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Opportunities for Launch Site Integrated System Health Engineering and Management

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Abstract: The launch site processing flow involves operations such as functional verification, preflight servicing and launch. These operations often include hazards that must be controlled to protect human life and critical space hardware assets. Existing command and control capabilities are limited to simple limit checking during automated monitoring. Contingency actions are highly dependent on human recognition, decision making, and execution. Many opportunities for Integrated System Health Engineering and Management (ISHEM) exist throughout the processing flow. This paper will present the current human-centered approach to health management as performed today for the shuttle and space station programs. In addition, it will address some of the more critical ISHEM needs, and provide recommendations for future implementation of ISHEM at the launch site.

Introduction to Launch Site Operations

Launch site operations begin with the arrival of flight hardware which can range from an individual component shipped from a vendor to a fully assembled vehicle that has returned from a recent space mission. Upon arrival, acceptance tests and inspections are performed to assess the

hardware's health. Hardware that arrives from a vendor is usually subjected to a complete end-to-end test of its electrical systems, including copper path (continuity) checks, stray voltage (isolation) checks and channelization (interface) tests. Hardware which is reusable and has proven system functionality during flight is generally not subjected to the same rigorous test protocols that are required for new hardware. Copper path testing is performed to verify signal continuity following connector de-mates. These de-mates are often the result of intrusive redundancy test procedures.

Prior to flight, functional testing is performed to certify hardware capabilities such as system functionality and redundancy paths. Hardware capabilities are often tested in a non-integrated environment such as the Orbiter Processing Facility (OPF) which is used to test only an orbiter and not a fully assembled shuttle. These functional tests are frequently re-performed at the Launch Pad after the orbiter has been stacked with its Solid Rocket Boosters (SRB) and External Tank (ET) into an integrated shuttle system and moved into launch position. Some functional tests are performed each time power is applied regardless of where the orbiter is in its processing flow.

Human Centered Health Engineering and Management

In today's launch site test environment, system health engineering and management is typically human-centered. Tests are performed by engineers who determine when non-conformances occur and initiate the proper paperwork to document the anomaly. In some cases, software is used to automate data collection or summarize results but it is ultimately the responsibility of the engineer to evaluate the data to determine if an anomalous condition exists.

Today's Human-Centered Health Engineering and Management (HCHEM) approach to launch site test and evaluation is costly, inefficient and dependent on the available engineering expertise. The goal of an ISHEM approach is to improve the

ability to accurately detect anomalies in a more timely and consistent manner than HCHEM techniques can provide.

The following sections will discuss current launch site health engineering and management problems and will suggest areas where replacing HCHEM with ISHEM will benefit launch site operations.

Space Shuttle Turnaround Operations

Most of the time required to turnaround space shuttle hardware is spent determining hardware condition following the previous flight[i]. The majority of this time is spent performing structural and thermal protection system inspections; and verifying the integrity of the various fluid systems. A significant amount of additional time is spent performing unplanned work associated with troubleshooting anomalies, replacing failed components (including removal of system components to gain access) and performing retest. Finally, system functional testing is performed to assess the hardware's readiness to support the next phase of the processing flow.

Inspections are typically labor-intensive operations where an experienced engineer uses techniques such as: dye penetrant inspections to detect the depth of dings and scratches; eddy current measurements to assess structural health; other non-destructive evaluation approaches which have become available throughout the years. These techniques provide the engineer with information that can be used to determine if an anomalous condition exists and rely on the engineer's knowledge of system specifications and previous test results. In the case of dye penetrant inspections, acceptable dings and scratches are entered into a "Ding Log" which is used to document and track known conditions. These logs require manual entries that cite

the position, shape and depth of the anomaly.

Fluid systems are revalidated after every flight because all fluid systems leak. Many of the fluids, such as oxygen and hypergols, are corrosive and will damage system seals and components over time which will lead to leaks. Some leaks that are deemed acceptable following an inspection may become unacceptable at a later point in time. One area of particular concern is the ability to accurately characterize the current state of a fluid system. This characterization is impeded by two problems. The first problem is that many fluid system areas are not instrumented so the ability to directly sense the current state is not available and must be inferred. The second problem is that many shuttle sensors are not regularly calibrated and can therefore provide inaccurate information. To compensate, engineers maintain manual "cheat sheets" that adjust for error based on sensor readings that are obtained under known conditions; such as the value of ambient pressure a pressure sensor should read at sea level. The engineer must calculate the actual pressure value based on the returned sensor reading and the known error obtained from the "cheat sheet." For example, a pressure sensor should read ambient pressure at sea level as 14.7 psia; however some shuttle pressure sensors may read this value within a range of -2.0 to 45 psia. A pressure sensor whose "cheat sheet" value indicates that it reads ambient pressure as 5 psia is offset by 9.7 psia. So when the sensor indicates that the system is at a pressure of 15 psia, the engineer must actually add the offset value to determine that the actual pressure is 24.7 psia. This scenario occurred in 1995 in the orbiter's Orbital Maneuvering System (OMS). A test engineer inadvertently failed to compare the value returned by a pressure sensor against the "cheat sheet" offset and

believed that the OMS system was at ambient pressure. When a technician opened the joint instrumented by this sensor, fluid escaped and started a fire in the OPF around the orbiter Discovery.[ii]
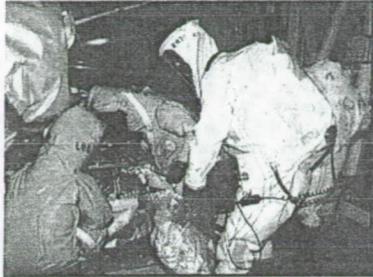
Unplanned work is the result of an HCHEM system that reacts to component failures as opposed to an ISHEM system that detects component degradation before failure limits have been exceeded. In other words, current launch site monitoring capability is designed to react based on pass/fail criteria as opposed to determining the component health and annunciating degraded conditions[iii]. In the case of a valve with open and closed positions, indicators provide insight into when an open or closed command is sent to the valve and whether or not the valve responded properly. While these indications generally provide enough information to declare the valve either functional or non-functional, they provide little insight into its health. An experienced engineer may be able to infer some health information from the indicator readings; however, the scope of what can be inferred is limited by the type of information being sensed.

For example, timing data is collected when Main Propulsion System (MPS) propellant valves are cycled open or closed. In this case, the propellant valve has two indicators, one located at the open position and the other at the closed position. When the valve is commanded open, the closed indicator will change state first. The open indicator will then change state once the valve has traveled to the fully open position. An experienced engineer uses this data to infer

whether or not the valve has become sluggish when starting to move or slow to cycle from one position to another. This inferred health detection is accomplished by: comparing the time the command is sent to when the first indicator changes state (detects sluggish valve); and comparing the time the first indicator changes state to when the second indicator changes state (detects slow to cycle).

System functional testing includes redundancy verification including: power, command paths and data paths. While avionics systems have more redundant paths than electro-mechanical systems, testing is generally more automated and therefore less time-consuming.

Space Station Element Integrated Testing

The Kennedy Space Station Payload Processing Directorate tests all of the payload items that will go into the Shuttle Bay. This includes the elements of the International Space Station (ISS), the Multi-Purpose Logistics Modules (MPLM), and experiments that will fly onboard the ISS or Shuttle. This testing is done in the Space Station Processing Facility (SSPF) and is the final functional testing performed before launch.

ISS Test & Verification

Multi-Element Integrated Testing (MEIT) is the testing of system functionality and interface compatibility between International Space Station elements. A standalone test is the testing of a single element to ensure functionality after shipment to KSC and prior to interfacing with the ISS. It can also satisfy requirements that haven't been met through previous testing at a different site. A MEIT or Standalone takes several years to develop and execute. Agreements are made during

Phase A (source gathering), such as concepts, testing ground rules, and responsibility test plan need to be made between International Partners, participants, and the ISS Program. Detailed Test Objectives (DTO) need to be developed evaluated and approved during Phase B (definition). This includes identifying support equipment and software, testing timeline, interdependent subsystems and their associated activities. Phase C (design) involves requirements development for functional testing, support equipment and software. For Space Station Processing requirements are known as ACOMC or OMRSD. During Phase D (development) test schedules are base-lined, integrated test procedures and test support products are developed, team members are identified and a console team is formed, test site preparations are completed, and off-site risk reduction activities are performed at ISIL. All pre-test (constraints review, readiness review, and pre-test briefing) and test activities are performed during Phase E (Operations). Phase F is the closure phase. The post-test debriefings are conducted, all paper is dispositioned and closed, and lessons learned are gathered.

MEIT 1 included 3A (Z1 Truss/Pressurized Module Adaptor #3), 4A (Integrated Electronics Assembly/P6 Long Spacer), 5A (US Lab), 5A.1 (Racks), 6A (Space Station Robotic Manipulator System), Flight Emulator (Node), and CITE (Cargo Integration Test Equipment). There were six configuration changes in MEIT1. MEIT 2 included 8A (S0 Truss/Mobile Transporter/Mobile Base System), 9A (S1 Truss), 11A (P1 Truss), 12A (P3/P4 Trusses), Flight Emulator (Node and US Lab). MEIT had five different configurations. MEIT 3 included 10A (Node 2), 1J (Japanese Experiment Module – Pressurized Module), and the Flight Emulator. Each of these includes regression testing for requirements that weren't met due to time constraints or technical issues and needed to be re-tested.

ISS Utilization/Research
Payloads/experiments can be accommodated in Facility Racks, EXPRESS Rack/Pallet, Mid-decks, and as Attached Payloads which connects them to the United States International Standard Payload Rack Checkout Unit (USICU) in the SSPF Intermediate Bay. The USICU emulates ISS. The verification and acceptance testing that is performed is the final payload-to-ISS functional interface testing and EXPRESS experiment-to-EXPRESS Rack functional interface testing. The USICU connects to the Payload Test and Checkout System (PTCS) which emulates the ground systems. PTCS includes an Enhanced Huntsville Operations Support Center (HOSC) which acts like the MSFC Payload Operations Integration Center (POIC).

ISS Re-supply and Return
The purpose of Re-supply and Return missions is to transfer racks, cargo, and Orbital Replacement Units to and from the ISS in order to keep the ISS operational and to maintain a capability for the ISS to conduct scientific research. Typical materiel transferred to and from the ISS includes: Science Payloads/Experiments; Flight Crew Items (food, clothing, personal hygiene, etc.); Logistics Items (tools, replacement parts, ORU, etc.). All of the items are transferred in a Multi-Purpose Logistics Module (MPLM).

MPLM Processing Flow:

MPLM Processing Flow
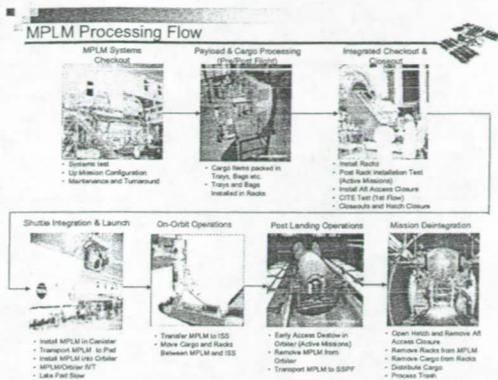
The Test Control Monitor System (TCMS) is utilized for all of the testing described above. TCMS consists of integrated networks of computers, software, data communications devices, displays, and controls required to control and monitor flight systems Ground Support Equipment (GSE) in direct support of International Space Station (ISS) ground operations at KSC. TCMS emulates MCC-H during local test operations and is a sub-set of S-band downlink telemetry.

Launch Pad Operations

Launch Pad operations involve performing activities that must be accomplished prior to Launch Countdown. These activities include: loading hazardous storable propellants, installing ordinance, performing unplanned maintenance activities and checkout of the integrated shuttle system. Prior to loading hazardous storable propellants ground personnel, suited in special protective gear, service ground support equipment and perform facility to vehicle connections. Loading can only occur after these preparations have been completed. During loading operations, automated ground software cycles valves as needed to maintain a strict pressure and temperature profile. Since the amount of propellant transferred to the orbiter's tanks cannot be directly measured, ground software performs complex calculations using pressure, flow rate and time to determine the actual density and amount of propellant loaded.

Final checkout of the integrated shuttle system includes performance of leak checks, hydraulic system conditioning, Inertial Measurement System calibrations, and payload end-to-end testing. Performing leak checks and isolating leaks to specific components is a particularly difficult task. The lack of sensing capability makes it difficult to directionally isolate the leak and determine its leak rate.
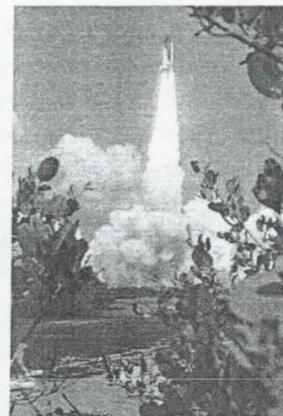
Ordinance loading requires the shuttle to be powered down and the launch Pad to be cleared of non-essential personnel.

Launch Countdown

Launch countdown involves powering up systems, configuring them for liftoff and performing final verification that that they are ready to support the launch and the mission.

One of the most hazardous launch tasks involves loading cryogenic hydrogen and oxygen into the external tank. Strict temperature control is maintained during cryogenic operations, and is particularly critical during oxygen loading. Excess heat buildup in the oxygen system can lead to bubble formation which will travel up the feed line on the outside of the ET. A "water hammer effect" will occur as the bubbles burst at the orbiter/ET interface where the plumbing makes a 90 turn. A "water hammer effect" can be of sufficient

magnitude to cause the line to rupture with catastrophic consequences.

The dynamic nature of cryogenic propellant loading requires continuous evaluation of system health to identify anomalous conditions. This evaluation is performed by comparing current data to data obtained during previous loading activities performed on the given shuttle. The harsh environment created by cryogenic activities usually causes multiple hardware failures during each propellant loading. These hardware failures must be identified, assessed, and remediated. The types of hardware failures most often observed are: leaks, loss of electrical continuity due to pin contraction, and sensor errors caused by impedance/resistance changes.

Integrated System Health Engineering and Management

Integrated System Health Engineering and Management will greatly improve safety, mission effectiveness and supportability over current launch site HCHEM techniques. ISHEM will tackle the problem space with an integrated scope, instead of focusing on one problem domain area. It will also provide an engineering approach to determining system health and will incorporate specific requirements and design solution space to adequately cover the integrated scope. Finally, it will provide a management function that will do more than just annunciate problems; it will work with the system's control authority to initiate remedial actions. Some specific areas that need to be addressed for future or derived launch systems are discussed below.

Sensing
Advances in sensing capability are needed to provide detection and isolation of defects such as cracks, weaknesses, and scratches in sealing surfaces. These advances must be accomplished without adding weight to the spacecraft or increasing power usage. Advances are needed in how failure mechanisms are directly sensed. For example, how do you sense the physics of a given failure as opposed to just monitoring the effect of the failure in the component? To illustrate this point, sensing technologies are needed that can detect when the tolerance between a valve piston and cylinder have changed or the spring constant has become degraded instead of just monitoring valve functions, such as open and close indications.

The change in valve piston-to-cylinder tolerance and degraded spring constant will ultimately lead to valve failure; however, they are extremely difficult to detect using current sensing technology.

Integrated Data Environment
Adequate monitoring and health determination require both current and historical data. An integrated capability is needed to easily access real-time and historical data based on a given part number and serial number or based on a given event. The current approach indexes data based on its vehicle location. For example, a measurement id might be V51P0088C1. "V51" indicates that this id is a measurement that belongs to the orbiter Landing and Deceleration System. "P" is a pressure designator. "0088" is its Landing and Deceleration System measurement location and "C1" is the data path the measurement takes to get to the ground. This measurement id is not easily correlated to a component after it is removed and placed in another location. This approach is not only inflexible it is incapable of correlating data with a specific component. In an integrated data environment, the measurement would include metadata that

would provide access to relevant data for any given component regardless of where it is located.

Configuration Data Automation

An ISHEM Configuration Data Automation capability would integrate measurement data, metadata and logistical data. The ability to track pertinent component configuration data is required to automate health assessment and improve situational awareness. For example, configuration data can be used to automatically track component power-on time. If the component fails after a given number of power-on hours, then all components with the same part number and comparable power-on hours must be evaluated. This would also aid in the tracking of hardware designated as Limited Operating Life Items (LOLI). This analysis today requires manual integration of data derived from multiple resources. Some of these resources currently provide limited data collection tools. Another example for configuration management would be the Electronic Connect/Disconnect Log (ECDL). The ECDL is entered manually in a database after a connection is mated or de-mated. This database could be linked to a drawing of the vehicle and updated when there is a connection made. A final example is the contents in the Re-supply Stowage Platforms (RSP), Re-supply Stowage Racks (RSR), or drawers. Currently the drawings and procedures have to be updated manually and weight and center of gravity measurements recalculated anytime something is removed or added. These items could be linked and aid in configuration management.

An ISHEM Configuration Data Automation capability is needed that will integrate all sources of configuration data with other relevant data sources. For example,

integrating component configuration data with its historical data would improve the ability to make detailed and refined health assessments.

Summary

Many ISHEM opportunities exist for future or derived vehicles that will be processed and launched at the launch site. This paper has merely scratched the surface by providing some of the higher priority ISHEM needs. Additional information on launch site health management needs can be found in the following documents: the Advanced Spaceport Technology Working Group (ASTWG) baseline report[iv] and the Advanced Range Technology Working Group (ARTWG) report[v]. These reports were generated by national working groups composed of leaders in industry, academia, and government.

Past health management focus has been concentrated on the vehicle side such as Integrated Vehicle Health Management, Integrated Intelligent Vehicle Health Management, etc. However many opportunities exist for ground and launch site health management. A truly Integrated System Health Engineering and Management system can only be developed and successfully implemented when both the ground and vehicle requirements are jointly considered during the design process.

[i] Carey McCleskey, Space Shuttle Operations and Infrastructure – A Systems Analysis of Design Root Causes and Effects, NASA/TP-2005-211519, April 2005

[ii] Interim Problem Report 069V-0037 "1995 OMS Fire during fuel feed line disconnect from thruster RIA", May 1995

[iii] Dougal Maclise, Scott Wilson, Orbital Space Plane Integrated Health Management Summit

Results, Recommendations and Lessons Learned,
April 2004
[iv] Cris Guidi, Advanced Spaceport Technologies
Working Group Baseline Report, November 2003
[v] Darin Skelly, Advanced Range Technologies
Working Group, March 2004