response during two successive 'Short Hot' is shown in Fig. 5. Theoretical discussion of crystal f-t response for this time duration is as follows:

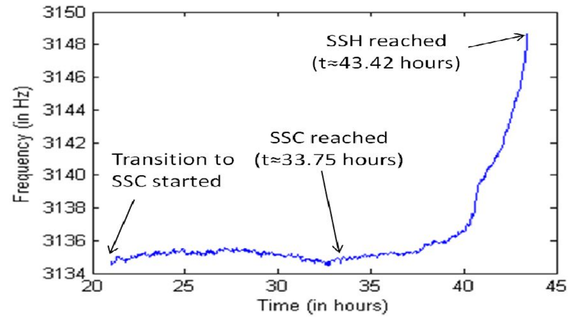

Fig. 5 Plot of crystal frequency with time during two successive 'Short Hot'.

On a pure theoretical basis the amount of contamination on
a surface at a time t is [11]

$$C_t = C_0 e^{-\frac{t}{\tau}} \quad (5)$$

where τ is the residence time which exponentially depends on desorption energy and temperature. It is calculated as [23, 24]

$$\tau = \tau_0 e^{\frac{E_{des}}{RT}} \quad (6)$$

where R is the gas constant and τ_0 is the vibrational period of contaminant molecule. Its value is approximately considered independent of temperature; $\tau_0 = 10^{-13}$ s . From (5) and (6) it is clear that an increase in temperature will result in an exponential-like increase in thermal outgassing. Such exponential-like variation in outgassing is seen in transition period to SSH. However such exponential-like increase in crystal frequency reading is not observed during FSH transition (see Fig. 4). The reason for this might be relatively short duration of SSH transition as compared to FSH transition [20]. SSH transition is approximately 3.2 hours faster than FSH transition. In context of desorption and diffusion a possible reason of this observation is discussed in next paragraph.

Much of the outgassing is released within first few hours of spacecraft exposed to vacuum. With this fact it can be concluded that by the time FSH transition starts (Fig. 4), the outgassing due to surface desorption was minimal while diffusive processes are still active to migrate contamination molecules to the surface. During SSC surface desorption will again be minimal due to low temperature and diffusive processes will continue to help contamination species for building up concentration towards the surfaces. This large surface concentration (as compared to surface concentration available during FSH) will show a prominent thermal outgassing with temperature. This could be a reason for an observed rise in crystal frequency during FSH transition (Fig. 5).

D. TQCM response during Long Cold Soak

After the SSH completed the next phase of spacecraft test starts which is known as 'Long Cold Soak' (LCS). During LCS spacecraft's elements temperatures are changed depending upon performance verification as per the mission

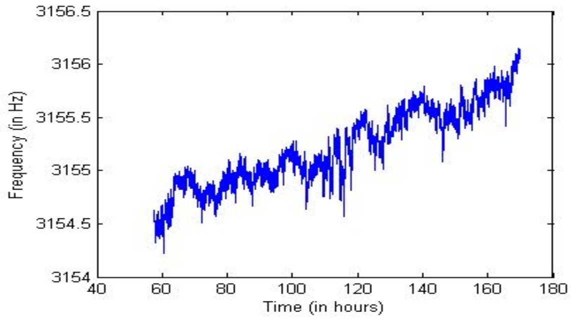

Fig. 6 Plot of crystal frequency with time during Long Cold Soak.

requirements. Usually their temperatures are maintained at relatively low temperature for a considerable long period of time. The duration of LCS for INSAT 3D is around 6730 minutes (≈ 4.6 days) in first TVP test. f-t plot for this duration is shown in Fig. 6. It can be seen that f-t profile is flat and crystal frequency change is only around 0.4 Hz/day. This small figure supports low outgassing due to comparatively low temperature of spacecraft in LCS.

E. TQCM response during Thermal Balance Test

After the completion of LCS, TBT of INSAT 3D was conducted in two parts, Cold TBT and Hot TBT. Total duration of TBT was around 21 hours. Stabilized temperature of spacecraft's elements during Cold TBT is lower than that of Hot TBT. f-t profile of the crystal for TBT duration is shown in Fig 7. It is noticeable that before the onset of Hot TBT transition, f-t profile is relatively flat. During Hot TBT, f-t profile is approximately increases with time. Total change in frequency for Hot TBT is 0.69 Hz which amounts to a change of 0.78 Hz/day.

F. TQCM response during Long Hot Soak

During spacecraft TVP test at Long Hot Soak (LHS), spacecraft's elements temperatures are raised and maintained at comparatively higher temperature for a long duration. Duration of LHS for INSAT 3D was around 6520 minutes (≈4.5 days). Some of the spacecrafts elements can go upto 50 ^{o}C [20] during LHS. As a result of comparative higher temperature of spacecraft much of the outgassing are forced out during LHS and one can expect substantial rise in TQCM crystal frequency. f-t profile of the crystal is shown in Fig. 8 for LHS duration. It can be seen that crystal frequency approximately linearly increases with time. Also a well defined peak having maxima at t=13924 min (≈232 hours) is noticeable which indicate a sudden increase in outgassing. This happen due to temporary shutdown of Cryo pumps during CATVAC operation. Due to this cryo heads temperature increased. As a result trapped outgassed molecules by Cryo pumps liberated back into the chamber and TQCM crystal frequency responded accordingly. f-t profile for the testing specimen (spacecraft) was restored after around one hour. It is because that cold chamber temperature -100^{o} C (as compared to TQCM crystal temperature -40^{o} C)

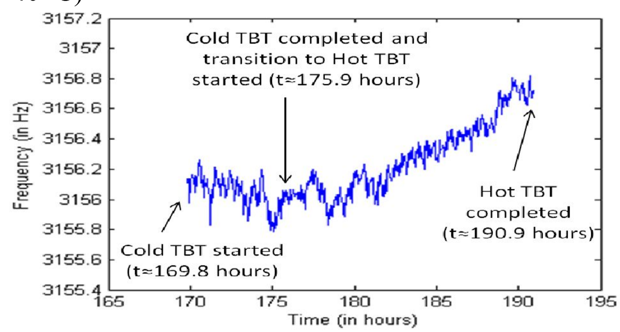

Fig. 7 Plot of crystal frequency with time during Thermal Balance Test.

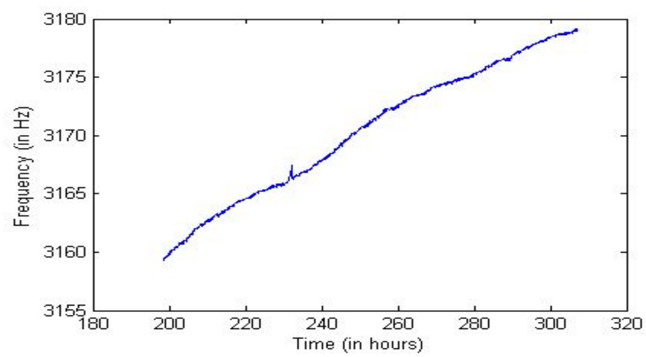

Fig. 8 Plot of crystal frequency with time during Long Hot Soak.

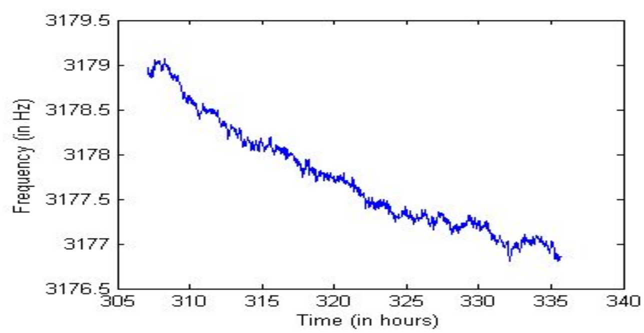

Fig. 9 Plot of crystal frequency during ambient transition of satellite after the end of Long Hot Soak.

acts as a large scavenger panel and hence acts as an efficient sink for the background outgassing [10]. This isolates background outgassing by condensing them on cold thermal shrouds. An average change in frequency during LHS is found to be 4.33 Hz/day.

G. TQCM response after the end of Long Hot Soak

Satellite transition to ambient started around t=18425 min (while thermal shrouds remain at -100^{o} C) and all tests were completed by t=20140 minutes (≈ 335.67 hours). f-t profile for this duration is shown in Fig. 9. With decrease in temperature outgassing decrease. This fact is reflected in f-t profile. Average change in frequency for this duration is found to be -1.89 Hz/day.

V. TQCM FREQUENCY CHANGE IN CONSECUTIVE HOURS OF TEST

Changes of TQCM frequency in each hour serve as important criteria for chamber certification/qualification for TVP tests, hardware bakeout, test article outgassing etc. For example QCM value of 300 Hz/hr is a general criterion for hardware bakeout process or chamber certification. Negligent QCM readings (< 1Hz/hr) represents that test article is required to meet stringent control over outgassing or the test conducted at low temperatures (see [10] for details).

INSAT 3D TVP test was conducted at comparatively low ambient temperature. It is because that around 90-95 K temperature environments were also provided to Sounder and Imager Cooler patches [20], [21] by the use of two unit area Cryo-target plates. The Cryo-target plates were cooled by liquid nitrogen in a closed loop circulation [25] and maintained around 80 K for duration of around 240 hours. This duration cover SSH, LCS, TBT and LHS. Hence one can expect an over all low outgassing (Δf/hr <1 Hz/hr) during the whole satellite test duration. Plot of frequency change in consecutive hours (Δf/hr) for LCS, and LHS durations is shown in Fig. 10 and 11 respectively. From these figures it is seen that |Δf/hr| <1 Hz/hr is accompanied (for MK10 15 MHz TQCM crystal). For LCS, Δf/hr is randomly distributed about zero. For LHS, Δf/hr values are more towards positive side indicating higher outgassing as compared to LCS. Only at few places Δf/hr is negative during LHS. The negative values is never smaller than -0.1 Hz/hr. Δf/hr < 1Hz/hr for LCS and LHS reflects excellent cleanliness of INSAT 3D in respect of outgassing at low temperature.

CONCLUSIONS

In this paper we have investigated the response of TQCM frequency in various phases of TVP test of INSAT 3D conducted in CATVAC. It is found that outgassing characteristics strongly depends upon satellite temperature. It is seen that much of the outgassing was removed upto Second Hot. Phenomena of surface desorption and thermal outgassing has been observed during First Short Cold and Second Short Hot transition. It is reasoned that prominent outgassing during Second Short Hot transition might be due to accumulation of contaminant molecule near to the surface as a result of migration in diffusive processes. We have pointed out that background outgassing is sensitively depends over temperature variation of thermal shrouds as well as temperature of cryo heads.

Average change of crystal frequency during Long Cold Soak and Long Hot Soak is 0.4 Hz/day and 4.33 Hz/day respectively. These figures indicate approximately eleven times more outgassing liberated during Long Hot Soak as compared to Long Cold Soak. For the whole duration of TVP test (≈334.9 hours) total TQCM frequency change was found to be 27.697 Hz . This small figure indicates excellent cleanliness of INSAT 3D spacecraft

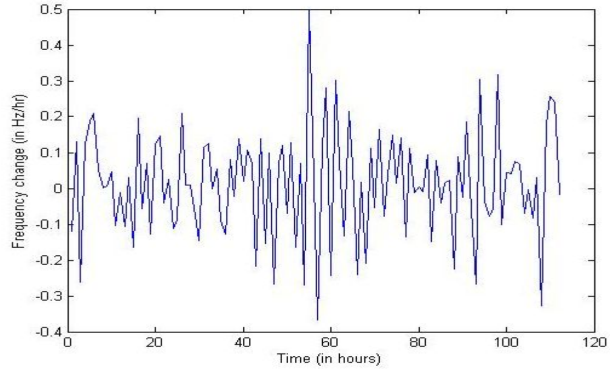

Fig. 10 Plot of TQCM frequency change in consecutive hours for the duration of Long Cold Soak. Note that Δf/hr is never more than 0.5 Hz/hr.

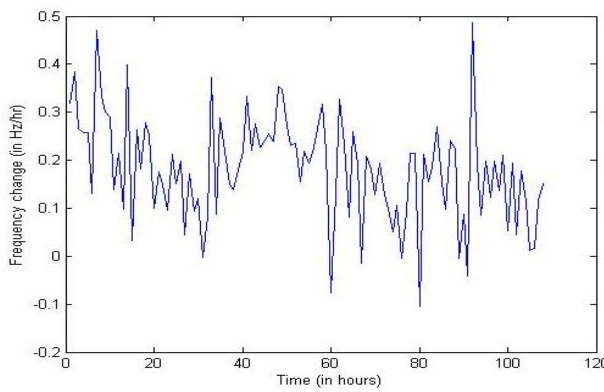

Fig. 11 Plot of TQCM frequency change in consecutive hours for the duration of Long Hot Soak. Note that Δf/hr is never more than 0.5 Hz/hr.

in respect of contamination outgassing in high vacuum at low temperature.

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