Cassini Main Engine Assembly Cover Flight Management and Performance

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Abstract—The Cassini spacecraft has performed its four year Prime Mission at Saturn and is currently in orbit at Saturn performing a two year extended mission. [1][2]Its main engine nozzles are susceptible to impact damage from micrometeoroids and on-orbit dust. The spacecraft has an articulating device known as the Main Engine Assembly (MEA) cover which can close and shield the main engines from these threats. The cover opens to allow for main engine burns that are necessary to maintain the trajectory. Periodically updated analyses of potential on-orbit dust hazard threats have resulted in the need to continue to use the MEA cover beyond its intended use and beyond its design life. This paper provides a detailed Systems-level overview of the flight management of the MEA cover device and its flight performance to date.

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1. INTRODUCTION

The Cassini-Huygens spacecraft was developed in the early 1990s with the Prime Mission of exploring the Saturnian system. It was developed by an international coalition headed by the National Aeronautics and Space Administration and partnered with the European Space Agency and the Italian Space Agency. The orbiter is equipped with a suite of 12 science instruments and carried the Huygens probe that soft landed on the surface of Titan, Cassini's largest moon. In order to keep Cassini on tour and perform close fly-bys of the various moons of Saturn, four thruster clusters (including a fully redundant set of thrusters) and the Main Engine Assembly (MEA, consisting of a prime and backup engine) are utilized during Trajectory Correction Maneuvers (TCMs), which were used to get Cassini to Saturn, and Orbit Trim Maneuvers (OTMs), which are used to keep Cassini on its prescribed orbital tour.

Late in the development of the spacecraft, it was determined that the MEA was vulnerable to micrometeoroid impacts during the cruise to Saturn. The primary susceptible object is the fragile disilicide coating, which prevents oxidization on the columbium nozzles of the MEA. Even a small chip to this outer coating could lead to engine burn-through which could be hardware catastrophic [1]. To protect the nozzles from micrometeoroid impacts, a retrofitted cover was designed and installed at the Jet Propulsion Laboratory. During the flight to Saturn, updated environmental threat analyses performed by Project Mission Planning (MP) resulted in the need to continue to use the MEA cover throughout the Prime Mission at Saturn (ended at 6/30/2008) and beyond (probably until 9/15/2017).

Requirement driven flight consumable constraints were imposed with respect to an operational articulation cycle life and the cumulative open duration from launch through flight past the Jovian system (6 AU). Continued use of the cover beyond Saturn orbit insertion (SOI) raised serious concerns with respect to its flight operational cycle life.

To avoid permanent damage to the cover and potentially the MEA by a main engine burn, a prelaunch requirement was established with respect to the acute angle that must be achieved (stow angle) by the open cover. The criterion required verification on the ground prior to commanding a main engine burn. During flight, increasing cover stiffness was observed and became a long-term anomaly. Increased cover stiffness caused a variation in the stow angle across the cover. As a result, a new stow angle criteria had to be developed for each main engine as the stow angle relative to the two nozzles was different.

In addition, a prelaunch criterion with respect to delaying closure of the cover over a hot nozzle had to be reevaluated

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to comply with SOI constraints. Flight experience revealed that the manner in which the cover was exposed to engine heat and subsequent cooling resulted in changes in the cover stiffness.

This paper provides a Systems-level overview of how the MEA cover use has been managed in flight to meet Project requirements while dealing with consumable constraints. It also provides a flight performance history of the MEA cover assembly. The paper focuses on early flight, the cruise to Saturn, SOI, the Prime Mission at Saturn, and touches on extended mission circumstances. Associated telemetry, commanding techniques, contingency planning, and anomalies are also addressed.

2. HARDWARE AND INSTRUMENTATION DESCRIPTION

The MEA cover is located on the +Z end of the spacecraft and stows towards the probe side of the spacecraft, shown in Figure 1 [1]. The cover is an articulating device that is driven by commanding a Dual Drive Actuator (DDA); either or both motors can be used. The MEA cover is closed (deployed) to protect the two main engine nozzles from micrometeoroid damage, and it is stowed to enable main engine use. When deployed, it forms a hemisphere over the main engines to protect them and when it is stowed it forms a folded wedge sufficiently flat to allow for the main engines to be used without harming either the main engines or the cover itself. Figure 2(a)-(c) shows the deployed, partially stowed, and stowed configuration of the engineering model of the cover on a test stand [2].

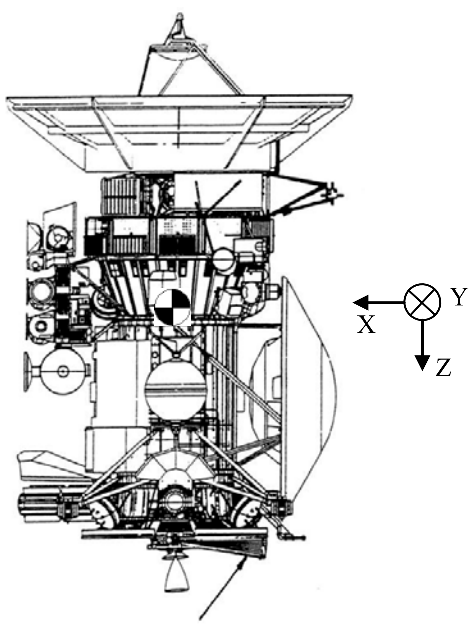


Figure 1 – Cassini spacecraft showing MEA cover

(a)
(b)
(c)

Figure 2(a)-(c) – Engineering model of MEA cover (a) deployed, (b) partially stowed, and (c) stowed while mounted to a test stand

The cover itself is composed of a multi-layered insulation (MLI) blanket attached to a framework of tubes that make the 2.1 m diameter hemispherical shape. The four layer MLI was originally designed to be made of two layers of beta cloth sandwiched between two layers of aluminized Kapton. However, because of flexibility and cracking issues with the aluminized Kapton, a material change was made for the flight unit substituting carbon-filled Kapton instead. The MLI is tied around a Fixed Bow on one end and a Drive Bow on the other end, both made of aluminum tubing. Between the Fixed and Drive Bows are eight Full Stays and seven Partial Stays, all made of graphite-epoxy, to give the hemispherical shape and structure and allow the cover to fold in an accordion like manner as shown in

Figure 2(c). The stays are sewn into pleats [1]. Figure 3 shows the flight cover on the spacecraft in the stowed position [2].

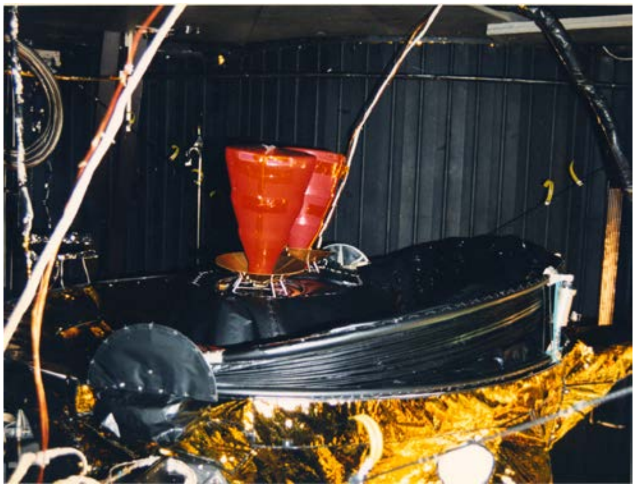


Figure 3 – Flight MEA cover mounted to the spacecraft in the stowed position

Each side has titanium hubs that guide the folding motion of the cover. The ends of the Fixed Bow are bolted to the hubs and the ends of the Drive Bow are contained within the hubs. One side contains the DDA and the other side an Idler mechanism, shown in Figure 4 [1]. The eight Full Stays between the bows also pivot within the hubs via 15-5 stainless steel rib end fittings that were bonded to the ends of the Full Stays. The Partial Stays were sewn into the cover between each Full Stay. The entire MEA cover assembly, including the DDA and Idler mechanism, has a mass of 26.47 kg. In the event of cover failure in the deployed or partially stowed position, where the use of the MEA is obstructed, pyrotechnic bolt cutters were installed to jettison the cover. The ejected mass of 18.28 kg does not include the DDA or Idler mechanism [1].

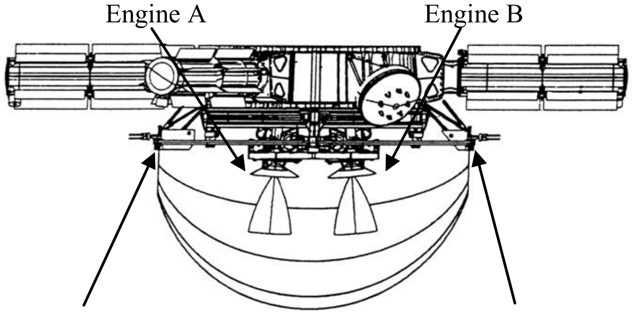


Figure 4 – Close-up of lower section of spacecraft showing MEA cover configuration

The MEA cover has been instrumented to provide the required telemetry to indicate the performance of the cover, its state at a given time, and to provide valuable anomaly resolution information. A potentiometer on the axis of rotation on the Idler side provides the position of the Drive Bow in terms of angular position in degrees. When the cover is stowed, the DDA compresses the cover into a folded wedge and the resistance of the folded cover determines the acute angle of the cover read by the potentiometer; the pre-load of the DDA is retained in the stow direction and the Drive Bow cannot be back driven. To deploy the cover, the DDA drives the Drive Bow onto a hard stop and the potentiometer indicates the cover is fully deployed at essentially 180 degrees. The DDA has two microswitches in it. One provides a stow indication and the other provides a fully deployed indication as determined at the DDA side of the axis of rotation. When the drive bow on the DDA side is in between these positions, the stow switch will indicate the cover is not stowed and the deploy switch will indicate the cover is not deployed [1]. Given the DDA is on the opposite side of the axis of rotation from the potentiometer, the potentiometer and microswitch readings can be used to estimate angular twist in the drive bow when the cover is stowed.

In addition, telemetry is provided for each motor in the DDA that reveals the temperature of the motor (°C), the load current the motor is drawing (Amps), and status indications that reveal if the motor is on or off. Status indication telemetry is also provided that shows if the bolt cutters have been fired or not, thus providing an indication of whether the cover has been jettisoned or not.

During the majority of the cruise to Saturn and on orbit, the above telemetry provided ample data to not only determine the state of the MEA cover, but also to observe the behavior of the cover in motion and the behavior of the motor(s) when powered.

3. Flight Management Overview

A Systems-level approach has been taken to manage the flight operations of the MEA cover as well as maintaining its health and safety. This approach is based upon a "Team" architecture that utilizes the skills of various Cassini Project Teams and cognizant development personnel.

The Thermal/Devices Team (T/D) within the Project's Spacecraft Operations Office (SCO) was tasked with operating the MEA cover and maintaining a direct link between the Project and cognizant development personnel throughout flight. T/D interfaces directly with cognizant development personnel on cover related issues and provides necessary support for them as required. T/D is responsible for all commanding generated for the MEA cover, for ensuring flight consumables associated with the cover are managed appropriately and reported to MP, for flight monitoring and reporting on cover performance to the

Project and to cognizant development personnel, and for being a focal point with respect to cover related contingency planning and anomaly resolution.

MP tracks and reports on spacecraft consumables and their allocations [3]. Since launch, they have periodically reevaluated the risk of environmental dangers (micrometeoroids/dust) to the main engine nozzles using updated knowledge and they have defined hazard periods where the cover must be deployed. In addition, they have worked with T/D and cognizant development personnel to update cover related consumables when required.

The SCO Systems Team works with T/D to strategically time cover articulations to be compatible with dust hazard periods and the use of the main engines for maneuvers. The two teams work together to incorporate cover articulation commanding into the command sequence development process and with respect to cover related contingency planning, which has also involved cognizant development personnel [4].

The Navigation Team, which plays a critical role in the development of maneuvers and their subsequent evaluation, also stays in the loop with respect to MEA cover planning to help ensure a needed maneuver is not jeopardized by a cover issue.

T/D also works with the SCO Attitude Control Team (AACS) to ensure the MEA cover is stowed for low altitude flybys of Saturn's moon Titan. These flybys travel through the upper rarefied atmosphere of Titan and having the cover stowed is beneficial to the AACS effort of reconstructing the atmospheric density profile the spacecraft has flown through.

The most frequent use of the MEA cover has been in orbit at Saturn. This is due to the number of dust hazards and the number of maneuvers required to remain on tour and meet the science objectives. As a result, regularly scheduled meetings have been held during the mission at Saturn for the purpose of reviewing the planned strategy for upcoming activity periods, identifying any potential problems that may arise, identifying contingency planning, and if need be, change the strategy if required.

4. RISK, CONSUMABLES AND CONSTRAINTS

Risk Management

The MEA cover is used frequently in the Saturn system to manage the risks of harmful dust impacts upon the main engine nozzles. The Cassini Project Policies and Requirements Document explicitly controls the risk of loss of mission due to environmental hazards [5]. However, loss of both nozzles does not constitute loss of mission, but merely loss of maneuverability. The spacecraft could continue to function and collect reduced science, though with very limited capabilities to navigate the Saturnian system. Furthermore, loss of one nozzle, such as a burn-through during a maneuver after a harmful dust impact, will not necessarily cause the redundant nozzle to fail. Therefore, the Project Policy requirement of 5% risk was applied to the nozzle risk management as a goal.

Prelaunch risk analysis for cruise led to an accumulative cover stowed duration consumable limit for the cover until the spacecraft passed a heliocentric distance of 6 AU on its cruise to Saturn. This consumable is discussed in more detail in the *Consumables* section below.

The MEA cover was designed to be used only during the cruise phase up until SOI and Cassini was launched while analyses showed this limited use of the cover would be sufficient for the entire mission. During cruise, updated risk analyses by MP showed it would be essential to continue to use the cover while on orbit. In order to continue to do this, a trade-off between risk to the nozzles and continued use of the cover was made.

For the four year Prime Mission, MP calculated the risk of losing a nozzle for each hazard period that the spacecraft would encounter on its trajectory based upon the most recent environmental model. Then the dust hazards were organized from highest risk to lowest risk. To determine the cover cycles required, the approach was to assume that the cover would be deployed for each dust hazard starting with the highest risk until the remaining lower risk dust hazards had an accumulated risk that met the 5% goal. This analysis was periodically updated as new environmental data became available. The latest post-mission risk assessment of losing a nozzle is 84.9% if the cover was not used. There were a sufficient number of relatively low risk dust hazards that to meet the 5% goal required unreasonable use of the cover. A realistic compromise was reached at the time of each reevaluation and the latest post-mission probability assessment of losing a nozzle is 9.3% given the cover usage that was employed for the Prime Mission.

The 5% risk goal has been applied to the extended missions as well. For the first extended mission (Equinox Mission), which is currently in progress and will continue until 7/1/2010, the latest assessment of the risk of losing a nozzle is 86.1% if the cover is not used. Current planned cover usage drops the risk to 4.9%. For the second extended mission (Solstice Mission) currently being planned, which would start on 7/1/2010 and end on 9/15/2017, the latest assessment of the risk of losing a nozzle is 76.5% if the cover is not used. Current planned cover usage drops the risk to 2.7%. Given these three missions constitute the complete Cassini mission as currently planned, the majority of the risk has been successfully navigated without nozzle damage prior to 2009.

Consumables

The MEA cover has two flight consumables associated with it. The first is the total accumulative cover stowed duration during cruise between launch and the time the spacecraft reaches a heliocentric distance of 6 AU on its trajectory to Saturn. The concern is exposure of the main engine nozzles to micrometeoroids and the significance of 6 AU is that this distance represents having flown beyond the Jovian system and having passed through the part of the cruise with the highest potential for nozzle damage. The consumable limit for this part of the cruise is an accumulative stowed duration of 10 days [3].

The flight duration from launch to 6 AU was approximately 3 years and 9.5 months and covered many activities where the MEA cover had to be stowed for a period of time. These activities included launch (the cover was stowed for launch), the Venting and Priming of the main engines, and TCMs. There were 17 TCMs planned during this period and five TCMs were cancelled. The actual total accumulative cover stowed duration consumable in flight turned out to be only 4 days and 34 minutes between launch and reaching 6 AU on 7/3/2001, which was well within the allowable 10 day limit, as seen in Figure 5. While no longer a consumable issue, between 6 AU and the stowing of the cover for SOI preparation on 5/27/2004, the strategy of minimizing the stow duration was continued as a safeguard for the nozzles.

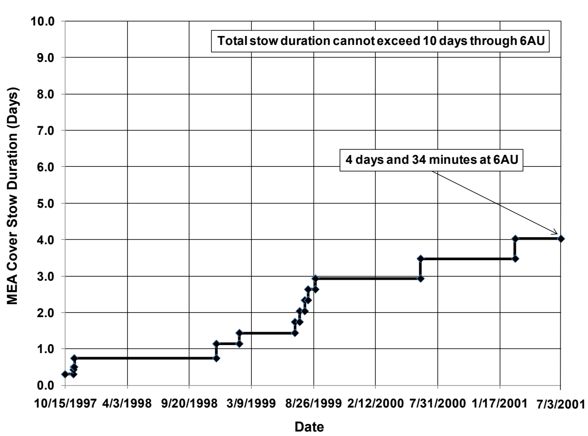


Figure 5 – MEA cover stow duration consumable history from launch

The second consumable is a design limit on the number of cycles the MEA cover can perform in flight. One cycle is the sum of both a deployment articulation and a stow articulation. A stow or deployment by itself is considered half a cycle. The design of the MEA cover was based upon the prelaunch requirement to only use the MEA cover up to SOI. The consumable limit was 50 cycles on the flight hardware in total with an operational life requirement of 20 cycles in flight, with 30 cycles being used prior to launch [3, 6, 7].

The 20 cycle in-flight limit was in part based upon the uniqueness of the device, potential unit-to-unit variability in workmanship, material changes, and intermediate stay size changes implemented for the flight unit [7].

Given the post launch deployment, the Venting and Priming activity, and 22 TCMs planned prior to the MEA cover being stowed for SOI, with only three being performed on thrusters (the cover can remain deployed for thruster TCMs), the 20 cycle limit appeared slightly in jeopardy. However, five of the TCMs were cancelled during cruise, resulting in only 15 flight cycles being used prior to SOI, which was within the 20 cycle limit.

Once in orbit, the cover was managed in a different manner. The approach was no longer to minimize the amount of time the cover was stowed, but rather to minimize the number of articulation cycles required. The cover had to be deployed for dust hazards defined by MP and it had to be stowed for all OTM windows planned. When there were more than one OTM window without a dust hazard in-between, the cover would remain stowed. When there were more than one dust hazard without an OTM window in-between, the cover would remain deployed.

SOI was on 7/1/2004 and on 4/1/2005 the 20 cycle consumable limit was reached; the Prime Mission would continue until 7/1/2008. Anticipating this problem from updated risk analyses for the Prime Mission, T/D worked with cognizant development personnel, MP, and Project management to reevaluate the possibility of extending the consumable limit. If not, the cover could not be used after 20 flight cycles. A ruling by the development organization concluded that an extension was valid on the basis of the similarity of the engineering model tested to the flight unit and that the difference in flight materials constituted a better design with respect to brittleness and stiffness [7]. As a result, on 3/22/2005 the flight cycle consumable limit was increased to 37 cycles.

The Prime Mission lasted until 7/1/2008 with a follow on Equinox Mission lasting until 7/1/2010. MEA cover cycle 37 would be reached on 3/13/2008. Here again the consumable limit needed to be readdressed. This time it would not be a matter of reevaluating the development testing as there was no question the 37 flight cycle limit was appropriate, but rather performing a risk tradeoff between continuing to use the MEA cover beyond its design life versus the threat to the nozzles if its use were discontinued. Here again T/D worked with cognizant development personnel, MP, and Project management to address the issue.

While only a few months of the Prime Mission remained, an updated analysis suggested that discontinuing the use of the cover after 37 flight cycles would increase the risk of losing a nozzle by approximately 14% with only 2.5 additional cycles required to complete the Prime Mission. An evaluation of a two year Equinox Mission had been made by that time and those results suggested the risk of a nozzle loss without cover use would be roughly 54% over the two year period. This risk level was more than a factor of 10 above the prescribed 5% goal. It was estimated that approximately 19.5 additional cycles would be required in the Equinox Mission, which would bring the flight total up to 59 cycles. Thus, the total cycles on the flight unit (ground testing plus flight) would be approximately 89 cycles.

As part of the effort to address the consumable limit issue, development and operations personnel focused on many aging MEA cover hardware issues such as cover stiffness, cover material cracking and shedding, aging pyrotechnic (bolt cutter) reliability, DDA failure, jam in the pivot hub, and loss of telemetry. After several months of evaluation it was concluded that the risk of continued MEA cover use was low to moderate compared to the risk to the nozzles from future dust hazards. The Cassini Project proposed waiving the in-flight cycle consumable after 37 cycles for the remainder of the flight and to continue to use the MEA cover on a best effort basis. A contingency plan, already in place, would be used to deal with anomalies should they occur and cognizant development personnel would continue to work with the Project, as appropriate [4]. A review was held on the subject on 11/2/2007 and cognizant development personnel agreed on the solution and agreed to work for a development organization consensus required for approval of the waiver. This was accomplished and the waiver was approved on 2/6/2008 when 36 in-flight cycles had been used to date.

The latest risk evaluation for the Equinox Mission period shows the probability of losing a nozzle without cover use is now up to 86.1%, which has resulted in two additional cover cycles being required. As a result, now 21.5 cycles are required for the Equinox Mission to bring the risk down to 4.9%. That will bring the flight total up to 61 cycles and the total cycles on the flight unit up to 91 cycles by the end of the Equinox Mission on 6/30/2010.

Cognizant development personnel remain in the loop with T/D and continue to review flight performance data looking for signs of degradation and potential failure mechanisms. In addition, due to age and radiation exposure of the bolt cutters' booster charge, concern remains with respect to their reliability. A test program has been proposed and is currently under evaluation by the Cassini Project.

Thermal Considerations

No explicit temperature requirements were levied on the cover itself, but they were on the DDA. These were operational and non-operational flight allowable temperature limits [8]. The allowable temperature range for DDA operation was -35°C to +44°C and for non-operational conditions -48°C to +55°C. These temperature ranges were for the motors in the DDA, which were equipped with temperature sensors. Over the course of the flight to date, typically the quiescent motors have been in the range of +10°C to +25°C. During the early flight activities (post-launch deployment, Venting and Priming, and TCM-1) a single motor was used for an articulation and was turned on for 10 minutes. This resulted in a +6°C to +7°C rise of the active motor temperature and approximately +2°C for the motor not used. In subsequent articulations, a motor would be turned on for 6 minutes. This resulted in a +3°C to +4°C rise of the active motor temperature and approximately +1°C for the motor not used.

From available telemetry throughout the flight to date, the motors have never been colder than +10°C and never hotter than +34°C following a large main engine burn. It is clear the motor temperatures have stayed well within flight allowable temperature limits.

Figure 6 shows the cruise trajectory from launch to Saturn. The heliocentric distance variation was from 0.67 AU at Venus to 9.04 AU at SOI. During the Prime Mission the heliocentric distance at Saturn only varied from 9.04 to 9.31 AU and for the Equinox Mission the heliocentric distance is not expected to exceed 9.54 AU.

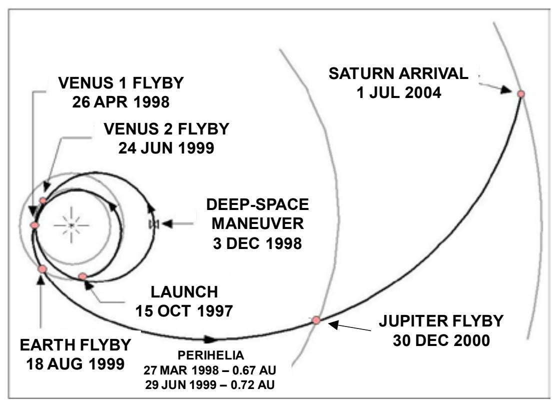


Figure 6 – Cassini cruise trajectory

Inside 5 AU, thermal requirements dictated that the spacecraft remain sun pointed and the high gain antenna be used to shade it [8]. One exception was that at certain times the spacecraft could point at Earth when the sun and Earth were lined up properly such that the angle between them was small. The other exception was that the spacecraft could turn off sun temporarily to perform TCMs with the condition that it must do this in a certain manner and within a limited time that was a function of heliocentric distance [8]. This limited time protected spacecraft hardware from overheating, including the MEA cover materials. The stowed cover was folded on the –X side and was exposed to the sun in such cases.

Prior to commanding a main engine burn, it has to be verified from telemetry that the stow angle has met the criterion of being sufficiently stowed so that the burn cannot thermally damage the cover. From a thermal perspective, it was important to know how long to wait post-burn to safely deploy the cover. During cruise, the cover had to be deployed between two and four hours after a main engine burn. This was conservative timing based upon pre-launch analysis that was designed to keep the cover from being deployed too soon for thermal reasons and also assumed there would be no need to deploy the cover sooner.

Detailed analysis required for SOI would lead to the elimination of the required two hour delay in deploying the cover for the rest of the flight and leave the option open to deploy the cover as early as 2 minutes and 5 seconds after main engine burn completion, if conditions required such a quick response [9]. It was determined that 2 minutes and 5 seconds after burn completion, exposure to the hot nozzle could no longer damage the cover because of the cooling the nozzle had experienced during this short time period. Deploying the cover this soon did increase the soakback temperature effect for the MEA, but not enough to be a thermal concern. If the need to deploy soon was not urgent, such as to protect the nozzles against a defined dust hazard, then it was recommended that the cover not be deployed for two hours post-burn to allow for thermal equilibration of the main engine.

Stow and Deployment Criteria

In order to prevent thermal damage, a stow criterion for the cover was required and had to be verified in telemetry before a main engine burn could be performed. Early in flight, based upon prelaunch analysis, the stow criterion was that the acute angle formed by the folded cover when stowed was ≤ 30 degrees as indicated by the potentiometer telemetry [10].

Later in flight, as the cover material experienced increased stiffness, criteria had to be established that was main engine dependent due to twist encountered in the drive bow [11]. In Figure 4 it can be seen that Engine A is closer to the DDA and Engine B is closer to the Idler and potentiometer. As a result, the stow angle is less for Engine A than Engine B due to stiffness in the cover causing twist in the drive bow. While the microswitch in the DDA would indicate the stow angle was ≤ 25 degrees the potentiometer on the Idler side may read a larger angle. By analysis, the new criteria developed for Engine A were that the potentiometer reading could be ≤ 45 degrees if a stowed indication was provided by the microswitch in the DDA. The potentiometer reading could only be ≤ 35 degrees if the stow microswitch failed in the DDA and no reading was provided. The new criteria developed for Engine B was that the potentiometer reading could only be ≤ 35 degrees with or without an indication of being stowed by the stow microswitch in the DDA. The deployment criteria is relatively simple in that the deploy microswitch must indicate the cover is deployed and the potentiometer must read ≥174 degrees.

Only Engine A has been used throughout the flight to date and there is no plan to use Engine B unless an anomaly would make it necessary. Engine B is a redundant main engine that can replace Engine A should it fail.

5. OPERATIONAL STRATEGY

The operational strategy for the MEA cover differed significantly during cruise, for SOI, and on orbit and needs to be addressed individually.

During the cruise to Saturn, the MEA cover was stowed only when necessary and as close to an activity as could reasonably be done. It would be deployed as soon as possible after an activity. This strategy ensured the consumable limits with respect to the accumulative stowed duration up to a heliocentric distance of 6 AU and the number of flight cycles were not violated. Only Motor A in the DDA was used and Motor B was available if needed. The exception was TCM-19, which is discussed later in this section.

The MEA cover would typically be stowed before an event with sufficient time to allow time for two sets of contingency commands, should an anomaly occur, in order to fix a problem and be able to continue with the planned activity. Two sets of contingency commands were considered sufficient for a simple anomaly and if that was not adequate then the activity would have to be delayed to deal with a more serious cover anomaly. The timing of the stow relative to the activity varied with the geocentric distance as the geocentric distance governed the amount of time it would take for commands to reach the spacecraft and the amount of time it would take for downlink telemetry to reach Earth.

Stow telemetry was monitored in real time when possible and verification by T/D of the acceptable stow criteria had to be made before the subsequent activity could be commanded.

The spacecraft went permanently to high gain antenna use on 2/1/2000, allowing MEA cover telemetry data to update every 64 seconds. This facilitated real-time monitoring of motion, motor current, and temperature signatures. Prior to that time the spacecraft most often used a low gain antenna and the data rate would vary as a function of geocentric distance, but would never provide cover telemetry more frequently than every 64 seconds. Prior to 2/1/2000, there were five TCMs performed at geocentric distances where relatively low telemetry rates were used and real-time monitoring was not practical. For these situations, memory read-outs (MROs) were commanded to downlink certain cover telemetry at specific times in order to verify the stow criteria had been met in a timely manner. However, when downlink rates were inadequate for deployment signatures to be discerned, typically MROs were not used and the data was monitored when available to determine that the deployment was complete. Contingency command files were ready in case a deployment anomaly occurred.

Cognizant development personnel were on call for all cover articulations to be able to respond should an anomaly occur. When available, the motion, motor current, and temperature signatures were provided after a cover articulation to cognizant development personnel for review. The results of each articulation would be included in a TCM report authored by T/D.

This strategy was also used beyond a heliocentric distance of 6 AU and all the way to TCM-20 on 5/27/2004, when the MEA cover was stowed in preparation for SOI on 7/1/2004.

For SOI, the MEA cover needed to be deployed as soon as possible after the main engine burn to avoid a relatively large dust hazard risk to the nozzles from the descending ring plane crossing. In addition, the commanding had to be single fault tolerant as ground intervention was not possible. In order to be single fault tolerant, both DDA motors had to be commanded simultaneously.

A detailed analysis was required to determine how soon after the burn the MEA cover could begin deployment [9]. The cover would have to be deployed after an 88 minute main engine burn and the early deployment would increase the soakback temperatures in the main engines. For SOI it was possible that the main engines could be swapped by the spacecraft to complete the burn and both nozzles and engines could be quite hot at SOI completion. The main engines are gimbaled, being controlled by the attitude control system, and the gimbal positioning post-burn also had to be taken into account as nozzle position was important. The analysis result was that the deployment could begin 2 minutes and 5 seconds after the burn completion without overheating any cover related hardware. This would cause the main engine combustion chamber and fuel and oxidizer valves to experience greater soakback heating, but was not a problem.

In order to be able to perform the dual motor deployment at SOI, a flight test was needed as Motor B had never been used in flight and not simultaneously with Motor A. The flight test had to provide verification for the predicted thermal behavior as well. No remaining main engine burn prior to SOI would be nearly as large as SOI. The flight test had to be performed in time to reevaluate the strategy should the flight test reveal a problem. For hardware safety considerations, the flight test was done as part of a relatively small main engine TCM so an unexpected result would not thermally harm the hardware. Given these considerations, it was decided to perform the test at TCM-19 on 5/1/2003, which was a relatively small main engine TCM (17.5 second burn) and was approximately 14 months before SOI. The MEA cover was commanded to start the deployment using both motors at 2 minutes and 5 seconds after the burn completion. From a thermal perspective, the thermal verification of the SOI solution would be made by thermally modeling TCM-19 and using the accuracy of the thermal analysis for TCM-19 (flight versus predict) to verify the thermal analysis approach used for SOI. The results for the MEA cover deployment revealed Motor B performance virtually identical to Motor A and completely nominal simultaneous motor operation as well. Thermally, the good correlation between predicts and flight performance for TCM-19 verified the thermal analysis approach used for SOI [12]. Motor B would only be used for TCM-19 and SOI. After SOI it would again become a backup motor to replace Motor A should it be needed.

Cognizant development personnel were on call for the SOI cover articulation and the data was reviewed as soon as it could be sent to the ground post event. A comprehensive contingency plan was in place for the MEA cover as part of a larger SOI contingency plan for anomaly resolution. The MEA cover contingency plan was later stripped out of the larger plan and became a single document [4]. The MEA cover deployment and all thermal aspects of performance at SOI were as expected.

On orbit, the strategy changed significantly. The goal was to minimize the number of cover cycles required while being able to perform anticipated OTMs and low altitude Titan flybys and still protect the nozzles from dust hazards. The only consumable applicable to the MEA cover would be the number of in-flight cycles.

MP determined which dust hazards required having the MEA cover deployed. This was accomplished for the entire Prime Mission and the Equinox Mission and an initial assessment has been made for the Solstice Mission. This knowledge was used in the command sequence development process to provide cover commanding for background command sequences that are loaded onboard the spacecraft and execute over long periods of time. Real time commands for cover articulations would only be used if needed for anomaly resolution as part of the contingency planning.

All OTMs would have backup windows associated with them and the MEA cover would have to be stowed for all these OTM opportunities, prime and backup, as any of these opportunities could end up being main engine OTMs. OTMs would be more frequent on orbit than had been the case for TCMs in cruise. While a cancellation of an OTM would be fairly common, this decision would typically be within a day or so of the OTM and too late to change the planned commanding of MEA cover articulations. Of the 161 OTMs planned for the four year Prime Mission, only 48 would end up being cancelled.

For all Titan flybys where the closest approach would be less than 1300 km, the spacecraft would be flying through the upper rarefied atmosphere and would have the cover stowed. This is the expected state, as typically these Titan flybys are between two OTMs. Having the cover stowed is beneficial to AACS which reconstructs the atmospheric density profile the spacecraft has flown through.

To minimize the number of cover cycles, the cover would remain deployed for periods of time where there were more than one dust hazard with no OTMs or low altitude Titan flybys in-between and it would remain stowed for periods of time where there were more than one OTM and/or low altitude Titan flybys with no dust hazards in-between.

T/D would immediately notify the Project and cognizant development personnel of the articulation performance for both stows and deployments. In addition, T/D would provide the data to cognizant development personnel for evaluation and include them in an OTM report. Cognizant development personnel would be on call for each articulation for potential anomaly support if required.

6. CONTINGENCY PLANNING

Failure of the MEA cover could eventually result in high mission risk if not dealt with rapidly and systematically. The two main faults the MEA cover can experience are an inability for the cover to articulate to the desired configuration or having inconsistent (or missing) telemetry outputs regarding the cover status. To deal with these two main faults, a systematic approach was developed for anomaly resolution. With the aid of the cognizant development personnel, who have a unique perspective on the hardware, an in-depth contingency plan was put together to deal with all the possible scenarios that may be encountered in flight [4].

The action taken during an anomaly is highly dependent on the fault scenario. Careful review of the telemetry and comparison to predicts or prior performance data is used to identify the anomaly or determine a telemetry inconsistency. In the event a cover articulation does not seem to execute as expected and the cause is not due to an obvious fault condition, then careful examination of the available data is necessary to determine the probable cause and course of action. Because indication of cover operation is based on a variety of independent telemetry, any of which can fail, detailed truth tables were developed to help decide whether an anomaly is due to failed telemetry or actual hardware failure. After going through the truth table, a number of scenarios may unfold. For a stow, there could be a successful stow with a telemetry anomaly, a conditional stow (Engine A is safe to use, but Engine B cannot be used), a conditional stow with a telemetry anomaly, an unsuccessful stow, and an unsuccessful stow with a telemetry anomaly. In the case of a deploy, there could be a successful deploy with a telemetry anomaly, an unsuccessful deploy, and an unsuccessful deploy with a telemetry anomaly.

If it is determined that a stow or deploy did not execute nominally, then a recovery plan is executed based on the decisions made by the project with the support of the cognizant development personnel. A general recovery plan exists and is a systematic progression of actions that can be used to determine and solve various failure modes such as one or more motors failing or cover stiffness [4]. In the event the cognizant development personnel are not available, the recovery plan can be used as written.

An additional option exists to eject the cover. However, to eject the cover at anytime would involve a project level decision with all associated parties weighing in due to the high risk. Ejection of the cover would only be considered if there were no practical alternatives. One of the main issues with cover ejection is the risk of incomplete ejection. This could potentially lead to a situation of the cover partially attached to the spacecraft which may affect attitude control. Further compounding the risk is the aging bolt-cutters. Due to the age and space environment the pyrotechnic boosters have experienced, there is a concern that the boosters may not operate properly. The project is considering doing a ground test on a booster to determine the potential degradation.

7. FLIGHT PERFORMANCE

Early Flight

This period covers essentially the first three weeks of flight and the MEA cover activities associated with launch (10/15/1997), the Venting and Priming activity for the main engines (11/7-8/1997), and the first main engine maneuver (TCM-1 on 11/9/1997). The cover was deployed shortly after launch. It was stowed before the Venting and Priming activity and then deployed afterward. It was stowed before TCM-1 and then deployed afterward. All of these articulations were performed by Motor A in the DDA and the motor was commanded on for a period of 10 minutes for each articulation. Besides needing to perform these articulations to support flight activities, this was a period of evaluation and familiarity to determine if the cover assembly was healthy and performing nominally. During this period of time the downlink data updated every 64 seconds so motion, motor current, and temperature signatures could be captured for evaluation.

Prior to launch vehicle separation, the cover was in the stowed state and constrained in place with a stow angle of 14 degrees. During launch vehicle separation the cover was allowed to expand from the preloaded state it had been in and the stow angle increased to 24 degrees.

For the post-launch deployment and the articulations associated with Venting and Priming, the spacecraft was sun pointing and the cover was in the shade. For TCM-1 the spacecraft turned off sun and placed the stowed cover in the sun for the main engine burn at a heliocentric distance of

1.01 AU. This would be the first time the cover would be exposed to solar and main engine heating in the stowed position.

For these cover related activities, all of the downlink telemetry channels were providing telemetry as expected. The microswitches (stow and deployment indicators) in the DDA and the potentiometer in the Idler were working as expected.

It was known prior to launch that the calibration curve in the ground system for the potentiometer would not provide desired values. It was believed to have been set to read a zero degree value when the stow angle prior to vehicle separation was constrained to 14 degrees. The preference post-launch was to have it read the actual stow angle. This matter was brought up with development personnel and the problem was confirmed to be a simple offset in the calibration curve and it was fixed in the ground system after this early flight period [13].

The temperature of Motor A in the DDA remained between +18°C and +31°C during this period and experienced a rise of about 7°C as a result of being on for 10 minutes for an articulation. Motor B stayed well within this range and saw a rise of approximately 2°C as a result of Motor A being on for 10 minutes. These results were well within required temperature limits and were as expected.

The 10 minute motor on time was based upon much colder conditions and was used as a precaution. While the 64 second data frequency limited the visibility, it could be estimated that it was taking no more than roughly 3.5 minutes to complete an articulation. This was based upon the time required to receive a microswitch indication. As a result, it could be assumed that the motor was sitting in hard stall for over six minutes. Cognizant development personnel recommended reducing the motor on time to six minutes to reduce the stall period now that the flight DDA temperature level was better understood [13]. This would be implemented after this early flight period.

It was observed that with the cover stowed, the temperature of the DDA would begin to drop. It was clear that in a steady-state situation this would also affect the temperature of the main engines and the central body of the spacecraft, including the propellant tanks, which could affect engine performance [1]. This made sense as the cover itself was essentially a MLI blanket. However, cover stowed steady-state conditions would not be experienced for years until after the cover was stowed in preparation for SOI.

Motion, motor current, and temperature signatures for all five articulations (2.5 cycles) were provided to cognizant development personnel for their evaluation. With the 64 second data frequency, the variation in timing between the commanding of the motor and the telemetry sampling caused some variation in each type of signature; however, they remain sufficiently similar to be interpreted for performance purposes. With the correct calibration (adding 14 degrees to telemetry readings), the potentiometer value stow angle achieved for both stows was 21 degrees.

Figures 7, 8, and 9 provide typical examples of motion, motor current, and temperature signatures for a cover stow articulation and Figures 10, 11, and 12 provide typical examples of motion, motor current, and temperature signatures for a deployment articulation. Note that UTC stands for Universal Time Code and is equivalent to Greenwich Mean Time. Both EU and DN curves are shown for the motion signatures and come from potentiometer readings. EU represents engineering units in degrees and 14 degrees should be added to the values in the plots to get the correct value. DN represents quantized telemetry values coming from the spacecraft that has to be processed using the calibration curve in the ground system software to get the EU values. As can be seen in Figure 7, it is typical to see some post articulation relaxation of the cover that reduces the stow angle slightly. In this case it occurred several minutes after the cover had initially stowed. In the first part of the motor current signatures the values are relatively low and vary significantly between Remote Engineering Units (REUs) A and B. This is the period of time where the cover is in motion. The REUs collect motor current data separately and at slightly different times. It is common to see differences between them due to small variations in motor current draw. The relatively high current values that follow are where the motor is stalled indicating the articulation has been completed. The temperature signatures show the relatively larger rise in the temperature Motor A experiences due to being powered and the relatively small temperature rise in Motor B due to being heated by Motor A.

Figure 13 shows the cover stow angle for the period during TCM-1 activities where the cover was stowed. The turn taking the spacecraft off sun and putting sun on the cover was completed at 19:55 UTC and the main engine burn was started at 20:00 UTC and lasted for 30 seconds. The spacecraft returned back to sun pointing putting the cover in the shade by 21:09 UTC. Both the burn and the sun exposure warmed the folded cover and a relaxation of the cover occurred that reduced the stow angle as much as 5 degrees. This behavior was consistent with the sensitivity of the cover mechanical properties to temperature [13]. The drive bow stored a finite amount of preload based upon the resistance of the folded cover. When the cover warmed, its folding resistance decreased, thus allowing the preload stored to further compress the stowed cover.

A complete report on the behavior of the MEA cover assembly was put together by T/D for this early flight period and was provided to the cognizant development personnel for their evaluation [14]. After a complete evaluation of the early flight data the conclusion arrived at by the cognizant development personnel was that the performance of the MEA cover assembly was nominal and representative of a healthy device [13].

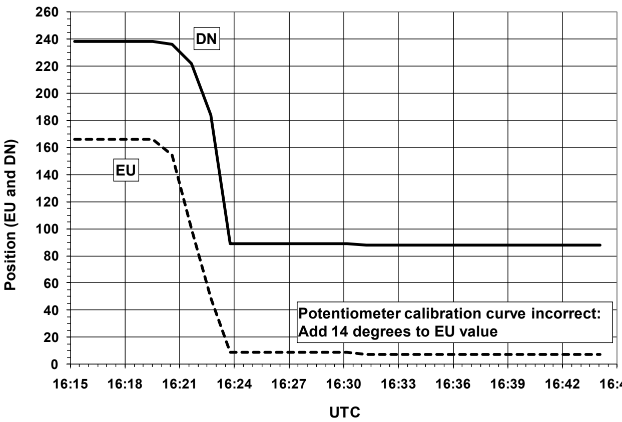


Figure 7 – MEA cover position during stow for TCM-1

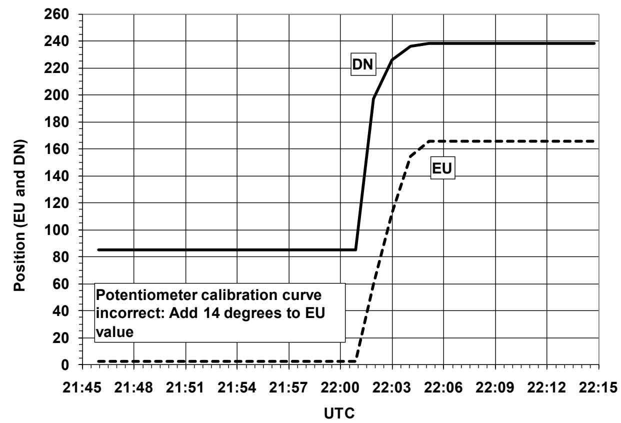


Figure 10 – MEA cover position during deploy after TCM-1

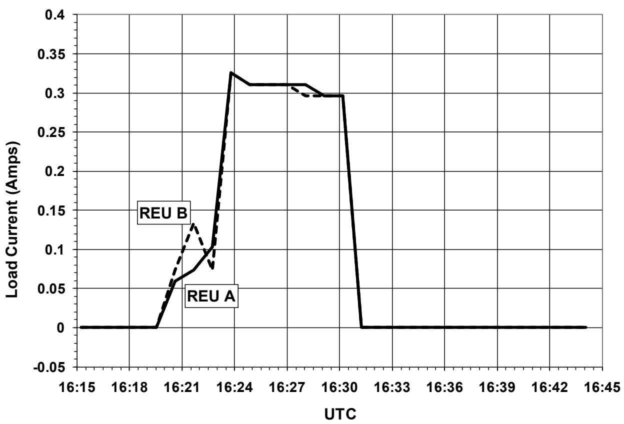


Figure 8 – MEA cover Motor A reverse load current (REU A & B) during stow for TCM-1

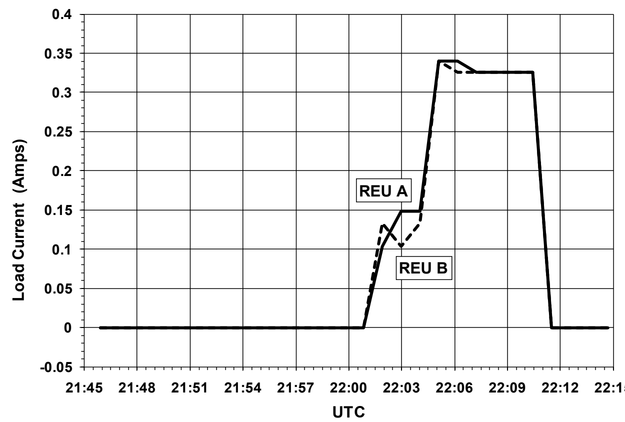


Figure 11 – MEA cover Motor A forward load current (REU A & B) during deploy after TCM-1

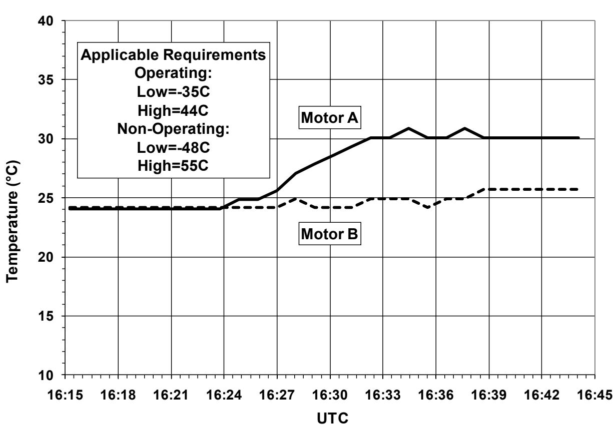


Figure 9 – MEA cover Motor A and B temperatures during stow for TCM-1

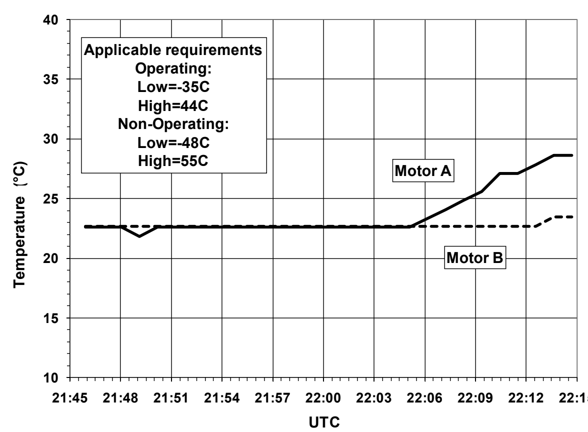


Figure 12 – MEA cover Motor A and B temperatures during deploy after TCM-1

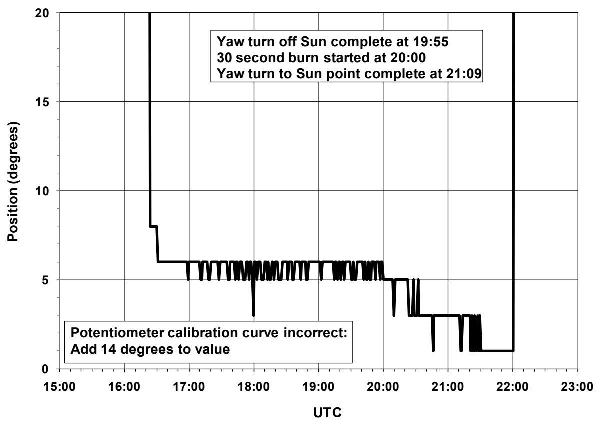


Figure 13 – MEA cover position while stowed during TCM-1

Cruise

The cruise period will be considered from TCM-1 (11/9/1997) up until SOI (7/1/2004). During this period the cover was stowed for 12 main engine TCMs and deployed afterward. It was subsequently stowed for TCM-20 (5/27/2004) and left stowed for TCM-21 (6/16/2004) and SOI. The range of heliocentric distances at which main engine TCMs were performed was from 1.13 AU to 9.02 AU. 12.5 cycles were used for a total of 15 in-flight cycles prior to SOI. At this point the use was still within the 20 in-flight cycle consumable limit and the MEA cover had served the purpose it was originally designed for when Cassini was launched.

During a significant part of this time period the spacecraft was on a low gain antenna and sufficiently far from Earth that five of the main engine TCMs had downlink data rates too low to capture motion, current, and temperature signatures for the articulations. For these TCMs, MROs were downlinked after an articulation to provide limited articulation and final state telemetry information. The motion, current, and temperature signatures that were captured during the cruise period were all indicative of a healthy DDA and no degradation trend in DDA performance was observed.

Between early flight and cruise phases, the potentiometer calibration curve had been corrected in the ground software and the change had been made to only power the DDA for six minutes to reduce stall durations. Reducing the motor on-time to 6 minutes reduced the temperature rise in Motor A to 3 to 4°C and in the unused Motor B to approximately 1°C.

During the cruise phase, all telemetry channels provided correct telemetry and the stow and deploy microswitches in the DDA and the potentiometer continued to work correctly. During this period only Motor A was used in the DDA except for the deployment after TCM-19, which used both motors as a flight demonstration for SOI.

The first main engine TCM during this time period was the Deep Space Maneuver (DSM/TCM-5), which occurred on 12/3/1998 and was approximately 13 months after TCM-1. Prior to DSM, an informal contingency plan to deal with a cover anomaly had been put in place and contingency commanding files were created to be used as real-time commands if needed. A hierarchy of commanding was defined, pertinent development data was gathered together, and it had been agreed upon to have cognizant development personnel on call for all articulations and they would be an integral part of the decision making process should an anomaly occur.

DSM was the second longest main engine burn in the flight, being 88 minutes long, and was essential for Cassini to be able to leave the inner solar system. MROs were required to confirm the cover stow for DSM met the stow criteria. The criteria for an acceptable stow was that the stow angle be ≤ 30 degrees, as indicated by the potentiometer. Due to a tracking station problem, only a portion of the planned MRO data became available. This data indicated the potentiometer final stow angle was 34.8 degrees and the microswitch had provided a stow indication. The stow criteria had not been met.

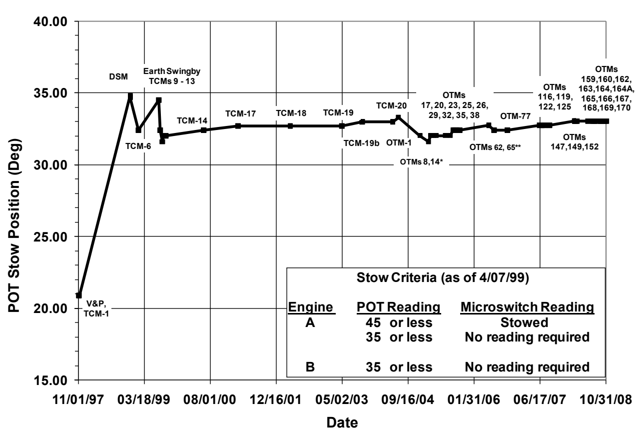
T/D alerted the Project and immediately contacted the on-call cognizant development personnel and proceeded to work the problem with them in real time to avoid aborting the maneuver. A decision was quickly arrived at to command the stow again to discern between a DDA related problem and a cover stiffness problem. In the mean time, the thermal aspects of such a large stow angle were being reviewed. The second stow attempt resulted in a potentiometer stow angle of 34.7 degrees with a microswitch indication of a stow and sufficient information was gained to verify Motor A was healthy and had stalled as the cover was exhibiting a surprising amount of stiffness. A review of the required thermal development information and quick analysis led to the conclusion that the 30 degree potentiometer criterion was conservative and DSM could be performed with the 34.7 degree stow angle indicated by the potentiometer, given the microswitch indication ensured a position of 25 degrees or less on the DDA side. The Project was briefed and the decision was quickly made to proceed. DSM was successful, the contingency planning had paid off, and subsequently the post DSM deployment was nominal.

A post event analysis was conducted by the cognizant development personnel and T/D to evaluate and understand the change in MEA cover behavior [11, 15]. The cause of the increased stow angle was due to an increase in the folding resistance. This could be due to environmental effects such as temperature differences and degradation due to exposure to the space environment. A detailed thermal analysis was conducted and it was determined that while the cover stiffness has some thermal dependence, temperature differences could not explain the stiffness change observed since TCM-1. Exposure to the space environment could reduce the tensile strength and the elongation of the carbon-filled Kapton with time; however, the materials selected for the cover MLI were deemed acceptable in this respect. It was concluded that the reason for the change was related to time spent in the space environment, but a precise and quantitative explanation remained obscure.

While the analysis was still in progress, TCM-6 was performed on 2/4/1999 and the stow angle was 32.4 degrees. This lead to speculation that perhaps more frequent use of the cover would reduce the stiffness.

At DSM, the drive bow had a twist in it of approximately 10 degrees and possibly more given the potentiometer reading on one side of 34.7 degrees and the microswitch stow indication on the DDA side indicated no more than 25 degrees. With the twist in the drive bow the cover was stowed to a smaller angle for Engine A than Engine B. At this point in time, a detailed thermal analysis was conducted to develop the new stow criteria which was engine dependent [11].

Figure 14 shows a stow history plot for the entire mission at the time of the writing of this paper in terms of the stow angle as read by the potentiometer. The TCMs and OTMs indicated are the maneuvers for which the cover was stowed. When the cover stows, there is a small amount of relaxation that takes place in a relatively short period of time and in general the stow values plotted were post relaxation values given a wait of 20 to 30 minutes after the DDA had shut off. This is the most accurate appraisal of the stow angle.



Note: *Estimate of off track stow

**Estimate of end of track stow

Figure 14 – MEA cover stow history

With time an interesting behavior became evident which started with DSM and was seen again about 7 months later at TCM-9 (7/6/1999). If a main engine burn of roughly 8 minutes or longer occurred and then if the cover were not deployed for two hours after the burn, when it was subsequently stowed at a later date it would stow to a smaller stow angle. Subsequent analysis led to the conclusion that the wait after the burn completion needs to only be 20 minutes or more to see this effect. It appeared this thermal conditioning had reduced the stiffness in the cover. However, if after roughly an 8 minute or longer burn the cover deployment is started 2 minutes and 5 seconds after the burn completion, then when the cover is subsequently stowed it is stiffer and does not stow as tightly. This is seen at the stow for OTM-1 which followed SOI. Only four main engine burns have been near eight minutes or longer in duration during the flight: a) DSM at 88 minutes, b) TCM-9 at 7 minutes and 53 seconds, c) SOI at 96 minutes, and d) OTM-2 at 51 minutes, with no more planned.

It can be seen in Figure 14 that during cruise, the stow angle would never return to levels seen during early flight and that the trend would not turn out to be a threat to main engine use. It appeared as if the degradation mechanism was close to fully matured. During cruise, as the spacecraft heliocentric distance increased, the solar thermal influence on the relaxing of the cover while the spacecraft was off sun for a maneuver decreased to eventually having no effect at all. In addition, by TCM-20 (5/27/2004), main engine burns of at least 8 minutes were required to cause any cover relaxation. TCM-20 was a main engine burn of 6 minutes and no relaxation resulted.

As noted in the OPERATIONAL STRATEGY section above, TCM-19 (5/1/2003) was a demonstration for SOI (7/1/2004) in terms of verifying the cover deployment could start at 2 minutes and 5 seconds after burn completion and it could be performed using both DDA motors simultaneously in a single fault tolerant manner. In addition, TCM-19 validated the thermal analysis approach for SOI and verified Motor B was healthy [9, 12]. As expected, the cover deployed at virtually twice the angular rate it would have using one motor. With the dual motor drive for six minutes, both motors experienced a temperature rise of approximately 5.5°C. The demonstration was considered completely successful and a validation of how the deployment would be done for SOI. Plots of dual drive performance signatures for SOI will be shown and discussed in the subsequent *Saturn Orbit Insertion* section.

With the cover being stowed for TCM-20 (5/27/2004) and not being deployed again until after the SOI burn (7/1/2004), this was the first time in flight to see the central body and propulsion systems experience steady-state temperatures in a cover stowed configuration. A thermal analysis had to be performed during the cruise phase to predict the steady-state cover stowed temperatures expected and to develop a new strategy for the usage of the heaters associated with the main engines for the on-orbit tour at Saturn. The new strategy took into account the range of temperatures the main engines would experience between steady-state cover deployed conditions and steady-state cover stowed conditions.

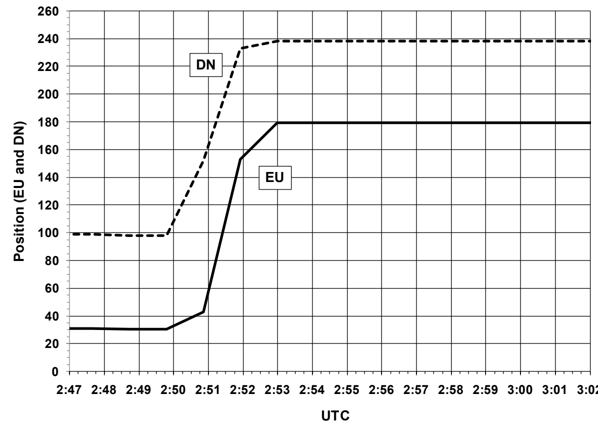
In addition, Propulsion performance calculations require predicts of bulk propellant temperatures for maneuvers. This calculation process had to be changed to accommodate the larger range of temperatures that would be experienced on orbit given the cover would be deployed for long periods of time and stowed for long periods of time. For Bulk Monomethyl Hydrazine the temperature change could be 1.3°C, for bulk Nitrogen Tetroxide 3.0°C, and for monopropellant Hydrazine 3.0°C.

Saturn Orbit Insertion

With the success of the TCM-19 demonstration, the strategy was set for SOI [9, 12]. For SOI the MEA cover was deployed starting at 2 minutes and 5 seconds after the main engine burn to avoid the risk to the nozzles from the descending ring plane crossing. It was a requirement for SOI that the commanding be single fault tolerant, so both DDA motors had to be commanded simultaneously.

For SOI there could be no downlink telemetry in real time so the data was recorded and subsequently played back. Figure 15 displays the motion signature for the deployment. The motor current signatures are shown in Figures 16 and 17 for Motor A and B, respectively. Given the uncertainty associated with the quantized telemetry, these two figures display virtually the same performance. Analysis of Figures 15 through 17 reveal the angular rate of motion of the cover movement is essentially twice that of a single motor deployment, as expected. The temperature history of Motor A and B is shown in Figures 18 and 19, respectively. SOI was completed in a single burn with Engine A without interruption. The burn started at approximately 7/1/2004 at 01:12 and continued for 96 minutes until 02:48. The deployment began 2 minutes and 5 seconds later. In these figures the majority of the temperature rise in the motors during this time period is due to heating from the Engine A burn (in close proximity to the DDA). The actual temperature rise in the motors due to the deployment was estimated at 5°C to 6°C, but it is difficult to completely separate the main engine thermal influence on the motors from the DDA thermal influence on themselves. It should be noted with respect to these figures that at approximately three hours after the deployment there is a cover stow performed by Motor A in preparation for OTM-1. This can be seen at approximately 7/1/2004 06:00 hours.

Cognizant development personnel were on call for the SOI cover deployment and the data was reviewed as soon as it could be sent to the ground post event. The MEA cover deployment and all thermal aspects of performance at SOI were as expected. At this point in time 15.5 in-flight cycles had been placed on the cover, which was still within the 20 cycle consumable.



Figures 15 – MEA cover position during deployment after SOI

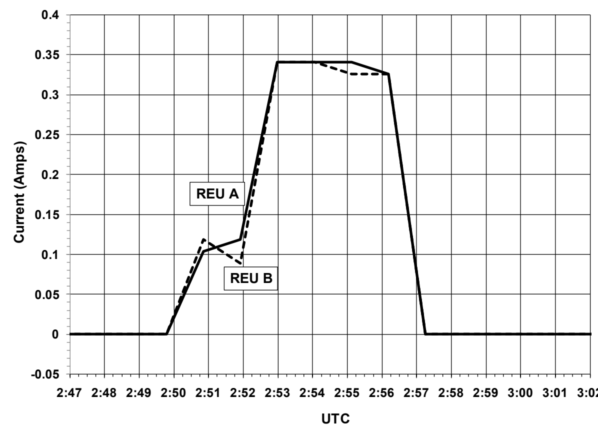


Figure 16 – MEA cover Motor A forward load current (REU A & B) during deploy after SOI

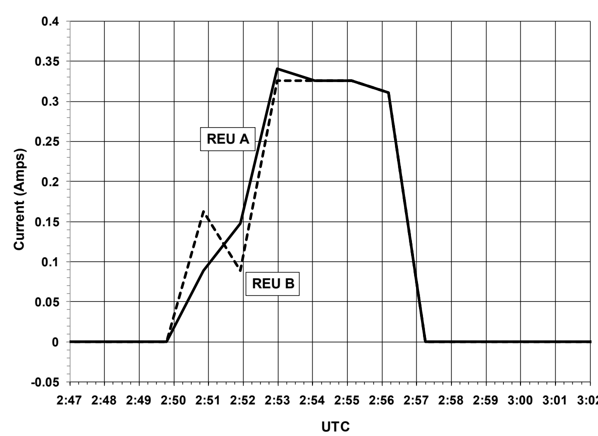


Figure 17 – MEA cover Motor B forward load current (REU A & B) during deploy after SOI

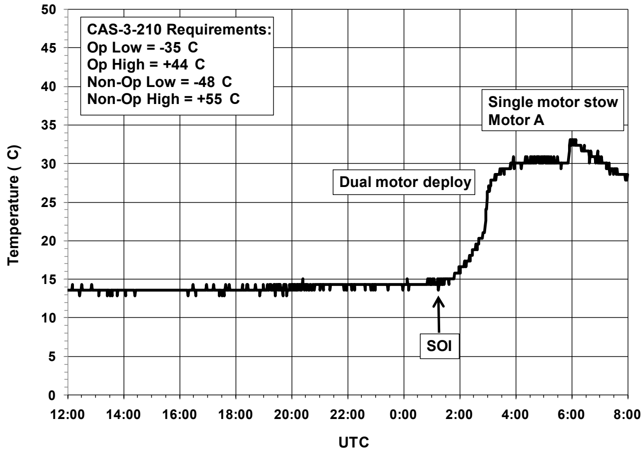


Figure 18 – MEA cover Motor A temperature trend during SOI

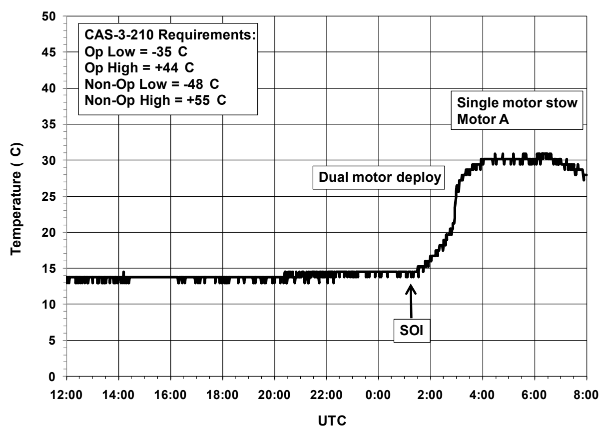


Figure 19 – MEA cover Motor B temperature trend during SOI

Prime Mission

The Prime Mission lasted four years from 7/1/2004 through 6/30/2008. MP performed analyses for the Prime Mission and identified the dust hazards that required the cover to be deployed. These analyses were updated periodically during the Prime Mission as new environmental data became available.

The strategy was to minimize the use of the cover by having deployments and stows about dust hazards and leaving the cover stowed for all OTM windows prior to dust hazards and leaving the cover deployed for dust hazards if more than one dust hazard occurred between OTM windows. In addition, the cover was also stowed for all relatively low altitude Titan flybys (within 1300 km closest approach). Some low altitude flybys of the moon Enceladus through the rarefied regions of its geysers would also occur and require the cover to be deployed, but this was not a separate consideration as these flybys coincided with dust hazards.

Up to this point, the 15.5 cycles put on the MEA cover assembly had occurred over a period of approximately 6 years and 8.5 months. On average over the Prime Mission, the frequency of use would significantly rise due to the rate of recurrence and proximity of dust hazards and OTMs. Over these four years cover use on a yearly basis required 6.5 cycles, 7.5 cycles, 3.5 cycles, and 6.5 cycles, respectively, for a total of 24 cycles in four years. These cycles were in response to the number of dust hazards requiring cover deployment, which were 11, 10, 3, and 8, over the four years, respectively. There were 26, 40, 54, and 41 OTMs planned (with both prime and backup windows) during the four years of the Prime Mission, respectively. While 48 OTMs in total would be cancelled, this typically did not change the need for cover articulations. Over these four years on a yearly basis, the number of cover stowed low altitude Titan flybys were 3, 1, 15, and 8, respectively. At the end of the Prime Mission the total number of in-flight cycles used was 39.5, which had almost doubled the original 20 cycle consumable limit. These statistics come from T/D records and from MP tour event summaries [16].

Given the number of cycles involved, there were two significant consumable issues to be resolved during the Prime Mission (See *Consumables* section above). Knowing that on 4/1/2005 the conservative 20 cycle flight consumable limit would be reached, this limit was revisited by T/D, cognizant development personnel, MP, and the Project management. The in-flight cycle consumable limit was increased to 37 in-flight cycles on 3/22/2005. The Prime Mission would end on 6/30/2008 and the Equinox Mission would follow, going through 6/30/2010. On 3/13/2008 in-flight cycle 37 would be reached. It was clear the consumable limit could not be extended and to continue to use the cover would require a waiver to the consumable limit. A risk tradeoff was made between continued use of the cover beyond its design life versus the threat to the nozzles if the cover were not used beyond 37 in-flight cycles. It was decided to continue use of the cover and a waiver on the consumable limit on cover cycles was approved on 2/6/2008 when 36 in-flight cycles had been used to date. The cover fulfilled its design obligation completing the 37th in-flight cycle on 3/13/2008.

Deploying the cover quickly after the long SOI main engine burn had caused the cover to stiffen slightly and, as shown in Figure 14, the stow angle for OTM-1 (7/3/2004) was higher at 33.3 degrees. Note that SOI is not in the figure, as the cover was last stowed before SOI at TCM-20. OTM-2 occurred on 8/23/2004 and had a main engine burn duration of 51 minutes, being the third largest maneuver in flight. The cover remained stowed after OTM-2 for approximately four months. As a result, when it was subsequently deployed for a dust hazard and then stowed for OTM-8 there was a reduction in stiffness resulting in a stow angle of 32.03 degrees. OTM-2 was the last OTM planned in flight that would have main engine burn durations long enough to help reduce the cover stiffness.

The stow angle for OTM-14 (2/18/2005) appears lower, but is only an estimate as this was the only stow performed on orbit in the blind without being on a downlink track. The stow angle for OTM-65 (7/5/2006) at the end of a downlink track did actually decrease slightly and remained there until it increased slightly for OTM-116 (6/16/2007). While there are some small ups and downs in the stow angle trend during the Prime Mission, the overall trend is toward a slight stiffening after the decrease caused by OTM-2. However, the trend remained shallow, not being a threat to the use of either main engine. At the end of the Prime Mission, the stow angle was 33.04 degrees, which was still slightly below the value at OTM-1 of 33.3 degrees.

During the Prime Mission all telemetry channels continued to provide correct telemetry and the stow and deploy microswitches in the DDA and the potentiometer on the Idler side continued to work correctly. Only Motor A was used during the Prime Mission. The temperature of the motors in the DDA remained between +10°C and +34°C during the Prime Mission. +34°C only occurred post SOI for the stow for OTM-1. The temperature rise in Motor A due to a six minute on time continued to be 3°C to 4°C accompanied with an approximately 1°C rise in unused Motor B.

The stows were monitored in real time (except for one performed off track) by T/D and notifications were sent out providing the results to appropriate cognizant development and Project personnel. Deployments were monitored in most cases with appropriate notifications sent out. Cognizant development personnel were on call for every articulation. The performance of each articulation performed between OTMs was included in the subsequent T/D OTM report. Performance data for every articulation was given to the cognizant development personnel for evaluation. Upcoming articulations were included in frequently held meetings for the purpose of reviewing future planned activities and being able to make changes if required.

As noted previously under *Early Flight*, the time interval between commanding the motor on and the spacecraft telemetry sampling would vary for articulations and have some effect on the motion, current, and temperature signatures. However, even with these timing induced variations, the performance could easily be evaluated. After many articulations, familiar patterns could be clearly seen. Deployments would stop at a hard stop, while stows would have a rather crisp stop and then a small relaxation would follow. Having the benefit of evaluating many articulations since the early flight experience, it has been concluded that the articulation motion prior to motor stall takes approximately 3 minutes and 15 seconds. This tends to be true for both deployments and stows. This motion period differs little from the rough estimate of 3.5 minutes from early flight.

At the end of the Prime Mission 39.5 in-flight cycles had been performed by the MEA cover assembly and it had been used beyond its intended use prior to launch and beyond its design life. Under continued scrutiny, no discernable degradation in DDA performance has been observed. The general stiffness in the cover has remained and the trend, while shallow, is still towards increased stiffness; however, the rate of increase is not projected to be a problem with respect to the stow criteria to use either main engine. The current plan is to continue to use only Main Engine A, which has the least constraining stow criteria.

Extended Mission Considerations

Currently, Cassini is performing the extended mission, known as the Equinox Mission. The Equinox Mission started on 7/1/2008 and will go through 6/30/2010. MP has performed analyses for the Equinox Mission and has identified the dust hazards that require the cover to be deployed. The current assessment of losing a main engine nozzle is 4.9% with cover use during the Equinox Mission. These analyses have been periodically updated as new environmental data has become available. The strategy for cover use remains unchanged from the Prime Mission.

Going into the Equinox Mission, the cover had experienced 39.5 flight cycles. Between 7/1/2008 and 11/1/2008 the cover has experienced 10.5 additional cycles. During this period of time there have been 16 dust hazards, 10 planned OTMs, and no low altitude Titan flybys. Only one of the OTMs was cancelled. There were three Enceladus flybys requiring the cover to be deployed that coincided with dust hazards. Here again, these statistics come from T/D records and from MP tour event summaries [16]. At this point in the mission, the cover has experienced 50 in-flight cycles with a total of 80 cycles on the flight cover and this represents the last usage of the cover at the time of the writing of this paper.

During the Equinox Mission to date, all telemetry channels have continued to provide correct telemetry and the stow and deploy microswitches in the DDA and the potentiometer on the Idler side have continued to work correctly. Only DDA Motor A has been used and with a six minute on duration for all articulations. The temperature of the motors in the DDA remained between +10°C and +26°C. The temperature rise in Motor A due to a six minute on duration continued to be 3°C to 4°C accompanied with an approximately 1°C rise in unused Motor B. To date in flight, Motor A has accumulated 5 hours and 14 minutes of operational time performing stows and 5 hours and 12 minutes performing deployments. Motor B has only accumulated 12 minutes of operation during the dual motor deployments at TCM-19 and SOI. The current plan is to perform all future articulations with Motor A.

As was the case for the Prime Mission, stows and deployments are typically monitored in real time and notifications are sent out providing the results to appropriate cognizant development and Project personnel. Cognizant development personnel are on call for every articulation. The performance of each articulation performed between OTMs is included in the subsequent T/D OTM report. Performance data for every articulation is given to the cognizant development personnel for evaluation. Upcoming articulations are included in frequently held meetings for the purpose of reviewing future planned activities and being able to make changes if required.

Figures 20, 21, and 22 provide motion, motor current, and temperature signatures for an exemplary deployment and Figures 23, 24, and 25 provide motion, motor current, and temperature signatures for an exemplary stow in the Equinox Mission. The stow is the last articulation performed (11/1/2008) as of the writing of this paper. The temperature rise in the motors is still virtually the same as it was early in cruise when the six minute motor on duration was adopted. The rate of motion also remains the same for a single motor articulation. Articulations continue to be accomplished (reach stall) in approximately 3.25 minutes. For the first time in this paper the current signatures display the characteristic shape of the six minute motor on duration. The differences seen in the shape of the current signatures are indicative of patterns seen frequently which result from the difference in the timing between the time the motor is commanded on and the time at which telemetry samples are taken at 64 second intervals. These signatures help show that no discernable degradation has occurred with respect to the articulating operation of the cover through 50 in-flight cycles.

Based upon the most recent MP analysis, 11 more cover cycles are planned for the remainder of the Equinox Mission. This would result in the total number of in-flight cycles being 61 and the total number of cycles on the cover (ground and flight) being 91 by the end of the Equinox Mission on 6/30/2010.

The Cassini Project is planning a second extended mission known as the Solstice Mission. This mission would begin on 7/1/2010 and continue until 9/15/2017. Based upon the most recent MP analysis, the current plan is to use 25 additional cover cycles during this time period. This would result in the total number of in-flight cycles being 86 and the total number of cycles on the cover (ground and flight) being 116 by the end of the Solstice Mission. With planned cover usage per analysis, the risk of losing a main engine nozzle to a dust hazard is currently calculated to be 2.7% over the course of the Solstice Mission.

The current plan is to manage the use of the cover during the Solstice Mission in the same manner in which it has been managed during the Prime Mission and is being managed during the current Equinox Mission. This overall approach emphasizes being able to detect and react to any early signs of degradation in performance. A comprehensive contingency plan remains in place to deal

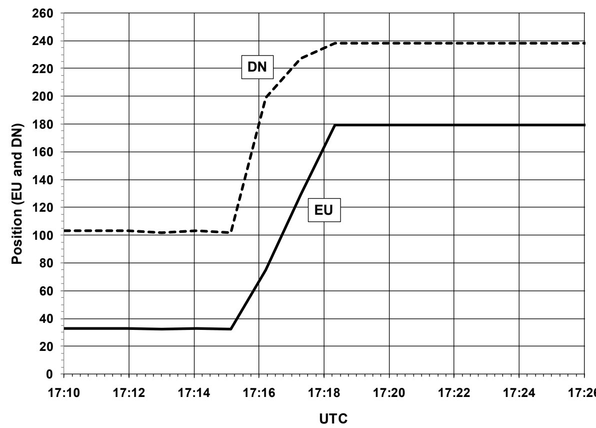


Figure 20 – MEA cover position during deployment

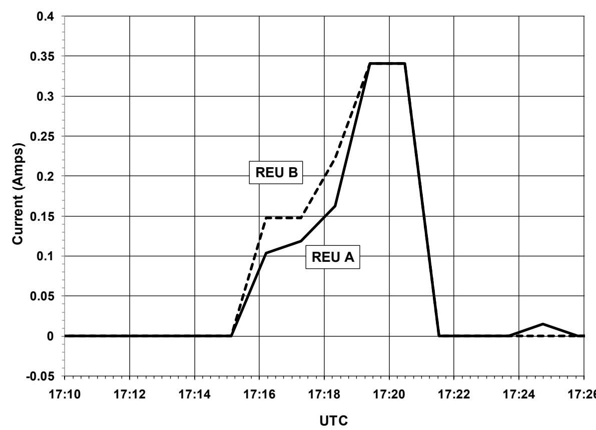


Figure 21 – MEA cover Motor A forward load current (REU A & B) during deployment

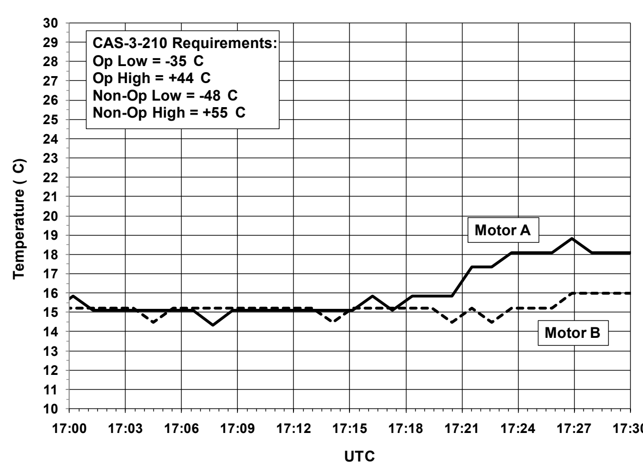


Figure 22 – MEA cover motor temperature trend during deployment

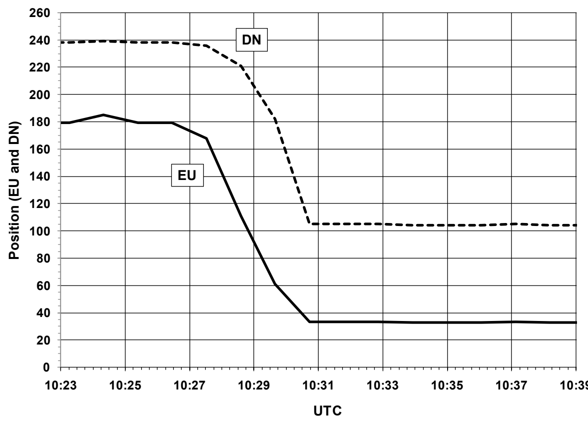


Figure 23 – MEA cover position during stow

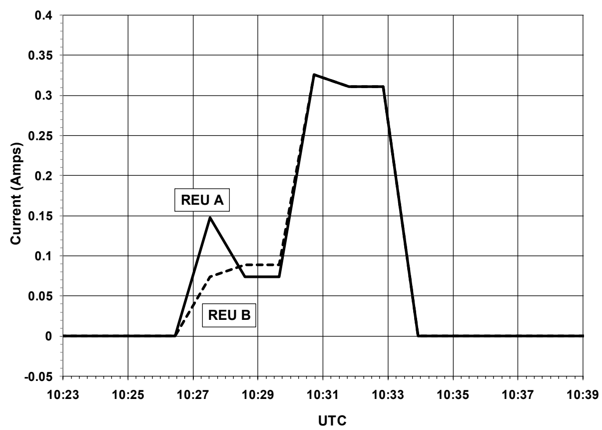


Figure 24 – MEA cover Motor A reverse load current (REU A & B) during stow

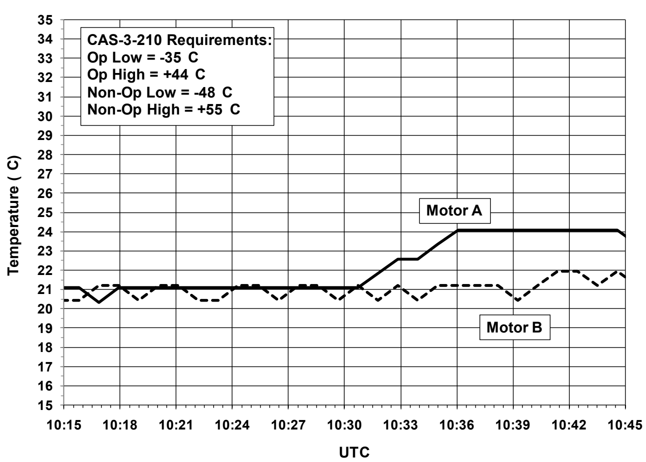


Figure 25 – MEA cover motor temperature trend during stow

with problems that may arise [4]. T/D remains responsible for the management and operation of the cover assembly within the Cassini Project and is also the Project link to cognizant development personnel.

As of the completion of the 50th in-flight cycle on 11/1/2008, the flight cover assembly continues to perform in a manner indicative of a healthy device. Thermally there will be an insignificant change in quiescent DDA temperature with respect to operational performance between now and the end of the Solstice Mission. While there is nothing apparent as of 11/1/2008 that would preclude the successful use of the cover assembly through the Solstice Mission, it is essential the flight team remain vigilant with respect to observing early signs of performance degradation. In addition, there are four potential concerns which may need additional attention focused on them in the future. These are: 1) the cover stiffness anomaly, 2) loss of state telemetry, 3) the effect of long term exposure to the space environment in the Solar System and especially in the Saturnian environment, and 4) the aging pyrotechnic devices in the bolt cutters required for cover jettison.

8. CONCLUSIONS

This paper complements Reference 1, which relates the JPL development of MEA Cover assembly, by providing a Systems-level overview of its subsequent flight experience (management and performance) as of the writing of this paper. The purpose of this device and the focus on its use in flight has been to protect the fragile disilicide coating on the main engine nozzles from damaging micrometeoroid/dust impacts. This has been successfully accomplished by the Cassini Project.

The flight management approach has been a Sytems-level approach that has emphasized a “Team” architecture that utilizes the organized skills of the various Cassini Project flight teams plus cognizant development personnel. Keeping the cognizant development personnel in the loop as an integral part of this approach has been a key factor in the success of this effort, given their unique knowledge base and insight regarding the cover hardware.

While originally designed only for the cruise to Saturn, updated post launch nozzle threat analyses, based upon environmental knowledge gained during flight, have shown an essential need to continue the use of the cover throughout the flight of the spacecraft. Facing this post-launch challenge, the Project has successfully applied an adaptive cover usage strategy to each mission phase that utilizes updated threat analyses and risk management, which takes into account mission risk and hardware risk to protect both the nozzles and the cover hardware.

During the cruise to Saturn, all design-based consumable constraints were complied with. The continued use of the cover on orbit has been extensive compared to the use during cruise due to the post-launch updated understanding of the dust threat in the Saturnian system. The cover assembly has fulfilled its need beyond its design life during the four year Prime Mission and continues to do so during the subsequent two year Equinox Mission. Its performance has been robust, providing confidence in its ability to meet the challenge presented by the remainder of the Equinox Mission and subsequent over seven year Solstice Mission. While pre-launch it was anticipated it would perform no more than 50 articulation cycles (30 pre-flight and 20 in flight), it has performed 80 cycles (30 pre-flight and 50 in flight) as of the writing of this paper. In addition, all the cover related downlink telemetry remains operational. The stow angle related stiffness experienced in the cover itself, while a precise and quantitative explanation remains obscure, has not become a problem. It has not posed an obstacle to the cover use strategy or how it is operated.

While comprehensive contingency plans are in place should a problem arise, It is currently anticipated the cover assembly has an ample amount of performance life left in it that by the end of the Solstice Mission the cover will have performed approximately 116 cycles successfully (30 pre-flight and 86 in flight).

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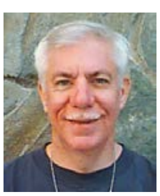
BIOGRAPHY

Ruwan Somawardhana is a Thermal Engineer at the Jet Propulsion Laboratory and works on both the developmental and mission operations side of spacecraft thermal subsystems. He has been on Cassini's Thermal/Devices team for the past two years. Both his BSME and MSME are from the University of Texas at Austin.



Jerry Millard has 37 years of spacecraft experience in the fields of Contamination Control, Materials, and Thermal Engineering. Twenty years were involved in spacecraft engineering hardware and instrument development. Seventeen years have been in Mission Operations on the Galileo and Cassini flight teams specializing in thermal control and mechanical devices. He is currently the team lead for thermal control and mechanical devices engineering for the Cassini spacecraft. He has a BSAE from California State Polytechnic University, Pomona and a MSME from California State University, Los Angeles.