National Aeronautics and
Space Administration

Office of Inspector General
Washington, DC 20546-0001

January 5, 2009

TO: Project Manager, External Tank Project Office

FROM: Assistant Inspector General for Auditing

SUBJECT: Final Memorandum on the Review of the Space Shuttle Liquid Hydrogen Fuel Tank Sensors
(Report No. IG-09-009; Assignment No. S-08-011-00)

Since March 2006, Marshall Space Flight Center's (MSFC) Engineering Department has been performing assurance testing on the cryogenic liquid level sensors used in the Space Shuttle Program's liquid hydrogen (LH2) fuel tank. The MSFC Engineering Department screens the sensors after the supplier delivers them to the prime contractor and after the contractor completes normal acceptance testing on the sensors. The MSFC Engineering Department found, as a result of their screening, that a number of LH2 sensors did not conform to the required design specifications, even though the sensors had passed the contractor's acceptance testing.

The overall objective of this review was to determine whether the Space Shuttle Program appropriately accounted for, used, or disposed of nonconforming LH2 sensors. We focused our review on actions taken by the External Tank Project Office (Project Office) after it identified nonconforming LH2 sensors. In addition, we reviewed the results of the LH2 sensor screening and ranking performed by the MSFC Engineering Department's Electrical, Electronic, and Electromechanical Parts Analysis Team, using the NanoFocus Lab,[1] and the LH2 sensor inventory records maintained by the contractor. (See Enclosure 1 for details on the review's scope and methodology.)

Executive Summary

We found that the Project Office initiated appropriate actions to identify and resolve LH2 sensor nonconformance issues by reviewing manufacturing and testing processes. As a result, the Project Office recommended that modifications be made to the supplier's manufacturing process and to the contractor's acceptance testing processes. In addition, we found that because of the Project Office's review, the contractor implemented a detailed inventory control measure that segregated the sensors into two inventories—Flight Ready inventory and 74L4-2 Parts inventory.

[1] The NanoFocus Lab is a modular, 3-dimension, profilometer system for non-contact surface characterization. It uses nondestructive X-ray technology to inspect the sensors to ensure the quality of construction.

The 74L4-2 Parts inventory contains sensors not yet screened by the MSFC Engineering Department, sensors determined to be low ranking, damaged, questionable, and certain other sensors. To mitigate the risks inherent in using nonconforming sensors, the contractor labeled all the pre-process improvement LH2 sensors as nonconforming parts to ensure that questionable sensors were not used inadvertently in a mission critical position within the LH2 fuel tank. In addition, all LH2 sensors the contractor receives from the supplier are not considered flight ready until the MSFC Engineering Department uses the NanoFocus Lab to screen them. After the sensors pass the screening, the contractor assigns a new part number, which indicates they are flight ready. However, the contractor has not screened all the LH2 sensors and has continued to maintain low ranking, damaged, and questionable sensors in the 74L4-2 Parts inventory.

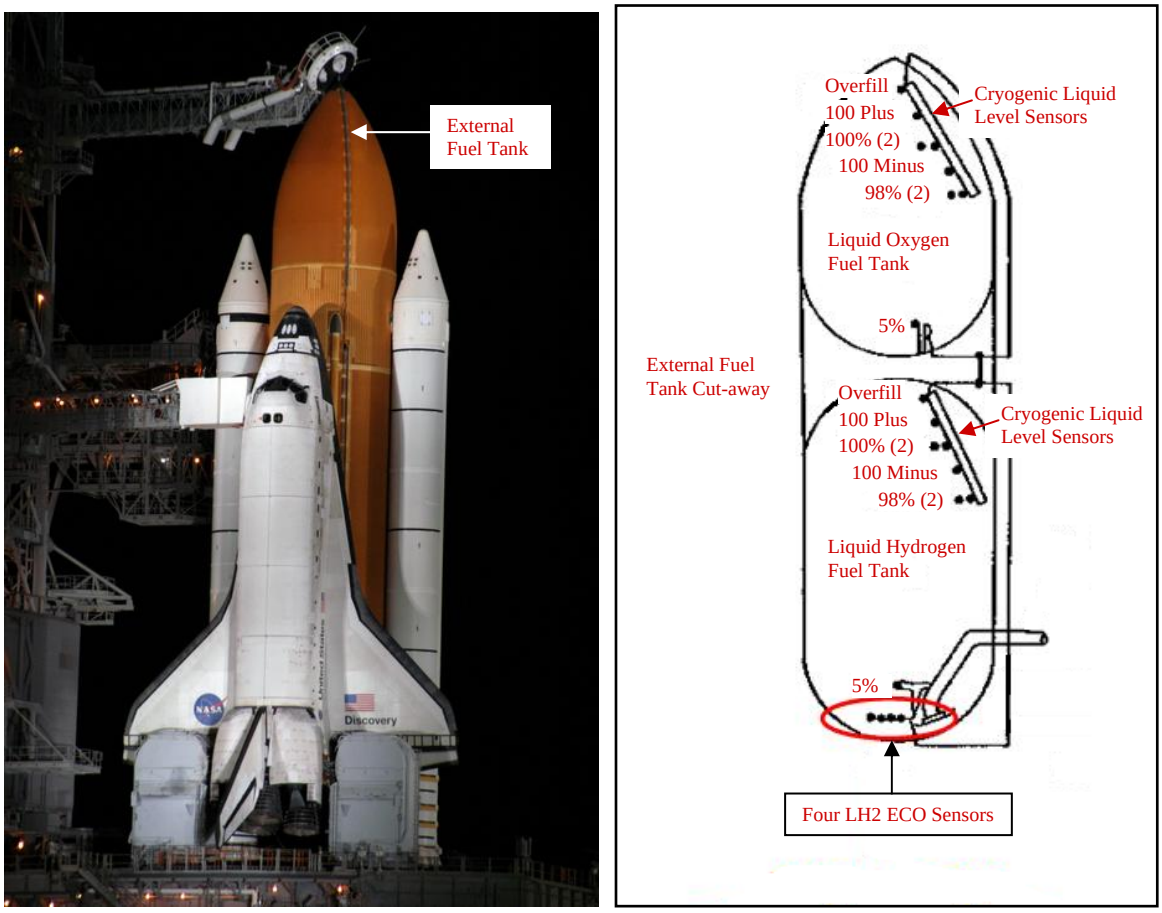
Although the Project Office and the contractor took appropriate actions to resolve quality- and inventory-control issues with nonconforming LH2 sensors, the 74L4-2 Parts inventory still contains sensors that have not been screened using the NanoFocus Lab, thus their usability is unknown, and also contains sensors that the Project Office does not intend to ever use. Maintaining parts in inventory that are not suitable or intended for use introduces unnecessary risk. In our November 4, 2008, draft of this memorandum, we recommended that the Project Office determine the usability of all remaining LH2 sensors labeled as nonconforming parts and dispose of the sensors not intended for use.

In commenting on the draft of this memorandum (see Enclosure 2), the Program Manager, Space Shuttle Program, generally concurred with our recommendations and will transfer the nonconforming, pre-process improvement LH2 sensors, which are not intended for use, to MSFC to be held in bonded storage. In addition, post-process improvement sensors held in the 74L4-2 Parts inventory will be evaluated to determine their final disposition. Management's comments on the draft of this memorandum are responsive; therefore, we consider the recommendations resolved and will close them upon completion and verification of management's corrective action.

Background

The external fuel tank used on the Space Shuttle is comprised of two separate internal tanks. The upper tank contains liquid oxygen and the lower tank contains LH2. The two tanks contain a total of 20 similar cryogenic liquid level sensors—8 liquid oxygen sensors in the upper tank and 12 LH2 sensors in the lower tank. Of the 12 LH2 sensors in the lower tank, 7 sensors are used in the forward fueling positions to indicate when the tank is full, 1 is a 5 percent fueling sensor, and 4 are engine cutoff (ECO) sensors used to ensure the safe shut down of the main engine if the tank runs out of LH2. The following figure illustrates the external fuel tank and associated sensors.

Figure. Space Shuttle and External Fuel Tank



Source: NASA Fact Sheet, "Engine Cutoff Sensor System," February 2008.

All of the sensors use two terminal posts that complete an electrical connection; a change in resistance is detected when covered by cryogenic liquid. Each terminal post has a terminal washer (on the bottom), a Belleville washer (on the top), and each terminal post is swaged[2] to secure the Belleville washer to the post. According to MSFC engineering personnel, the swaging of the terminal posts is a critical process because if the swage is not properly securing the Belleville washer to the assembly, the washer may become loose and may cause unpredictable sensor performance. The failure of two LH2 ECO sensors could cause the loss of life or the failure of a mission.

ECO Sensor Anomalies and Utilization

In July 2005, because an LH2 ECO sensor showed abnormal readings during the fueling of Space Transportation System (STS)-114, which resulted in a 2-week launch delay, the Project Office assembled a team to identify the anomalies that occurred. According to the Project Office, the team created a fault tree and determined that the LH2 sensors

[2] Swaging is a process used to reduce or increase the diameter of tubes and/or rods by placing the tube or rod inside a die that applies compressive force by hammering radially.

themselves were the likely cause of the abnormal readings. The team performed a process review to assess the manufacturing and acceptance testing process for the LH2 sensors and found that improvements could be made in the manufacturing process and acceptance testing process for the LH2 sensors.

The MSFC Engineering Department used the NanoFocus Lab to screen the LH2 sensors and found that many of the LH2 sensors contained washers that did not meet required specifications and other workmanship issues. Subsequently, the MFSC Engineering Department used the NanoFocus Lab to identify and rank the LH2 sensors better suited for the ECO position. The sensor supplier and contractor incorporated the results of these screenings by incrementally improving manufacturing and acceptance testing processes.[3]

In October 2006, the supplier began delivering sensors that incorporated process improvements. Consequently, MSFC engineering personnel stopped ranking the sensors in December 2006, though the sensors continue to be screened. However, because of the time between external tank assembly and shuttle launch, post-process improvement sensors were not immediately available for flight. For Space Shuttle flights STS-121 through STS-117 (July 2006 through June 2007), the external tanks contained ranked and screened pre-process improvement LH2 sensors in the four LH2 ECO positions and unscreened pre-process improvement sensors in the eight fueling sensor positions. According to the Project Office, pre-process improvement LH2 sensors were used because the process improvement review was either not completed or the supplier had not delivered any of the post-process improvement LH2 sensors. In addition, the Project Office determined that there was minimal mission risk associated with using unscreened pre-process improvement LH2 sensors for the eight fueling sensor positions. In August 2007, STS-118 was launched with the first screened post-process ECO sensors. In May 2008, STS-124 launched with screened post-process improvement ECO sensors and screened pre-process improvement sensors in the fueling positions.[4] The first Space Shuttle flight with all post-process improvement LH2 sensors is projected to be STS-119, scheduled for launch in February 2009. The following table shows the chronology of LH2 sensors and their utilization.

[3] The supplier began delivering post-process improvement sensors in October 2006. Process improvement refinement continued until the contractor established new standards for the sensors on August 23, 2007. Some of these improvements included the development of swage height requirements and measuring standards, updated soldering consistency for the bottom washer and the terminal post, additional record keeping and modernization of the equipment being used to perform the acceptance testing, and Defense Contract Management Agency personnel providing on-site monitoring during the manufacturing of the sensors.

[4] The one 5 percent fueling sensor for the external tank for STS-124 was an unscreened pre-process improvement LH2 sensor.

Table. Chronology of LH2 Sensors and Utilization			
Date	**Event**	**ECO Sensors**	**Fueling Sensors**
July 2005	STS-114 experiences abnormal ECO sensor readings, which resulted in a 2-week launch delay		
March 2006	MSFC Engineering Department begins screening and ranking sensors		
July 2006	STS-121 launch	Screened, pre-process improvement	Unscreened, pre-process improvement
August 2006	Contractor implements inventory controls to segregate flight ready and nonconforming sensors		
September 2006	STS-115 launch	Screened, pre-process improvement	Unscreened, pre-process improvement
October 2006	Supplier begins delivery of sensors incorporating process improvements		
December 2006	MSFC discontinues ranking sensors		
December 2006 June 2007	STS-116 launch STS-117 launch	Screened, pre-process improvement	Unscreened, pre-process improvement
August 2007	Contractor established new standards for sensors		
August 2007 October 2007 February 2008 March 2008	STS-118 launch STS-120 launch STS-122 launch STS-123 launch	Screened, post-process improvement	Unscreened, pre-process improvement
May 2008	STS-124 launch	Screened, post-process improvement	Screened, pre-process improvement[a]
November 2008 (target date)	STS-126 launch	Screened, post-process improvement	Screened, pre-process improvement
February 2009 (target date)	STS-119 launch	Screened, post-process improvement	Screened, post-process improvement

[a] The one 5-percent fueling sensor for the external tank for STS-124 was an unscreened pre-process improvement LH2 sensor.

Assessment and Disposal of LH2 Sensors Inventory

Because of MSFC's process improvement review, the contractor began controlling all LH2 sensors inventory by separating the sensors into Flight Ready inventory and 74L4-2 Parts inventory. All the pre-process improvement LH2 sensors were labeled "nonconforming" and assigned to the 74L4-2 Parts inventory, to ensure that these sensors were not used in the LH2 ECO positions, and LH2 sensors received from the supplier were directly assigned to the 74L4-2 Parts inventory until the NanoFocus Lab could screen them. The contractor's policy was to send all LH2 sensors to the NanoFocus Lab to be screened before assigning the sensors a new part number that indicates they are flight ready.

According to the contractor's records, as of April 30, 2008, the contractor had a total of 114 LH2 sensors—8 LH2 sensors in the Flight Ready inventory and 106 LH2 sensors in the 74L4-2 Parts inventory. The 74L4-2 Parts inventory included

- 12 screened pre-process improvement LH2 sensors, which had low ranking and were therefore labeled as nonconforming;
- 65 unscreened pre-process improvement LH2 sensors;
- 9 screened post-process improvement LH2 sensors assessed as damaged or questionable;
- 8 screened post-process improvement LH2 sensors in the process of being returned to the supplier to be cleaned and repackaged;[5] and
- 12 post-process improvement LH2 sensors waiting to be screened by the NanoFocus Lab.

In addition to the 8 LH2 sensors in the Flight Ready inventory and the 106 sensors in the 74L4-2 Parts inventory identified above, the contractor, as of September 16, 2008, had received 36 additional sensors from the supplier and expects to receive approximately 60 more. The contractor intends to use the 8 LH2 sensors in the Flight Ready inventory and these additional 96 sensors, which include 24 spare sensors, in completing the final 10 Space Shuttle missions.[6]

The Project Office does not plan to use the 9 post-process improvement LH2 sensors that were damaged or questionable nor any of the 77 pre-process improvement sensors--i.e., the 12 screened pre-process improvement sensors ranked low by the NanoFocus Lab

[5] These sensors were labeled as nonconforming due to substandard packaging and will be reevaluated after the supplier cleans, repackages, and returns them to the contractor.

[6] The Shuttle LH2 sensor is reportedly the same sensor that will be used by the Ares V rocket currently under development, assuring sensor availability in the event that Shuttle flights are added beyond the planned 2010 retirement and the current LH2 sensor contract terminated.

process and the 65 unscreened pre-process improvement LH2 sensors. Although the Project Office does not plan to use any of the 65 unscreened pre-process improvement LH2 sensors, the contractor plans to maintain these sensors for future unanticipated mission requirements and, according to the Project Office, if any of the 65 unscreened pre-process improvement LH2 sensors are needed for use, they would be screened by the NanoFocus Lab and only used in the less critical fueling positions.

We recognize that the Project Office should generally maintain available resources for unanticipated mission requirements or other contingencies; therefore, the usability of the 65 unscreened pre-process improvement LH2 sensors needs to be determined. Unanticipated mission requirements can often be schedule–sensitive, and screening the LH2 sensors can be a time-consuming process due to competing contractor priorities. Maintaining parts in inventory that are not suitable or intended for use introduces unnecessary risk. Screening the 65 unscreened pre-process improvement LH2 sensors and disposing of sensors that are not suitable or intended for use will provide management with better information to make timely and informed choices concerning these sensors.

Recommendations, Management's Response, and Evaluation of Management's Response

Recommendation 1. We recommended that the Project Manager, External Tank Project Office, determine the usability of the 65 unscreened pre-process improvement LH2 sensors by coordinating with the MSFC Engineering Directorate to have them screened by the NanoFocus Lab.

Management's Response. The Program Manager, Space Shuttle Program, partially concurred, stating that inspecting the 65 sensors at this time is not a desirable option and the sensors will only be screened if absolutely necessary. Instead, the External Tank Project Office intends to replace the sensor inventory with new process-improved sensors. Once the sensor inventory is sufficiently restocked to complete the external tanks currently on contract, the nonconforming sensors will be marked as Non Production Units and released to the Engineering Directorate for testing purposes only. The projected completion date is June 4, 2009.

Evaluation of Management's Response. Management's planned action is generally responsive. Although the External Tank Project Office does not plan to screen the 65 sensors unless absolutely necessary, the intent of our recommendation, which was to reduce the risk of maintaining parts in inventory that are not suitable or intended for use, is satisfied by management's proposed action to release the 65 sensors to the Engineering Directorate for testing purposes only and, in response to our second recommendation, hold them in bonded storage. The recommendation is resolved and will be closed upon completion and verification of management's corrective action.

Recommendation 2. We recommended that the Project Manager, External Tank Project Office, dispose of any of the 65 pre-process improvement sensors that are found to be questionable by the NanoFocus Lab screening, the 9 screened post-process improvement LH2 sensors that were damaged or questionable, and the 12 screened pre-process improvement LH2 sensors in the 74L4-2 Parts inventory that are labeled as nonconforming and not intended for use.

> **Management's Response.** The Program Manager, Space Shuttle Program, concurred and will transfer the 65 non-screened pre-process improvement sensors and the 12 screened pre-process improvement LH2 sensors to MSFC to be held in bonded storage. The 9 screened post-process improvement LH2 sensors that were damaged or questionable will be evaluated by the contractor to determine their final disposition. In addition, due to the commonality in design, the External Tank Project Office will implement the same plan for the liquid oxygen level sensors. The projected completion date is June 4, 2009.
>
> **Evaluation of Management's Response.** Management's planned action is responsive. The recommendation is resolved and will be closed upon completion and verification of management's corrective action.

We appreciate the courtesies extended the audit staff during the review. If you have any questions or need additional information, please contact Mr. Raymond Tolomeo, Mission Programs and Projects Director, Office of Audits, at 202-358-7227.

signed

Evelyn R. Klemstine

2 Enclosures

cc:
Associate Administrator for Space Operations
Program Manager, Space Shuttle Program
Director, MSFC Engineering Directorate

Scope and Methodology

We performed this review from March 2008 through December 2008 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the review to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our review objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our review objectives.

We performed fieldwork at Marshall Space Flight Center and Michoud Assembly Facility. We held meetings with and obtained records from the External Tank Project Office, MSFC Engineering Directorate, and the External Tank Contractor.

To determine whether the nonconforming LH2 sensors were appropriately accounted for and disposed, we

- reviewed the actions taken by the External Tank Project Office after nonconforming LH2 sensors were identified;
- reviewed the results of the LH2 sensor screenings performed by the MSFC Engineering Department, Electrical, Electronic, and Electromechanical Parts Analysis Team, utilizing the NanoFocus Lab;
- reviewed LH2 sensor inventory records maintained by the contractor;
- reconciled the inventory records with the data obtained from MSFC Engineering Department;
- identified the process and the criteria used for selecting LH2 engine cutoff (ECO) sensors for flight; and
- determined the disposition of the LH2 sensors that the MSFC Engineering Department identified as nonconforming to design specifications (to include whether any may have been used for flight).

Computer-Processed Data. We did not fully assess the controls for the computer-processed data gathered from the contractor's inventory and build systems; however, we did compare the data gathered from contractor's inventory and build systems with records gathered from the NanoFocus Lab, nonconforming parts records, and build records. These comparisons did often result in adjustments to the contractor's inventory and build system data.

Prior Coverage. During the last 5 years, no reports have been issued concerning LH2 Sensors.

Management's Comments

National Aeronautics and
Space Administration
Lyndon B. Johnson Space Center
2101 NASA Parkway
Houston, Texas 77058-3696

December 10, 2008

Reply to Attn of MA-08-026

TO: NASA Headquarters
Attn: Assistant Inspector General for Auditing

FROM: MA/Manager, Space Shuttle Program

SUBJECT: Comments on the Draft Memorandum on the Review of the Space Shuttle Liquid Hydrogen Fuel Tank Sensors (Assignment No. S-08-011-00)

We have reviewed the draft memorandum and concur with the responses of the External Tank Project Office enclosed. If you have any questions or need additional information regarding our comments, please contact Mr. John Casper at (281) 244-7692 or john.h.casper@nasa.gov.

John P. Shannon

Enclosure

cc:
AC3/P. H. Ritterhouse
MA/L. E. Cain
HQ/SSP Office/W. C. Hill
MSFC/MP01/S. F. Cash
MSFC/RS03/K. H. Roberts

Comments on the Draft Memorandum on the Review of the Space Shuttle Liquid Hydrogen Fuel Tank Sensors (Assignment No. S-08-011-00)

Specific Comments

1. Page 3, paragraph 1, states "All of the sensors use two terminal posts that complete an electrical connection when covered by cryogenic liquid."

We recommend that this sentence be reworded to "All of the sensors use two terminal posts that complete an electrical connection and a change in resistance is detected when covered by a cryogenic liquid." Revised

2. Page 7, paragraph 1, states "Unanticipated mission requirements can often be schedule–sensitive, and screening the LH2 sensors can be a time-consuming process, requiring up to 3 months lead time, because the screenings must be scheduled based on the availability of the NanoFocus Lab."

The lead time is due to contractor requirements rather than the availability of the NanoFocus Lab. Sensor screenings are a priority and can be scheduled within a week and we are able to examine approximately 5 sensors per day. Therefore, we recommend that the section of the report that states "requiring up to 3 months lead time, because the screenings must be scheduled based on the availability of the NanoFocus Lab" be removed. Revised

Recommendations

1. The Project Manager, External Tank (ET) Project Office should determine the usability of the 65 unscreened pre-process improvement Liquid Hydrogen (LH_2) sensors by coordinating with the MSFC Engineering Directorate to have them screened by the NanoFocus Lab.

Response to Recommendation: Partially concur. The ET Project Office has evaluated the usability of the 65 unscreened sensors. Our plan of action is to replace the Michoud Assembly Facility (MAF) sensor inventory with new process improved (Part # 809) sensors and not use any of the 65 or 12 (Part# 74L4-2) sensors in question. Once the MAF sensor inventory is sufficiently restocked with new build (Part# 809) sensors to complete the External Tanks currently on contract, the nonconforming sensors transferred to MSFC will effectively be scrapped. These sensors will be marked as Non Production Units and released to the Engineering Directorate for testing purposes only. This plan differs from the OIG recommendation in that the existing sensors will not be NanoFocussed unless absolutely necessary to complete the External Tanks currently under contract. NanoFocus inspecting the 65 nonconforming (Part# 74L4-2) sensors is

Enclosure

not a desirable option for the ET Project at this time. However, if the vendor cannot keep the current schedule commitments, then this option will be revisited.

Corrective Action Official:	MSFC-MP31/John Chapman
Corrective Action Closure Official:	MSFC-DE01/Robin Henderson
Projected Closure Date:	June 4, 2009

2. The Project Manager, External Tank Project Office should dispose of any of the 65 pre-process improvement sensors that are found to be questionable by the NanoFocus Lab screening, the 9 screened post-process improvement LH2 sensors that were damaged or questionable, and the 12 screened pre-process improvement LH2 sensors in the 74L4-2 Parts inventory that are labeled as nonconforming and not intended for use.

Response to Recommendation: Concur. The ET Project Office will remove the 65 non-screened and 12 screened LH_2 preprocess improved sensors (Part# 74L4-2) from MAF and transfer them to bonded storage at Marshall Space Flight Center. This action will mitigate any threat of inadvertent installation of nonconforming sensors in future External Tank builds.

The 9 screened post-process improved (Part # 809) sensors that were damaged or are of questionable quality were placed on Non-Conforming Documentation and are currently being evaluated by Lockheed Martin (LM) Engineering. Once LM completes the engineering evaluation, recommendations will be sent to the ET Project for final disposition for use-as-is, return to the vendor or scrap the sensors.

The OIG inquiry was solely focused on the LH_2 liquid level sensors, but due to commonality in design, the ET Project Office and Lockheed Martin will mirror efforts to implement the same plan of action for both LH_2 and liquid oxygen level sensors (Part# 74L4-1).

Corrective Action Official:	MSFC-MP31/John Chapman
Corrective Action Closure Official:	MSFC-DE01/Robin Henderson
Projected Closure Date:	June 4, 2009