National Aeronautics and Space Administration

NASA Case Study SCSC-R-0213

STS-114: Engine Cut-Off Sensors Are a No-Go

Overview

Returning to Flight

As the first *Return to Flight* Space Shuttle mission since the loss of Shuttle Columbia and its crew in 2003, Space Shuttle Discovery was scheduled to launch on July 13, 2005, bound for a 13-day mission. Designated as STS-114, the mission would be Discovery's 31st flight and the 114th flight of the Space Shuttle program. Anticipation was high as STS-114 was originally scheduled to launch in March of 2003. NASA had taken 18 months to restructure its inspection and repair procedures to return the shuttle safely to flight. On July 13, 2005, STS-114 was finally ready to launch – well almost. Discovery's crew of seven astronauts including mission commander Eileen Collins, pilot James Kelly, and mission specialists Soichi Noguchi[1], Stephen Robinson, Andrew Thomas, Wendy Lawrence, and Charles Camarda were suiting up to board. The rocket was being prepared for fueling and the routine prelaunch checks were underway. However, during the launch countdown a liquid hydrogen tank low-level fuel cut-off sensor failed, and with it so did NASA's first attempt to return to flight.

Liquid-Hydrogen Cut-off Sensors

Twenty-four propellant level sensors are within the shuttle's external tank (ET) – twelve in the oxygen section and twelve in the hydrogen section. Of the dozen sensors in the hydrogen section, four are used to measure the amount of residual propellant present in the tank during ascent. These four sensors are known as engine cutoff, or ECO, sensors. Mounted on a single, shock-isolated carrier plate approximately four feet from the very bottom of the liquid hydrogen (LH_2) fuel tank, they are part of a backup system designed to protect the space shuttle main engines (SSMEs) from catastrophic failure due to propellant depletion [9]. The ECO sensors consist of a platinum wire sensing element mounted on an alumina printed wiring board (PWB) and encased in an aluminum housing [12, p.8]. Other components of the

[1]From the Japan Aerospace Exploration Agency (JAXA)

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level sensing system include harnesses, a series of connectors, and point sensor box (PSB) electronics in the orbiter. The voltage across the sensors in the tank is measured through wires by the PSB in the orbiter, which in turn sends data signals to the orbiter's onboard computer system. The sensor wires lead to a feed-through connector in the lower tank wall and are routed through other ET factory connectors. External cables run up the external tank vertical strut to the orbiter interface at the two orbiter/ET electrical monoball connectors [7, p.2]. The circuit is then routed inside the orbiter to the avionics bay where the PSB services the signal from the LH_2 ECO sensors.

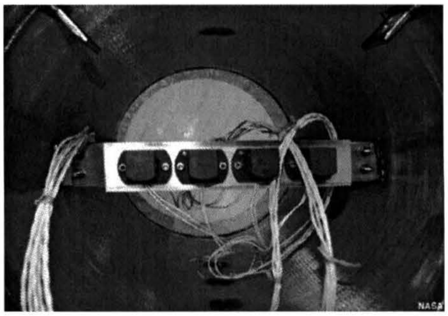

Fig.1. *Engine cut-off sensors located at bottom of external tank* [2].

The PSB services all twenty-four level sensors within the external tank, including the four engine cutoff sensors within the LH_2 section. Mounted on a coldplate in avionics bay-5 of the orbiter, the PSB supplies each sensor circuit with a constant current and reads the voltage across each sensor's thermosensor wire element [7, p.3]. The platinum wire sensing element of the sensor acts as a variable resistance which changes on exposure to cryogenic liquid [12, p.9]. At ambient temperature, when the sensor wire resistance is high, the measured voltage is considered above the preset trip level in the box and provides a "dry" indication. At liquid hydrogen temperature, -423°F, the voltage drops below the trip level and the signal is perceived as "wet". Flight software checks for the presence of "wet" indications from the sensors to indicate the presence of propellant and "dry" indications to indicate the engines are at risk of running too low. The LH_2 ECO sensors are coded to read "wet" once propellant loading begins to mean they are covered with cryogenic propellant [9]. Should the PSB electronics fail to provide an output signal or if an open circuit develops between the PSB and the sensor, a "wet" state is also indicated. Therefore, the box design includes self-check electronics which are activated by ground simulation commanding to help distinguish between a "wet" sensor output and a failed "wet" output [7, p.3].

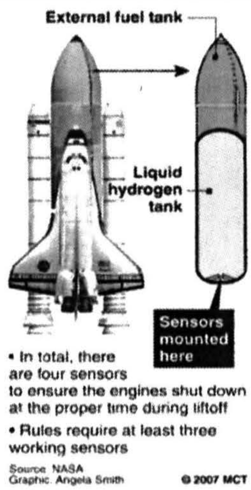

Fig.2. *External Fuel Tank Sensor Mount* [11].

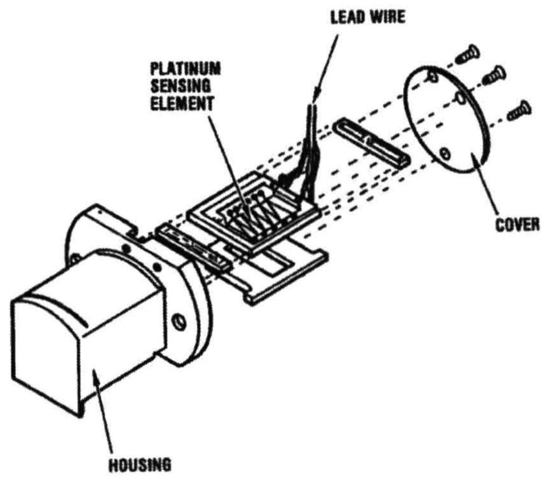

Fig. 3. *ECO Sensor System Overview* [7].

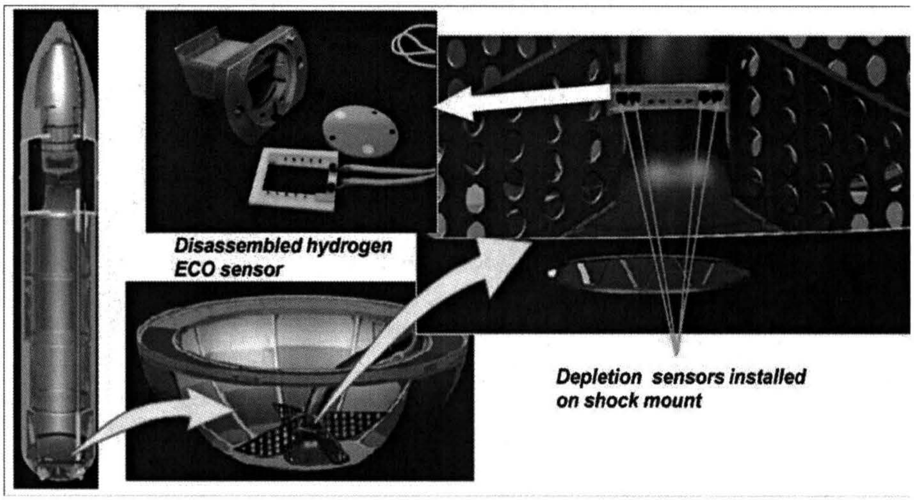

Fig. 4. *Liquid hydrogen ECO sensors installed at bottom of external tank* [7]

Responsible for protecting the Shuttle's main engines by triggering their shutdown in the event fuel runs unexpectedly low, the ECO sensor system is quite essential to proper Shuttle function. If a low level of liquid hydrogen were to occur in the 15-story fuel tank due to the main engines using more liquid hydrogen than predicted, it is crucial that the sensory system detects the condition immediately. The use of four sensors helps to ensure that multiple sensors agree that the tank is either empty, or not. The first "dry" indication from any of the ECO sensors is discarded to protect against a faulty sensor, but the subsequent presence of at least two more "dry" indications will result in a command to shutdown the SSMEs [12, p.9]. Once at least two of the three "active" sensors agree that the liquid hydrogen level is low, the main engines then shut down.

A premature engine shutdown could prevent a crew from reaching orbit. The orbital maneuvering system engines do not have the ability to make up for early main engine cutoff. Additionally, a delayed shutdown could be extreme, especially if liquid oxygen alone flowed through the engines. In the absence of a proper mixture, the main engines' turbo pumps would spin at an ever-increasing rate leading to engine fire or explosion and catastrophic destruction of the engines, the shuttle, and its crew.

Since the Challenger disaster of 1986, NASA's Launch Commit Criteria (LCC) has required four-of-four operational ECO sensors for a countdown to proceed. None of the four sensors can indicate "dry" prior to liftoff. Thus, when an ECO sensor anomaly occurred on the morning of July 13, the first attempt for an STS-114 launch was scrubbed and an investigation into possible causes was initiated immediately.

Challenges

Pre-Launch

Challenges with ECO sensors occurred as early as April 2005 during preparation for STS-114. Two sensors, ECO-3 and -4, operated intermittently during a tanking test. ECO-4 failed to indicate "wet" while fully loaded with propellants and ECO-3 failed to indicate "dry" up to ninety minutes after the tank was fully drained. To correct the issue, NASA engineers performed checkout of all hardware associated with the original failure, including the PSB. Once the PSB was confirmed to be operational, engineers were unable to trace the root cause of the performance error. It was decided to replace the PSB with the controller from Shuttle Atlantis and conduct a second tanking test. PSB serial number 108 was removed as suspect from Shuttle Discovery and replaced with serial number 110 [7, p.4]. The monoball harness was also removed and replaced. With these replacements, a second tanking test was performed in May 2005 during which the sensors worked normally. No ECO anomalies were observed during cryogenic loading. The fact that the original external tank, ET-120, was retested successfully during this second loading seemed to indict the removed PSB 108 and the original monoball harness [7, p.4].

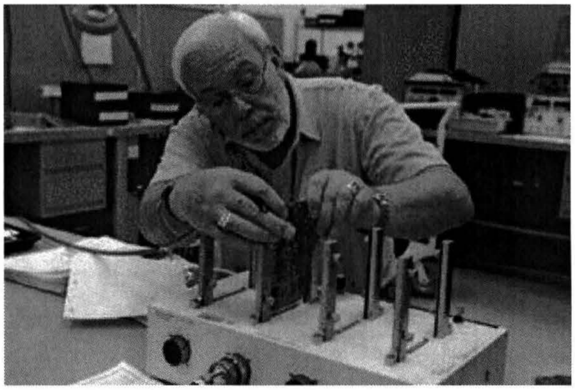

Fig. 5. *NASA test engineer Lloyd Pierce checks electronic components related to the faulty sensor readings in the LH_2 tank low-level fuel cut-off sensor* [5].

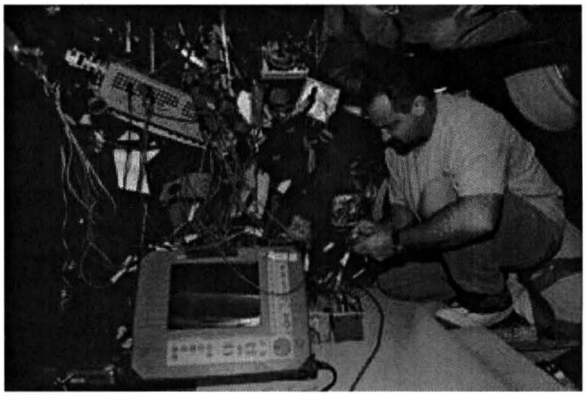

Fig. 6. *Jack Colella, with United Space Alliance, conducts electromagnetic interference and ground resistance testing on wiring in the aft engine compartment on Space Shuttle Discovery* [6].

Later testing led to the replacement of Discovery's external tank and a second replacement of its PSB due to unrelated issues. So at the time of the July 13, 2005 launch, Shuttle Discovery was equipped with a new controller, replacement cabling, and a new ET. It was presumed that all of the proper steps to fix the issue had been taken. But during the official launch countdown, the LH_2 ECO-4 sensor still failed to transition from "wet" to "dry" when signaled during a computer simulation. During de-tank, the same sensor failed to transition to "dry" when the propellant level within the tank dropped below the sensor, but did transition several minutes later [12, p.10]. After de-tank, ECO-2, which had not experienced any trouble before, failed to transition from "wet" to "dry" during a "dry-when-wet" command. This sensor remained "wet" until about three hours into de-tank boil-off when it transitioned to "dry" [12, p.10]. NASA officials became concerned that once the sensors were armed in flight, they could fail to cutoff the SSMEs in a fuel depletion situation. Thus, the ECO sensor issue remained to be an unexplained anomaly by NASA managers and the launch was scrubbed.

Preparing for 2nd Launch Attempt

To prepare Shuttle Discovery for a 2nd launch attempt, several measures were taken to understand the ECO sensor system anomaly and to recreate the anomalous system behavior. Engineers tried to isolate different areas to determine which area failed. To start, the entire electrical path from the orbiter PSB and through the sensors was verified via resistance checks and time domain reflectometry [7, p.5]. Additional troubleshooting included subjecting components to thermal and vibration testing to levels above those seen on the vehicle during flight. Various loading conditions, including coldplate settings, purge flowrates, and electrical switching, were duplicated on the STS-114 integrated stack [7, p.5]. However, the cryogenic propellant liquid hydrogen was unable to be loaded. Retired NASA official Robert Kichak[2] recalls, "Manufacturer acceptance testing of the ECO sensors was performed in liquid nitrogen, and this had at the time been believed to be adequate. Liquid hydrogen testing is much more difficult to perform, since it is hazardous," [3]. Thus, the Space Shuttle Program did not test ECO sensors prior to launch countdown in liquid hydrogen at -423°F, but rather in liquid nitrogen at -320°F [12, p.12]. Additionally, NASA engineers were constrained by the limited number of cycles on the tank. As Mark Nappi[3] also noted, "You can't just continue to tank [test] looking for a problem. It's expensive and may cause the tank to not be used anymore," [8]. So without the exact recreation of launch configuration, troubleshooting was impaired.

Fig. 7. Members of the engineering team are meeting in the Launch Control Center to review data and possible troubleshooting plans for the liquid hydrogen tank low-level fuel cutoff sensor [4].

Over the next few weeks, NASA engineers continued to find it difficult to pinpoint the source of the error. The point sensor box was eventually torn completely apart, but none of the discrepancies could be traced to either of the original failures. It only occurred when the vehicle was fueled and ready for launch. Swapping ECO sensors between two PSB signal conditioner channels was presented as a possible solution to facilitate troubleshooting, but was constrained by a programmatic requirement to maintain the vehicle in a launch-ready configuration [12, p.11]. Troubleshooting of the anomaly was extensive, but the root cause of the failures observed during STS-114's first attempt to launch was not identified. Even NASA's Engineering and Safety Center (NESC) consultation team, whose support was requested shortly following the initial anomaly, had limited findings and observations. While no definite cause could be pinpointed after weeks of investigation, probable causes included loss of continuity within both the ECO-3 and ECO-4 sensors' circuitry which manifested as a result of thermal effects. These thermal effects may have been induced by either exposure of associated hardware to cryogenic temperatures or

[2] Served as the National Engineering and Safety Center (NESC) Discipline Engineer for Avionics; co-author of "STS-114 Engine Cut-off Sensor Anomaly Technical Consultation Report"

[3] Former United Space Alliance Vice President of Launch and Recovery Systems

heating effects within the PSB resulting from the increased steady state circuit current experienced when ET sensors are submersed in cryogenic liquid [10, p.30].

Decision Time

Following the July 13, 2005 STS-114 initial launch attempt, NASA's Mission Management Team (MMT) was faced with some very tough decisions. With inconclusive results from weeks of investigation, were they to proceed with launch? If the sensors failed again during countdown, were they to override the LCC? In the history of the Space Shuttle Program, the LH_2 ECO system had never initiated an engine shut down. Ascent performance margin and fuel bias provided additional protection against premature fuel depletion [9]. However, since the Challenger disaster in 1986, NASA's Launch Commit Criteria required four of four functioning sensors to launch. Space Shuttle Management could override these qualifications with reasonable justification, but since the beginning of the Shuttle Program in 1981, no Shuttle had ever lifted off without a fully functioning ECO system.

Proceeding with launch would have other implications as well. NASA engineers and its contractors would never be able to investigate the external tank flown in this mission again. Unlike the solid rocket boosters, the external tank and its elements, including the liquid hydrogen engine cut-off sensors, are not recovered and re-used. The ET is separated from the Space Shuttle after main engine cut-off and disintegrated upon reentry into the earth's atmosphere. Each tank used for a Shuttle mission is a new tank. Therefore, NASA engineers are never able to investigate ET system anomalies post-mission. As Mark Nappi noted, "The problem might be tank specific where the condition exists on one tank and it doesn't exist on another tank. So you could continue tanking [testing] a tank that will never fail. And of course you don't get the tank back so you can never do forensics on the hardware after the mission," [8]. The ET cannot be physically disassembled and studied after it is flown. The mission could proceed and the team could never know what the real issue ever was, especially if it never reoccurred.

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