Flight Systems Integration & Test: Lessons Learned for Future Success

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Abstract

This paper offers a comprehensive view of flight system integration and test (I&T) lessons learned related to mishaps and close calls, focusing on what can be done to improve the I&T process to avoid recurrence. Specific areas within the realm of I&T that are covered in this paper include: I&T team communication and training; design of flight and ground systems for I&T; planning and scheduling; configuration management and process documentation; ground support equipment and tools; cleanrooms and contamination; mechanical integration, handling, and deployments; electrical integration and electrostatic discharge; functional testing and troubleshooting; environmental testing and facilities; and launch site operations. To illustrate "real-world" lessons learned for I&T, examples from throughout the history of the U.S. space program are presented. Also presented are some best practices for I&T that can help mitigate mishaps and close calls on the ground or during flight.

Introduction

"Those who cannot remember the past are condemned to repeat it."
– George Santayana, *The Life of Reason* (1905) [1]

The flight systems lessons learned presented cover all levels or phases of I&T, from subsystem and instrument I&T, through spacecraft bus and observatory I&T, and finally launch site operations. They apply to a variety of flight systems, from instruments and observatories, to Mars rovers and crewed vehicles.

The focus of this manuscript is on mishaps due to errors or omissions related to I&T, not to design, fabrication, or mission operations. This paper is also not a treatise on root-cause analysis, or on organizational or individual culpability for specific mishaps. It also is not an exhaustive collection of I&T incidents and lessons learned, as one would find in a repository like NASA's Lessons Learned Information System (LLIS) [2]. Rather, it offers general interpretations of representative incidents based on mishap investigation board (MIB) reports, case studies, documented lessons learned.

For the purposes of this paper, I&T can be considered synonymous with terms like test and verification (T&V); assembly, integration, and test (AI&T); and assembly, test, and launch operations (ATLO). Further, terms like "should," "can," and "must" are used interchangeably, since the recommendations identified here are not considered formal requirements. Nevertheless, the hard-learned lessons from history *should* be taken seriously; the mishaps of the past *must* be heeded to help ensure success in the future.

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I&T: The Last Defense

Flight system I&T is the process or program by which a spaceflight system is mechanically assembled, electrically connected, functionally and environmentally tested, and otherwise prepared for a spaceflight mission. It has been said that I&T is the last defense against any flight system problems prior to launch. Instruments, spacecraft, and other complex systems need to operate for months or years in the extreme environment of space; if there are any problems discovered following launch, there is usually no means to correct them.

Unfortunately, I&T is also the project phase that involves the most concentration of effort with little or no time to spare, especially if delivery of subsystem or instrument components are delayed. Further, there has never been an I&T program that went perfectly as planned. Many unexpected problems discovered during I&T may ultimately make the difference between mission success and failure.

The Concept of "Lessons Learned"

A *lesson learned* in the context of aerospace projects refers to a mitigating process or behavior arising from an awareness that usually follows an accident or "mishap." It can be identified by anyone familiar with the incident, including an individual, a project, or a MIB. A formal lesson learned is typically documented and vetted for reference by others, with the intent of helping to avoid recurrence of similar mishaps in the future.

Many mishaps, failures, and close calls in flight systems either: (a) could have been avoided had proper steps been taken during I&T, (b) were a consequence of actual oversights or mistakes made during I&T, or (c) problems seen during I&T that were left undiagnosed. Most have more than one root cause, usually involving human error. Common root causes include inadequate team communication, insufficient training, improper test or procedure protocol, and no end-to-end testing in flight configuration ("test-like-you-fly").

The term *lesson learned* is, however, somewhat of a misnomer: Lessons from a close call, mishap, or accident can be identified, acknowledged, and reported, but not necessarily *learned*. History is replete with mishaps that could have been avoided, had the participants been aware of and heeded previous lessons learned. Some of the more infamous examples of lessons not being learned include the space shuttle Columbia accident. In this case, the lessons from Challenger on Space Transportation Sytem (STS)-51L had not been learned well enough to help STS-107. Although the proximate cause was different, one of the root causes was the same: Accepting recurring damage to flight-critical components as acceptable ("in family"), what Diane Vaughan termed the "normalization of deviance" [3].

This normalization of deviance often occurs in I&T, as well. It includes practices such as relying on untrained personnel to perform critical tasks, frequently implementing non-standard practices that are unsafe, compromising process discipline under schedule pressure, and misuse or inadequate verification of ground support equipment (GSE) that interfaces with flight systems. Other common root causes of mishaps involve poor configuration management during I&T, not only related to insufficient rigor in tracking changes to documentation, but also a lack of discipline when it comes to modifying flight or even ground systems. Some I&T-related problems are more organizational in nature, such as inadequate team communication, or misunderstanding of team roles and responsibilities.

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Most lessons learned for I&T, however, can be broadly applied for any flight project, and across multiple disciplines. Regrettably, all valuable lessons cannot be covered in this paper, since there have been literally thousands of incidents, some considered proprietary and many not documented at all. It is hoped, however, that becoming aware of at least some key lessons from mishaps and close calls will help reduce the probability of recurrence.

Categories of I&T Lessons

There are several main categories of lessons learned for I&T, under which many mishaps and close calls have root causes or contributing factors:

- I&T team communication and training;
- Design of flight and ground systems for I&T;
- I&T planning and scheduling;
- Configuration management and process documentation;
- GSE and tools;
- Cleanrooms and contamination;
- Mechanical integration, handling, and deployments;
- Electrical integration and electrostatic discharge (ESD);
- Functional testing and troubleshooting;
- Environmental testing and facilities;
- Launch site operations;
- Other miscellaneous incidents and lessons learned not falling into other categories.

Using these categories, the table in Appendix A summarizes some representative mishaps and associated lessons covering a wide range of flight system I&T lessons. It includes only those causes and lessons of mishaps or close calls related to I&T, i.e., not causes and lessons that are not specific to I&T. The descriptions are intentionally succinct to enable a quick-look reference for I&T, citing archived lessons and reports if more details are needed. Some incidents involving several lessons are cited in multiple categories for ease of reference.

Team Communication and Training

Inadequacy of team training or familiarization with flight or ground systems figures prominently in many mishap investigations. Yet probably the most common contributing factor to mishaps and close-calls during I&T is inadequate, ineffective, or even nonexistent communication among the team.

A well-known example of this is the National Oceanic and Atmospheric Adminstration (NOAA) N-Prime mishap in 2004, in which the satellite fell off a turn-over cart (TOC) during a normally "routine" rotation (Figure 1). The proximate cause was 24 missing bolts on the adapter ring, due to improper procedure execution. However, there were multiple root causes covering several categories mentioned above, including: team familiarization and communication, planning and scheduling, configuration management and documentation, and mechanical handling. Among the many reported deficiencies, the hastily planned task involved insufficient oversight and poor communication of team roles and responsibilities. It is instructive to read the actual MIB report [4] for details, including several "missed opportunities" to recognize the absence of the critical fasteners. This seeming blind-sightedness involves what the MIB cited as

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a common error of highly structured, repetitive procedures, in which the operator has a narrow focus on the task at hand, without regard to the big picture.

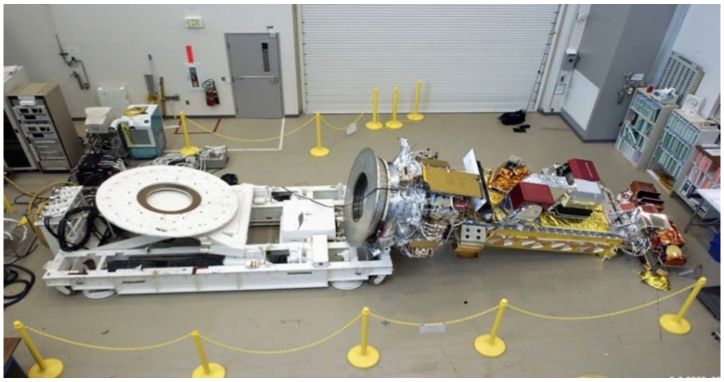

Figure 1: NOAA N-Prime mishap scene [4].

More generally, any I&T team member should be trained to identify unsafe situations, and even feel comfortable raising questions if he or she suspects something is not quite right. Any team member should be empowered to call a halt to an operation (hazardous or not) in an unsafe situation. At that point, safety is the priority – first human and then hardware. Emergency procedures are then implemented, if needed. If a mishap has occurred that is stable (e.g., powered-off flight hardware is accidentally impacted), then work stops in order to assess the situation, record details, take photos, and notify management. No work should continue until approval is obtained by the appropriate team leads, as defined by the project.

Many MIB reports have documented as a contributing cause lack of team communication regarding suspected or even observed risks and potential problems. Many more mishaps and close calls were avoided, often thanks to the diligence of a single team member who took the personal risk to speak up. A good example of this was during Magellan pad operations at the Kennedy Space Center (KSC) in 1989, when a technician was supporting closeout of the Solid Rocket Motor (SRM) Explosive Transfer Assembly (ETA) lines [5]. Due to unclear procedures and a diagram error, the lines were incorrectly connected to inert ports on the safe and arm (S&A) devices. There was also no cognizant engineer familiar with the S&A device present, and the plug on the inert port was not secure. The technician, who had concerns about the installation, took the initiative to research it further and verified that indeed the connection was in error. Thanks to this technician's diligence, Magellan's SRM ignited at Venus for a successful orbit insertion the following year.

Many other incidents in history could have been avoided had the advice or admonishment of technical experts been forwarded up the management chain, or even simply heeded by those involved. In the case of NOAA N-Prime, one of the root causes was that an earlier comment by the technician supervisor regarding the missing bolts was apparently dismissed [4]. Historical examples of advice being ignored include the shuttle SRB engineers' report of repeated "blow-by" of the viton o-rings under certain conditions, and their admonishment not to launch Challenger the morning of January 28, 1986 [7]. History eventually repeated itself 17 years later with the reinforced carbon-carbon (RCC) on Columbia – admittedly a different proximate cause, but nevertheless a common root cause involving management ignoring the advice of experts [8].

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A clear definition of roles and responsibilities is also important to ensure effective I&T, not only during the task at hand, but in the overall scheme of a project. For the former case, unclear roles may result in a critical task (like installing bolts) not being performed. For projects, ambiguous roles can result in a perfunctory approach to completing work, and a lack of respect for role boundaries among the team can affect morale. Any of these conditions can lead to mishaps or close calls.

With regards to team training, a safe and successful I&T program depends on a team that is well-trained and familiar, not only with the systems they use but also with the tasks they perform. It is common for mission operations teams to perform a series of ground simulations to be well-prepared for on-orbit operations. This same approach should be implemented for I&T, whereby dry-runs of critical tasks (e.g., prelaunch servicing) are conducted to ensure that the team is prepared, that procedures are accurate, and that equipment is operationally sound.

Once I&T begins, regular operations updates to the team, usually distributed by the I&T manager, can help to ensure everyone is on the same page. This can include the latest hardware configuration, near-term schedule, who is responsible for what, and resource requirements. It can also include specific actions for specific individuals, and a deadline for completion (the latter often left open-ended). An online shift log is also helpful, that can be reviewed by incoming shifts for any operational details. However, logs should not take the place of preshift and pretask briefings, both of which serve to inform those involved of current system status, any open items and actions, upcoming tasks, and potential hazards.

With respect to leadership of the team itself, the I&T manager must be at the same time experienced and trusted. He or she should not only have the *responsibility* of implementing an I&T program that meets requirements and schedule, but also be afforded the *authority* necessary to carry it out effectively.

Lastly, establishing a cohesive team that works well together may be one of the most important factors to ensure a safe and effective I&T program. Team building activities, such as I&T "retreats" or periodic team lunches, may be enough to help facilitate an environment of trust and camaraderie [9].

Designing for I&T

Many incidents, mishaps, and close calls can be traced to a lack of proper ground or flight system design that fails to mitigate human error during I&T. Examples include electrical designs that incorporate identical adjacent connectors, inadequate labeling of components, inability to verify final flight interfaces, and inaccessibility for tasks such as prelaunch maintenance and closeouts. This includes avoiding "blind" electrical comnectors or mechanical fasteners, and locating components to allow replacing nonflight units with flight units following environmental testing (e.g., batteries).

One example of designing for I&T that is not always considered is the ability to verify final flight mates of electro-explosive devices (EED's). This flight closeout typically involves installing an arm plug to connect an EED, such as a NASA Standard Initiator (NSI), and enable it to fire when commanded – usually a mission-critical function. Since functional verification of an EED is not feasible, a parallel test connector is required in the circuit in order to verify the final arm plug interface. Although the probability (likelihood) of a failure in the arm connector is low, the severity (consequence) of the EED not firing is usually high. Thus, designing into the circuit a means to perform a final electrical interface verification during I&T is highly recommended, and something the author codified as a Goddard Open Learning Design (GOLD) "rule" [10].

Other examples of designing for I&T is determining how best to layout GSE to access existing flight hardware, such as that required for prelaunch closeouts.

Planning and Scheduling

Planning and scheduling for I&T might not be considered an area of concern as a factor in mishaps. However, several mishap investigations have cited inadequate planning and scheduling as root causes.

Most flight projects develop an I&T plan that covers all aspects of I&T, including I&T organization and processes, resource requirements like facilities and equipment, and tasks to be performed during all phases of I&T, from integration of individual subsystems, to integrated testing and environmental verification. Flight systems I&T generally benefits from development of such a plan, in that it helps identify I&T support requirements and ensures the project team is in agreement with regards to what needs to be accomplished, how it is to be performed, who is to perform it, and what resources are required.

One example of schedule pressure that led to a mishap was on Gravity Probe B I&T, prior to transfer between facilities [11]. Gaseous nitrogen was erroneously connected to the guard tank vent line, rather than gaseous helium. This resulting in blockage of the vent line from frozen nitrogen that had to be removed, and concomitant schedule delays. The mishap report cited schedule pressure leading to overwork as a root cause.

In planning I&T in advance, estimates for task durations should take into account what can be considered *normal I&T overhead,* such as: cleanroom and equipment preparations; procedure development and approval; and transfer, setup, and cleaning of hardware. Beyond this standard overhead are unforeseen situations, such as component delivery delays, facility conflicts and maintenance, interface incompatibilities, and weather disruptions. There are also labor costs associated with late arrival of key personnel, cleanroom suit-up, pretask and weekly meetings, not to mention morning coffee, breaks, and lunch. There may also be union-related constraints that add to schedule overhead, depending on contract requirements.

Once an I&T flow and schedule are drafted, it is helpful to convene a project-wide meeting with all the respective subsystems to review the flow step-by-step and modify, if necessary. This "systems-level" approach to defining the I&T process allows everyone to consider the various aspects of what needs to be done, in what order, and for how long. The schedule will change as time goes on, but a more accurate assessment of initial schedule and resource requirements facilitates better planning.

I&T is intended to not only verify flight system requirements and mission readiness, but also to flush-out unknown problems which invariably come to light. This takes time and flexibility. Schedules, plans, and task sequencing often need to be modified on a daily basis or even "on-the-fly," which adds risk. Also, I&T tends to be more relaxed and less efficient early on. As I&T progresses, a team that has already been working hard for months has to work even harder to meet a delivery date. This introduces the risk of human error, as fatigue and stress naturally set in. Consideration of these potential schedule impacts is especially important, since I&T is usually left with only what remains in the project schedule after other delays, and thus must recover schedule to meet delivery dates. One way to do this is to have "back-pocket" tasks ready as fillers when planned activities are scrubbed or there is otherwise time available.

Single-string teams can be particularly challenging for small projects on a tight budget. If, for example, a key team member with no backup leaves the project (even temporarily), this can delay schedule or introduce risk to the flight system. Once I&T starts, there is little time or available staff to train new personnel, or to rely on others (e.g., systems engineers) to fill in. This must be kept in mind during the early planning stages, including during proposal development, when I&T staff and budget requirements are being decided. Further, initial baseline schedules should be limited to single shifts, 5 days per week; adding shifts or days should be reserved for contingency later on.

Sometimes, a schedule originally planned as a serial sequence of events becomes more parallel to compress schedule. Regardless of what schedule changes are made, due consideration should be given to potential impacts on the both the flight system and people.

Configuration Management and Process Documentation

The term *configuration management*, or CM, generally refers to the process by which something is maintained and/or documented in a known state. It can refer to either hardware or software (flight or ground), as well as documentation (drawings, procedures, etc.). Often, the cause of a mishap can be traced to a lack of rigor or discipline in CM, leading to confusion regarding the actual system configuration.

CM of flight systems can be particularly challenging for projects involving mutliple spacecraft, such as Goddard Space Flight Center's (GSFC's) MMS (Figure 2) or Time History of Events and Macroscale Interactions during Substorms (THEMIS) missions. For the former, each individual spacecraft had its own I&T manager, and the configuration of each was carefully tracked using a color-coded system.

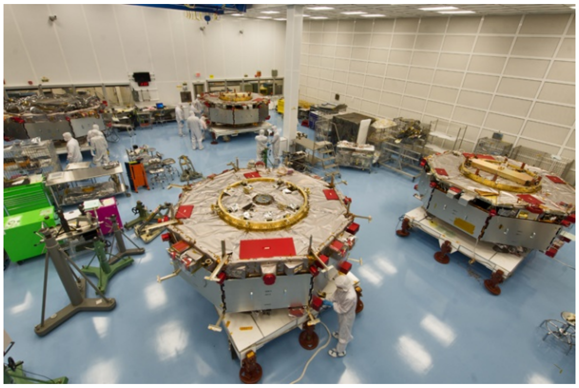

Figure 2: MMS constellation I&T at GSFC [12].

A good example of a lack of CM that resulted in a mishap, as well as of a well-written lesson learned, is the LLIS entry covering a fuel cell on the orbiter Atlantis damaged during ground operations at KSC [13]. In this case, a disconnected ground wire was not properly documented as a constraint to another task. A separate but related discrepancy was an

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undocumented requirement to leave a vent port uncovered in order to prevent hydrogen overpressure; this lead to damage of several internal components. Other root causes included an inexperienced team and failure to conduct a pretask walkdown. Ironically, a similar close call occurred just 2 weeks earlier, involving the same vent port on Columbia. In this case, an experienced technician caught the error in time, but the near miss was not communicated to the workforce. Thus, history was destined to repeat itself.

With regards to documentation, I&T procedures must be developed early enough to allow for proper review, approval, and release well prior to use. This is important to ensure the necessary resources are available and that personnel have time to familiarize themselves with the operations. Once operations begin, logbooks such as mate/demate and red/green (remove/install before flight) tag logs should be maintained on a real-time basis. This as-run record of operations and hardware configuration will be invaluable in case a mishap occurs.

Procedures that include any hazardous operations (including lifts) are consequently categorized as hazardous, and usually require review and approval by safety engineering. In addition, it is highly recommended to include in hazardous procedures detailed emergency response steps (e.g., power down, safing, etc.) as the final appendix, to allow ease of reference if needed. This is standard formatting for hazardous procedures at KSC.

It is fair to say that much of the documentation developed on flight projects is not value-added in itself; the process of writing the document is often more useful in identifying missing or misunderstood requirements. Also, there are often documents that cover redundant material, and often half of the content is common "boilerplate" introductory material (that no one reads). It is instructive to note that the Constellation Program Master Integrated Verification Plan (CxP 70008) was over 120 pages long [14]. The Apollo/Saturn-V Master Test Plan, on the other hand, was only 27 pages [15].

For low-cost, high-risk projects, known at NASA as "class D," the I&T team is by design limited in size and resources. In this case, documentation, review, and approvals should be streamlined to enable the team to devote their limited time to actually performing I&T.

GSE and Tools

GSE is often underestimated with regards to its importance to spaceflight missions. Yet, as the equipment that directly interfaces with the flight system, GSE can mean the difference between mission success and failure. A prime example is the GSE that was used to measure the curvature of the Hubble Space Telescope (HST) primary mirror before installation, referred to as the reflective null corrector (RNC). In this case, the cause of the spherical aberration was incorrect assembly of the RNC's metering rods, including no staking of the adjustment mechanism and no postassembly dimensional verification (see Figure 4). Misconfiguration of the GSE setup and lack of independent verification resulted in a textbook case of spherical aberration [16].

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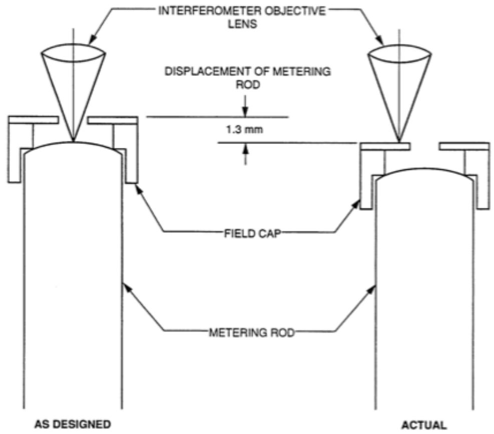

Figure 4: Incorrect displacement of HST mirror RNC, with interferometer focus on field cap instead of metering rod [16].

When it comes to safety, inadequacy or improper use has resulted in personnel injury or flight hardware damage, as the NOAA N-Prime mishap clearly illustrated. In other cases, GSE considered safe for use had an unidentified design flaw that eventually led to a mishap. In fact, something rather small, like a bolt or cap, can cause damage or injury.

Often, larger projects involving full spacecraft or observatories develop a nonflight system testbed, also referred to as a "flatsat." The flatsat system is usually comprised of EM's or spares of the spacecraft bus avionics, interconnected in a test lab on benches. This test system serves as a surrogate spacecraft for testing command/telemetry scripts, dry-running procedures, and new flight software loads. Once I&T is complete and mission operations begin, the flatsat can be used to verify new command sequences and flight software.

Cleanroom Facilities and Contamination

Cleanroom facilities to support flight system I&T include everything from portable cleantents, to large laminar-flow cleanrooms like the Spacecraft Systems Development and Integration Facility (SSDIF) at GSFC. Missions involving instruments with sensitive optics or operating at very cold temperatures (e.g., single-digit Kelvin) must be kept extremely clean during I&T. This usually imposes unique requirements such as: control of local contaminants, potential materials outgassing, and humidity; purging, monitoring, and protection, especially during transport; and special inspection and cleaning procedures.

To ensure that cleanroom facilities are available and certified before start of I&T, project and I&T management must layout, procure, develop, or reserve facilities well in advance. In some cases, an I&T facility is anticipated to be available for a project, but is still occupied by another project due to slips in that project's schedule (i.e., "squatters rights"). This has sometimes required the incoming project to design, develop, and certify a new cleanroom, at their own expense.

Once I&T starts, controlling contamination is a constant challenge. Training of all I&T personnel, particularly for contamination-sensitive hardware, should be mandated. Also, a contamination control engineer should be part of the I&T team through launch. Unique contamination control requirements must be clearly defined and followed during I&T, and contamination levels should be verified within limits via extended-duration testing [17]. Special contamination control requirements are usually necessary for missions requiring planetary protection (e.g., the Mars rovers, OSIRIS-REx, etc.). This typically requires extreme bake-out of flight hardware, such as dry-heat microbial reduction (DHMR).

Foreign object debris (FOD) also figures prominently in mishaps and close calls. Although this is an problem emphasized by aerospace organizations to workers and mitigated as best as possible [18], nevertheless some FOD still "falls through the cracks." One notable example was on STS-91, when a main engine combustion chamber pressure sensor froze during ascent, risking a return-to-launch-site (RTLS) abort or a catastrophic engine failure [19]. The cause was traced to a piece of viton from a test plug inadvertently left in after a propulsion leak check. In fact, viton was noted as missing during posttest tool removal. But after finding only part of the missing plug, the problem report was closed, and locating the remaining FOD was subsequently not pursued.

<u>Mechanical Integration, Handling, and Deployments</u>

Many mechanical integration mishaps occur during lifting operations, due in part to the routine nature of the task. However, crane lifts are still considered hazardous operation that requires both training and due diligence on the part of the team.

One lifting mishap involved the TOPography EXperiment for ocean circulation (TOPEX) /Poseidon spacecraft in 1992 [20]. The satellite rotated over 135 degrees while being lifted above a thermal test chamber, caused by an unstable lifting configuration. Although the lifting fixture was damaged in the incident, both the spacecraft and the chamber were spared. The MIB found that a stability analysis had not been performed, and that the GSE had not undergone a full review and dry run prior to the operation.

Once again, the NOAA N-Prime mishap can help inform future handling operations. Some related findings of the MIB include lack of proper configuration control of critical GSE, and no visual verification of fastener installation immediately prior to use [4].

Deployments can be particularly challenging to accomplish during I&T since the structures, and the mechanisms that deploy them, typically cannot operate in a 1-g environment. Thus, g-negation fixtures are usually required for a full deployment test. Further, a first-motion release ("pop-and-catch") is usually performed after significant stressors, such as vibration testing, thermal-vacuum testing, or shipment. Regardless, verification of deployment function, both mechanically and electrically, should be done as late as possible prior to vehicle integration, to ensure at least proper release after all flight hardware (e.g., cabling, blankets, etc.) is installed.

Some mishaps have involved excessive loads on the flight system experienced during transportation and handling. Though seemingly benign compared to launch, shipping and transportation can impact flight hardware due to unanticipated differences compared to the flight environment to which the system is designed and tested. In the case of the Galileo spacecraft, the high-gain antenna (HGA) failed to deploy following launch, resulting in a loss of real-time science telemetry and necessitating significant mission operations work-arounds. It was determined that the most probably cause was vibrations during transport that imparted excess loads on the antenna restraining pins [21].

Electrical Integration and ESD

Electrical integration involves not only installing wiring and cabling, but ensuring that workmanship and electrical interfaces are checked prior to connection with other elements.This usually performed via a safe-to-mate (STM) procedure. This can be done by using an automated STM machine, and should include power-on voltage measurements.

Common electrical errors contributing to mishaps involve mismating connectors or failure to perform a complete STM. The dramatic fire involving the Magellan spacecraft at KSC was a result of a blind mate to an active battery, and incidentally could have been avoided had the standard policy of not disturbing multilayer insulation (MLI) been waived in order to afford better access and visibility to the connector [22]. Other incidents of connection errors resulted in test failures. An I&T test failure on a Mars Exploration Rover (MER), for example, was traced to a connector that was recorded as mated, but was actually not connected. The root cause was a lack of procedural discipline to pause after each mate/demate and enter it in the log with QA verification [23].

ESD events are also a common cause of electrical system failures (see Figure 5). Often, the failure goes undetected until much later (latent failure). Progressive level of integration makes it even more difficult to repair, with potential risk to other flight hardware. Implementing ESD-safe practices during I&T can mitigate risk to sensitive electronics.

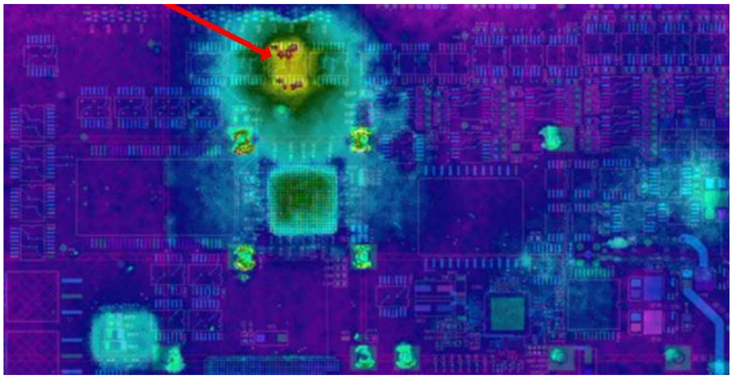

Figure 5: IR image of ESD damage on flight PC board.

Here are some general best practices for electrical integration and test [18]:

- Only trained and certified personnel should route cables, and mate/demate connectors.
- Perform safe-to-mates prior to connecting flight hardware.
- STM's should be performed after harness installation and any modifications to cabling.
- Ground cable and harness connectors prior to mating to drain any electrostatic charge, and verify proper grounding of flight hardware and GSE.
- Verify all power is off to the entire system (flight or GSE) prior to mating or demating connectors (power or signal), both for safety and to prevent transients during

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connection.

- Practice proper ESD protocol, including establishing an ESD safe area (ESA) with controlled and monitored humidity, and using ESD-protective equipment and garments.
- Record connector cycling in a mate/demate log to track flight configuration and connector maintenance.
- Use connector savers on flight connectors that are frequently mated and demated during the course of the I&T program, to minimize risk of damage.
- Protective caps should be installed on all unused connectors, and should be ESD-safe (usually black) when used on cables connecting to ESD-sensitive components.
- Disconnect meter probes and ground prior to changing functions or range scales, to avoid any inadvertent voltage.
- Connections to EED's shall be measured for stray voltage prior to mating, using a calibrated stray-voltage meter.

Functional Testing and Troubleshooting

A key aspect of flight systems I&T is functional testing, which ensures that elements function together as a system prior to testing the integrated flight system. Subsystem testing should be performed sequentially, after mechanical and electrical integration, to help identify any anomalies that may arise; integrating and testing more than one flight element in parallel makes troubleshooting any anomalies difficult. All newly integrated subsystem interfaces should be functionally verified. Functional testing is also performed following significant operations, such as hardware transfer and environment tests. More detailed tests, such as a comprehensive performance test (CPT), are performed to exercise the flight system in various flight modes. Full functional testing should be conducted at each stage of integration or level of assembly: from component to subassembly, to subsystem or instrument, to spacecraft and observatory, and finally to integration with the launch vehicle.

Often, schedule pressures invariably result in conscious decisions by a flight project to reduce or eliminate testing originally planned, while still retaining a lot of *project overhead*. This differs from *I&T overhead* mentioned earlier, and can include extraneous documentation and QA monitoring, excessive reporting and reviews, and management oversight. More reviews and documentation do not ensure success; risk can often be better mitigated by conducting a robust test program. On the other hand, as has been seen, critical checks-and-balances should not be minimized to the extent that safety of hardware and people is compromised. An "incompressible test list" is typically developed to ensure that, no matter what schedule pressures arise, there is a bare minimum of verifications predefined that must be performed.

During testing itself, the test team should remain engaged in the task at hand. There have been several mishaps that were caused in part by a lack of vigilance. Today, this situation could easily apply to someone who is more interested in texting on a smartphone than monitoring a test system display for any anomalous telemetry.

Certainly, one of the most well-known failures in test and verification involved the HST primary mirror (see *GSE and Tools*). Interestingly, errors discovered using other GSE were reportedly discounted by the contractor as invalid. Further, budget and schedule constraints led to not conducting an independent or end-to-end test [16].

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Another mission that was impacted (this time fatally) by a lack of end-to-end testing in flight configuration was the Wide-field InfraRed Explorer (WIRE) satellite. Shortly after a successful launch, an electronics transient to a pyrotechnic circuit initiated premature ejection of the cryostat cover, resulting in a rapid boil-off of hydrogen, which led to loss of stability and attitude control. Among other root causes was lack of fidelity in the test setup, inadequate troubleshooting, and incomplete understanding of an anomalous signal observed during testing [24]. A similar mistake occurred for a Milstar satellite in 1999, when data from not one, but two prelaunch tests was overlooked and misinterpreted (respectively) that could have prevented the loss of the $1.23 billion mission [6].

Further, in troubleshooting anomalies, configuration of both the flight and ground systems should be maintained to help ascertain both the actual problem and the cause. The exception is when there is imminent danger to hardware or personnel, in which case immediate power down and other emergency responses may be required. Regardless, I&T tasks should be halted until the problem is identified and, if necessary for continuing operations, resolved.

Environmental Testing

Requirements for environmental testing vary with organization, project, and level of integration (i.e., box, subsystem, instrument, spacecraft, observatory, etc.). The types of testing, extent, and sequence of tests vary as well, depending on requirements and facilities availability.

Although environmental verification requirements are usually defined by systems engineering, I&T is responsible for developing the I&T flow and arranging for test resources. In general, the preferred sequence of the major environmental tests is first electromagnetic interference and compatibility (EMI/EMC), then vibroacoustics, and finally thermal. This is based on the idea that the less complex and stressing tests should be performed before those that are more involved and require more resources. Further, if a problem is encountered that necessitates a design change, it is easier to reperform a test like EMI/EMC than to reperform a test as labor-intensive as thermal-vacuum.

Environmental testing at higher levels of integration, such as observatory I&T, is not intended to verify workmanship of subsystems or instruments; this should be performed at the lower levels of integration. Another good practice is to have the flight system powered up during vibration testing to detect undetected workmanship or design flaws, such as arching, open circuits, or relay chatter [25].

There have also been several cases where test chambers were either not designed to support the requirements, not certified, or inadequately maintained, including flight hardware for High-Energy Solar Spectroscopic Imager (HESSI), Lunar Atmosphere and Dust Environment Explorer (LADEE), and Juno. Test chamber problems can not only delay I&T, but also cause potential damage to flight hardware or injury to personnel. In the case of at least one of these projects, an awareness of test risks and review of lessons learned from earlier sine-burst test mishaps probably could have prevented a similar recurrence [26, 27, 28].

Launch Site Operations

Launch site operations can be the most interesting phase of I&T and ultimately the most rewarding, when one can finally see the fruition of typically years of work in a fully integrated

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spacecraft ready for launch. On the other hand, this time can also be the most stressful for a team, when 24/7 prelaunch operations in the midst of numerous hazards like propellants, ordnance, and heights can be very draining. Thus, this is a time is when everyone should be most vigilant to ensure safety of the team and of the spacecraft, while also addressing the inevitable unexpected problems that occur.

Following delivery, a full functional or comprehensive performance test is performed prior to encapsulation into the payload fairing for vehicle integration. It goes without saying that any late installations of flight hardware at this point introduce risk to mission success, since launch site operations are generally intended to perform just the minimum postdelivery and prelaunch tasks.

A final walkdown is also usually conducted by all engineering disciplines prior to encapsulation, to ensure proper configuration for flight. This should include inspection of cabling, thermal blankets and coatings, structures, mechanisms, instruments, and potential interference with separation or deployments. Other items include any remnant nonflight items or surface contamination. One example of a missed nonflight item was on Germany's TVSat-1 satellite, when hold-down clips that were not removed prevented one of the solar panels from deploying on orbit [6]. In cases like this or even losses-of-mission, remove-before-flight logs and close-out photographs taken prior to launch can prove invaluable.

JPL's 4-month launch campaign for the Wide-Field Infrared Survey Explorer (WISE), involving a hazardous cryogenic payload, faced numerous challenges, including the need for extensive scaffolding for 24/7 cryo operations, wildfires at Vandenburg Air Force Base (VAFB), utility outages, and pad space constraints for cryo GSE. Despite these challenges, WISE launch site operations were completed successfully without any major incidents. The team benefitted from previous lessons learned, and also conducted its own Post-Launch Assessment Review (PLAR). Below are several recommendations for successful launch site operations annotated in the archived WISE lesson learned [29].

Other Miscellaneous Incidents and Lessons Learned

Some aspects of I&T lessons learned either do not neatly fall into one of the above categories, or are so cross-cutting that they deserve special attention. Most notably is the idea that, due to frequently repetition or familiarity, a task involving flight hardware is considered "routine." This has led to mishaps involving lax procedural discipline or poor oversight [4].

A tragic example of this was the Apollo 1 fire, attributed to multiple root causes, including what astronaut Frank Borman and others referred to as a "failure of imagination." The plugs-out test at LC-34 was considered routine and safe, yet it was conducted under hazardous conditions, in a spacecraft with poor workmanship, and multiple risks of damage from loads induced by ground crews [30]. It had never occurred to the test team that a ground test, even on a flight spacecraft on the pad, could be potentially fatal.

Likewise, any flight systems I&T operation has inherent risks to both hardware and personnel. It behooves each person on the I&T team to be vigilant and proactive in addressing potential risks to prevent mishaps and close calls.

Another problem that often impacts I&T are late requirements that were not originally planned for, such as additional testing or processes, or modifications to flight hardware or GSE.

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Some Thoughts on Human Spaceflight

Those involved with human spaceflight missions have a unique responsibility to ensure that flight systems are qualified and safe for human spaceflight. This usually includes some level of crew training and familiarization, as well as sharp-edge inspections to ensure safety during extravehicular activity (EVA) (see Figure 6).

Figure 6: Author conducting a payload interface verification test (IVT) dry-run with the STS-107 crew.

Those involved in I&T also have the unique role after accidents, like Challenger and Columbia, of supporting investigations due to their intimate knowledge of the flight system. This can include providing information about what was done during I&T, and how any mishaps or anomalies encountered during I&T were addressed. This is when comprehensive, accurate records and notes come in handy.

For reference, Johnson Space Center (JSC) has developed an interactive database of "Significant Incidents and Close Calls in Human Spaceflight," that is very informative [19]. There are also suggestions related to shuttle payload I&T in the author's "Integration and Test of Shuttle Small Payloads," (NASA TM-2003-211611) that can still help inform I&T of flight systems today [9].

Conclusion: Lessons on Lessons

As alluded to earlier, lessons are not beneficial if they are not actually learned. Unless a project (or I&T manager) takes the initiative to research past lessons learned, history is bound to repeat itself. Some mishaps, such as the aforementioned fuel cell damage [13], are a consequence of an earlier close call either not being reported or not acted upon to prevent subsequent incidents. Unfortunately, most organizations do not have a simple, standard, and well-advertised means of reporting close calls or near misses. Nevertheless, it behooves those who witness or are involved in a close call to at least report it, to avoid potentially more serious recurrence (if not regret). There are mishaps that occur for which details are not released or easily accessible.

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Unfortunately, lack of communication regarding mishaps can unfortunately lead to recurrence of the same incident on future flight projects.

Some NASA centers like KSC have formalized the process of "recurrence control" (RC), whereby incidents, from minor problem reports to tragic accidents, are tracked for mitigation to avoid happening again. Sadly, RC is rarely achieved in reality: both the Challenger and Columbia accidents are testaments to a "normalization of deviance." Further, some existing RC systems have been inconsistently utilized in practice [31], and most organizations do not address RC at all.

Some organizations, such as the Jet Propulsion Laboratory (JPL), assess lessons learned at the beginning of a flight project, which has helped lead to successful missions like Kepler, Juno, and MER. JPL also develops a "lessons learned compliance matrix" for each project, to assign and track relevant lessons from the lessons archives [32]. Following launch of its missions, GSFC's Flight Projects Directorate holds "knowledge capture" sessions with the project team to discuss and document lessons learned.

There have been several undocumented "close calls" and mishaps that this author is aware of from only a small percentage of NASA flight projects. One can therefore infer that uncounted thousands of undocumented close calls and mishaps have occurred throughout the history of spaceflight. It is conceivable that any one of these, had they been made known, could have been enough to avoid a serious mishap, save a mission, or even save a life. Therefore, it behooves those of us in the I&T "trenches" to not only review and implement lessons learned, but to document those we are aware of, to ensure future mission success.

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Appendix A: I&T Mishaps and Lessons Learned

I&T Category	Item/Mission	Incident/Mishap	I&T-Related Cause (Proximate, Root, or Contributing)	Lessons Learned for I&T
Team Communication and Training	OV-104 [13]	Orbiter fuel cell damaged	Lack of familiarization w/ hardware, lack of procedural discipline, no walkdown, no comm. about near-miss 2 weeks earlier	Team training & familiarization (incl. QA), perform pretask walkdown, comm. critical near-misses
	OV-103 [33]	Payload bay door inadvertently rotated by GSE	Lack of supervision, no cross-shift debrief or walkdown, training deficiencies	Practice operational discipline, debrief between shifts, perform pretask walkdown; proper oversight, training & certification
	SSME-2032 [34]	Major Component Failure (MCF) issued, engine auto-shutdown by simulator during test	Missing valve component; no single responsible task leader	Identify a lead engineer with clear responsibilities
	Aquarius [35]	Hardware damage during acoustics test	Excess test levels due to operator error, unclear roles, lack of procedural discipline, lack of oversight (QA, engineering)	TC familiarity w/ "inner workings" of systems, possible errors; practice operational discipline; specify test roles/responsibilities
	MER [36]	Test system crashed during FSW test	Testbed config change not reported to test operator	Conduct preshift/pretest briefing, update proc, online shift log
	Mars Observer [37]	Payload Data System exposed to excess low temp in t'vac	Chamber operator override fail-safe/alarm, and trusted failed controller instead	Avoid arbitrary disregard/override of alarms; consult team (e.g., subsystem/discipline engrs)
	MPL/DS1 [38], Others [39]	"Single-string" teams pose risk to small projects	Replacing experts is difficult; limited oversight; inadequate support for parallel I&T ops, esp. if multiple spacecraft	Provide cross-training and backup support, mentoring, schedule mgmt, OT planning
	Magellan [5]	Potential failure of SRM to ignite @ Venus (mitigated)	Explosive Transfer Assy incorrectly connected to S&A device; unclear proc, diagram error, & no S&A engineer present; tech identified and follow-up to confirm error	Cognizant personnel req'd to review/approve critical or hazardous ops & procedures; independent verif. of untestable interfaces, cap unused connectors, practice critical ops
	Magellan [22]	Fire and damage to flight H/W and GSE	Short of battery during blind mate by inexperienced tech	Personnel who perform tasks must be trained and familiar
	MCO [40]	S/C trajectory incorrect; impacted Mars	Comm barriers between independent project teams	Include all groups in critical discussions; facilitate sharing of concerns & dispelling of assumptions
	STS-1 [41]	GN2 purge in orbiter aft compartment; 3 suffocated	Inadequate comm between shifts, between TCs & pad crew	Comm of hazards, open comm between crews
	NOAA N-Prime [61]	Observatory impacted cleanroom floor	Fasteners removed w/out coordination, participant observation/comments not heeded, lack of clear roles and responsibilities, inadequate oversight	Coordinate config. Changes, follow-up regarding concerns, establish clear roles, sufficient oversight
Planning and Scheduling	Multiple, incl. STS-51L [62]	Making up schedule time leads to overworked team and parallel ops, increasing risk of mistakes and mishaps	Schedule typically casual early on; late deliveries, ext. partner schedule, lack of foresight/planing wrt time req'd for tasks	Avoid complacency; practice constant comm; identify filler tasks; ensure adequate time and resources; afford some down-time
	NOAA N-Prime [4]	Observatory impacted cleanroom floor	Off-hours ops conducted by non-primary crew, lack of prep	Conduct critical ops with prime crew, avoid hasty rescheduling
	GP-B [11]	Frozen guard tank vent line	Wrong gas connected, no procedure, crew overworked	Use released procs, limit OT, ensure schedule is reasonable
	OV-103 [33]	P/L Bay Door inadvertently rotated by GSE	Task not cited in multiple schedules (i.e., OPF shop, KICS)	Coordinate and refer to planned task across disparate schedules
Design	DC-XA [43]	Land.gear undeployed; vehicle destroyed	Pneumatic line not verifiable after final connection	Design to verify interfaces and provide access for maintenance
	MGS [44], Magellan [22, 45]	Damage to flight H/W and GSE	Test battery shorted to wrong connector during blind mate	Design interfaces for access and clear line-of-sight
	Multiple [46]	Potential/actual damage to electrical system	Inadvertent mismating of flight interfaces having same connector types	Design w/ different connector part/keying, position, labels
	MER [47]	Fuse blown due to short of Rover Power Distribution Unit output	Miswire of Rover Electronics Module heater circuits not detectable thru measurement	Incorporate test points to verify thermostat-controlled circuits
	Galileo [48]	Photopolarimeter Radiometer cover impacted/damaged (3 times) during I&T	Tech garment snagged on sharp corner while in proximity, despite being experienced and with prior warning of risk	Design ext. areas of flight H/W with due consideration for I&T ops and access rqmts; avoid exposed sharp corners
	DS2 [49]	Battery power for each of 2 probes inadvertently applied, risking loss of battery power for mission	Flight design did not permit safing plug to remain installed throughout integration; mechanical switches enabled inadvertent ground paths for battery power	Accommodate use of safing devices thru-out I&T; ensure battery power cannot be inadvertently applied
	Orion [50], EPP	Access for late-flow or pad ops may be difficult or impossible (mitigated)	Critical elements requiring maintenance, installation, or close-out are difficult to access following vehicle integration	Design for accessibility (e.g., perimeter location, test conns); I&T s/b involved in flight H/W design early on

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I&T Category	Item/Mission	Incident/Mishap	I&T-Related Cause (Proximate, Root, or Contributing)	Lessons Learned for I&T
Configuration Management and Process Documentation	DC-XA [43]	Landing gear not deployed; crashed and burned	Lack of rigid procedure protocol and clarity of operations	Break critical tasks into separate steps, follow procedures
	NOAA N-Prime [4]	SRA inadvertently deployed during S/C rotation operation; radiator damaged	Devolution of procs to normalize nonstandard or unproven practices	Maintain standard/proven procedural protocol
	Cassini [51]	Erroneous red limit in telemetry delayed countdown	Telemetry database not updated, tested, and verified	Test database/procs in advance
	GP-B [11]	Frozen guard tank vent line	No written procedures to follow for connecting gas	Develop/follow procedures for ops involving flight H/W
	SSME [34]	Main Component Failure and auto-shutdown during test	Part not installed due to lack of procedural discipline	Establish defined procedures & protocol
	LDCM [52]	H/W damaged from battery short	Faulty EMI shielding not reworked prior to I&T	Assess open work before I&T for potential impact
	Swift [53]	BAT Power Control Board damaged; 4-month delay	Work order approvals streamlined to expedite schedule	Maintain established protocol for doc. approvals
	MER [23]	Navcam not powered during testing	Erroneous log entry indicating unmated connector as mated	Perform/verify mates/demates serially,practice log protocol
	NOAA-K [54]	AVHRR instrument overtemp on-orbit	Thermal louver cable not connected following postt'vac reinstallation	Practice proc protocol, maintain red/green tag log, vfy connections for flight
	SIRTF [55]	6 propulsion system pressure transducers failed	500V inadvertently applied to all connections due to proc error	Procs should specify voltages, and be reviewed by s/s engineer
	OV-104 [13]	Orbiter fuel cell damaged	Proc omission, disconnected ground wire not identified as a constraint to task	Identify critical tasks in procs, revise proc if in error, flag open work as constraint to start of task
	OV-103 [33]	P/L Bay Door inadvertently rotated by GSE	Missing proc steps, non-standard hardware configuration not identified as a constraint to task	Verify accuracy of procs, communicate/identify non-standard configuration as a constraint to task
GSE and Tools	NOAA-N Prime [56]	SRA inadvertently deployed during S/C rotation operation; radiator damaged	Insufficient access equipmt, makeshift MGSE failed	Adequate GSE; avoid temporary GSE configurations
	DC-XA [43]	Landing gear not deployed; crashed and burned	Insufficient access GSE; closeout interrupted/incomplete	Ensure adequate GSE; identify specialized GSE req'd for task
	Juno [57]	Component t'vac interrupted; 8 hours of test data lost	GSE test computer automously updated S/W	Ensure GSE background process cannot interrupt testing
	GP-B [11]	Frozen guard tank vent line	Gas bottles not clearly marked	Ensure GSE is clearly labeled
	KSC LC-39 LPS [58]	Test delays and disruptions	Ground systems not configured in advance for testing	Pretest checkout of ground system, incl. E2E & S/W config verif
	Multiple [59]	I&T schedule delays	Instrument GSE cabling too short, required real-time mod	Document req'd cable lengths in ICD, fabricate w/ extra length
	HST [16]	Mirror fabricated with incorrect curvature; spherical aberration	Test equipment not configured properly	Verify GSE setup, perform independent verification
	MSL [60]	Robotic Arm pressure during System Thermal Test not read by load cell	GSE not assembled properly and not verified prior to test	Ensure roper instructions for GSE assy, vfy op before critical test
	Galileo [6]	Multipath telemetry loss during mission due to reflection from conductive sunshade ribs	Transparent (vs. conductive) sunshade mockup used during groung testing	Use mockups that accurate simulate critical flight parameters
Facilities and Contamination	ISS MT [61]	Qualification model Linear Drive Unit functional test fixture damaged during testing	Facility power surge and failure	Use UPS w/ surge protection for flight H/W testing
	JSC Facility [62]	Simulation computer inadvertent shut down	Emergency power-off button mistaken for room exit button	Label critical buttons with due consideration to human factors
	IRAS [63]	Instrument required special contamination control processes	N/A (requirements met); contam. control processes worked well	Control contam; monitor, clean, and protect during transport
	OCO [64]	Multiple incidents of component contamination	Improper handling, materials, training	Conduct team training; contam. control engineer s/b involved in design, facility development, and I&T ops
	EMOS [17]	Instrument contam. from residual IPA	Special contam. control rqmts not followed	Follow unique rqmts; verify w/ extended testing
	Magellan [65]	Short circuit occurred during testing	Conductive fiber shed by ESD wrist strap	Use nonshedding ESD straps, esp. w/ electronic subassys
	MGS [66]	Inflow of unfiltered air into propulsion system	Loss of facility power, w/ no backup system	Ensure facility backup, contingency GSE design
	MSL [67]	Early test termination, loss of samples, risk to flt H/W and personnel, facility damage	Unauthorized facility maintenance, chilled water supply interruption led to flood of thermal chamber & lab	Coordination/approval of maintenance by facility and I&T mgmt, update critical facility list, haz ops training, incorporate alarm and auto-shutdown capability
	OV-104 [13]	Orbiter fuel cell damaged	Comm between test operator and tech difficult due to distance between control and task locations (i.e., LCC and OPF)	Establish control room in proximity to work on the floor
	HST [68]	Short and power outage halted test	Painter stepped on pipe, which cracked and sprayed water onto motor control center	Ensure electrical and mechanical equipment protected; use UPS during testing
	SSME (STS-91) [19]	Engine main combustion chamber pressure sensor froze after launch; potential for SSME shutdown and RTLS	Viton plug not removed from lee-jet following leak check; postcheck search for missing viton found only portion; PR closed	Practice procedural discipline, FOD awareness, posttest verif, review all lost parts
	Cassini [6]	Huygens internal foam insulation damaged; S/C destack from vehicle req'd; several weeks of delay to launch	Facility air conditioning output set 3.5 times too high	Verify facility services and utilities prior to use

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I&T Category	Item/Mission	Incident/Mishap	I&T-Related Cause (Proximate, Root, or Contributing)	Lessons Learned for I&T
Mechanical Integration, Handling, and Deployments	NOAA N-Prime [4]	Satellite slip from turn-over cart during rotation	Bolts not installed into base of TOC, lack of proc discipline	Vfy H/W config prior to task (walkdown), follow proc protocol
	DC-XA [43]	Landing gear not deployed; crashed and burned	Gas line not connected, not verified	Reverify all interfaces following final flight conn.
	GCP (STS-56)	P/L dropped more than a foot (0.3 m); 1-month delay to orbiter integration	Moving truck lift gate certified, but failed due to excessive load during previous lifting job	Ensure third-party equipment is certified, and ensure liability for damages and delays
	Galileo [21]	High-gain antenna failed to deploy; science telemetry loss	Vibration during transport imparted excess loads on restraining pins	Shipping and transport can impact flight H/W; vibrations/loads not same as flight environment
	MER [69]	ESD event at Rover Electronics Module chassis ground connection	Moving and opening shipping container induced charge	Vfy container by test and inspection prior to use; document procedures for packing/unpacking ESD-sensitive H/W; properly ground and label equipment
	USML-1 [70]	Installation problems associated w/ LiOH can containers	Fit check in flight config. was not performed prior to delivery	Perform H/W fit checks in flight config before delivery
	TOPEX/Poseidon [71, 20]	GSE damaged during S/C lift for t'vac test; risk to flight H/W and personnel	Unstable lifting config resulted in satellite rotation	Perform prior to lifts: stability analysis, MGSE review, dry-run of procedures
	NOAA-K [72]	Very High Frequency Real Time Antenna and -Y sunshade not fully deployed	(Suspected) Inadequate harness service loop at hinge	Ensure adequate sevice loop; deploy test in flight config.("test like you fly")
	MER [73]	High Gain Antenna dynamic test model pyro ejected pin and cap; hazard to H/W and personnel	Failure of cap and/or threads, inproper test setup	Remotely locate pyro tests, provide contingency protection
	TLS (MSL) [74]	Realignment of TLS difficult due to staking completed before I&T	No means to safely realign instrument, esp. following staking	Defer staking until final alignmts are completed during I&T
	Multiple [75]	Hydra-Set™ risks to H/W and personnel	Use of "unmodified" or undersized Hydra-Sets™	Use modified Hydra-Set™, protect against contam.
	TOPEX/Poseidon [76]	Solar Array Drive housing damaged due to being dropped	Employee unfamiliar w/ SAD tilted unit for measurement, unaware it was intentionally not attached to fixture	Only employees familiar w/ H/W should handle; ensure QA presence and proper protocol during use of GSE
	Galileo [48]	Photopolarimeter Radiometer cover impacted/damaged (3 times) during I&T	Tech garment snagged on sharp corner while in proximity, despite being experienced, and with prior warning of risk	Develop protective guards and procedures in advance, use second tech (buddy system) to monitor/assist during task
	MSL [77]	Mobility Assy pin nut broke during lift	Nut interfered with MGSE, resulting in excessive load; expected readings unknown during procedure execution	Incl. expected readings in proc, perform fit checks
	Genesis [78]	Canister detached from lift fixture fitting	Hoist ring fastener torque not verified since proof testing	Vfy fastener torque or striping prior to lifts
	Apollo 13 [79]	Oxygen tank jarred during handling prior to installation into Service Module, ultimately leading to in-flight explosion	Fill tube displacemt necessitated improvised detanking @ KSC, involving heater op and pressure cycling that exceeding qual.	Minimize flight H/W handing; vfy H/W integrity after accidental vibration events
Electrical Integration and ESD	Galileo [80]	Attitude control system reinitialized during test via power-on reset	Capacitive coupling between flight and ground systems	Analyze/verify AC and DC ground paths
	Swift [53]	BAT power control board damaged; schedule delayed 4-months, and $3M in damage incurred	GSE power harness reverse polarity; STMs not completed, due in part to schedule presssure; inadequate proc approval	Ensure proc approved; complete STMs prior to other elect. procedures
	CoNNeCT [81]	SpaceWire flight cable damage and failure following installation into flight enclosure	Improper fabrication, handling, and routing; unique electrical fabrication and assy processes required	Provide clear and complete instructions, have trained backup personnel; consult w/ external expertise for special processes
	LDCM [82]	Electrical component damage	Battery short to chassis thru harness shield; incorrect fabrication error (found during STM) was not corrected	Flag open problems as constraints to subsequent tasks, and review prior to start of task
	Multiple [83, 84]	Potential damage to electronic components	Incorrect practices and handling	Perform STMs, grounding, and proper ESD protocol; use connector savers and ESD-safe caps
	MER [85]	Electrical short & partial melting of power conn. and ground strap	Exposed ground straps shorted to facility power during H/W move	Insulate traveling ground straps
	MGS [43]	Transient energizing of Electrical Power System	Short to ground due to inadvertent pin contact during mating	Mate/demate only w/ power off & battery discharged
	MSL [86]	Motor Controller Sensor fuse blown	Short due to BOB misprobing during STM procedure	Perform measurements on circuits per proc and w/ care
	EFE [87]	Connector pins damaged	Excessive mating/demating of connectors	Use connector savers if frequent mating/demating is req'd
	Magellan [88]	Power Control Unit damaged during resistance measurement	Reverse polarity V during off-hours test, w/out QA or procedure	Conduct test w/ approved proc, oversight, and proper GSE use

I&T Category	Item/Mission	Incident/Mishap	I&T-Related Cause (Proximate, Root, or Contributing)	Lessons Learned for I&T
Functional Testing and Troubleshooting	SIRTF [89]	Rupture of cryogenic GSE burst discs	Lack of response to critical warning indications during test	Trust test data, regardless of previous discrepancies; solicit assessmt from independent discipline experts
	MER [90]	Encoder channels on 44 motors damaged	Faulty test cable; no STM, QA, or verif. following first test	Use written procs, STM, QA monitoring; functionally test ea.unit
	MPL [92]	Solar panel damaged by MGA impact during test	Not in flight config, no battery emergency power-off capability	Test in flight config, allow emergency power-down, hold TRR
	Aquarius [35]	H/W damage during acoustics test	Excessive test levels due to lack of procedural discipline	TC must follow defined procedures
	MPL [93]	Mission loss, FSW and thermal deficiencies	FSW not tested in flight config, inaccurate thermal model	"Test like you fly" should reflect mission profile; validate simulator models and include adequate margin
	MPL [93]	Mission-critical failure modes not detected during testing	Full leg deployment test not performed after wiring modification	Rerun test following any H/W or S/W modification
	ISS Node 1 [94]	Test replanned "on-the-fly"	Last-minute changes to scope and rqmts, excessive doc. rqmts	Assess/define test rqmts and configs in advance; assign lead test engineer, test lower assys before system-level integration
	ISS MT [61]	Qualification model Linear Drive Unit Functional Test Fixture damaged during testing	Power surge resulted in (suspected) electronics damage, causing anomalous mechanical movement; motor disconnected	Coordinate work (esp. troubleshooting) between teams; use UPS while testing flight H/W, ensure safe backout of proc if necessary
	Genesis [95]	Parachute deploy delays/failure	G-switch installed/wired backwards; no E2E test in flight config; GSE measurement cancelled out error	Condcut E2E test of final flight interfaces, validate GSE prior to test; beware of 1-time failures/anomalies
	Ariane-5 [96]	Inertial reference system shutdown; vehicle destroyed @ L+40 s	Reused Ariane-4 S/W incompatible w/ Ariane-5; insufficient testing	Conduct systems-level verif. of FSW and E2E simulation
	WIRE [24]	Premature instr. cover deployment; loss of mission	Insufficient fidelity of pyro box test; anomaly misdiagnosed	Conduct testing and sims in flight config; test like you fly
	STS-126 [97]	2 comm processes not configured for orbit	S/W incompatibility undetected; test anomaly ignored	Document & train for best practices; conduct E2E verif.; investigate all anomalies, even if unrelated
	Surveyor [98]	Potential inadvertent motor ignition	IVT involved commanding motor control w/ tank pressurized	Ensure at least 2 inhibits protect against irreversible actions
	Milstar [6]	Incorrect orbit; attitude errors	Misplaced decimal in FSW; test errors unnoticed/misinterpreted	Heed & diagnose data anomalies during testing
Environmental Testing	HESSI [27]	H/W damage during sine-burst test	Excessive test levels due to facility not being precertified; no independent cut-off switch; operator unfamiliar w/ system	Precertify vibe cell at req'd test levels w/ test load; incorporate independent force cutoff switch; operator training
	Aquarius [35]	H/W damage during acoustics test	Excessive test levels due to obsolete controller S/W	Maintain equipment, vfy proper controller config prior to test
	Mars Observer [99]	Payload Data System exposed to excess low temp in t'vac	Chamber temp. controller failure, fail-safe not config'd properly	Ensure chamber sensors and fail-safes meet rqmts
	Multiple [100]	Electrical component failure during vibration test	Loose FOD not detected during bench testing	Conduct vibe test w/ electronics boxes powered, at a minimum those powered on for launch
	Juno [28]	HGA damaged during shaker self-check	Self-check input load exceeded level of test (67g v. 33g)	Prior to test, vfy self-check signal set lower than any test level
	TIRS (MER) [101]	Kapton/MLI damage during t'vac test	Burn-thru from heaters on unit under test used to accelerate return of chamber to ambient temp	Current-limit all pwr supplies; install test thermocouple near heater; care in use of unit heaters to accelerate warm-up
	LADEE [26]	Propulsion structure mass model damaged, potential for flight structure damage	Shaker overexcitation prior to start of vibe test; similar failure to earlier HESSI mishap (L903); TC unfamiliar w/ equipment	Verify shaker precertified and operating properly, review relevant lessons before I&T; proper training and test discipline
Launch Site Operations	Viking [02]	Low receiver thresholds during prelaunch test	(Suspected) Launch pad environment effected test results	Consider vehicle/pad environment factors that can affect results
	Multiple, incl. STS-107 [6]	Information to support investigations of mission mishaps, accidents, and anomalies is often limited	Incomplete or unclear photographic record of as-flown H/W configuration	Take high-quality and complete closeout photos to support troubleshooting or investigation; develop a photo plan
	R-16 [103]	Vehicle explosion on pad; 120+ killed	Lax safety precautions, schedule pressure, poor CM/document'n	Limit access to hazardous ops to only participants, practice safety vigilance and procedural discipline
	TVSat-1 [6]	Solar array deploymentbt failure on-orbit, 50% power loss	Remove-before-flight hold-down clips left on during closeouts	Perform closeout procedure and take photos, maintain remove-before-flight log; procedural discipline
Other/Miscellaneous	SAGE-III [104]	Contamination control rqmts not met in foreign facilities	Rqmts misunderstood by foreign partner, U.S. provided required support and equipment	Plan for self-sufficiency, contingencies for international ops
	ISS 2A [105]	H/W configured for 1 task was deconfigured by another team; schedule delayed	Parallel tasks on same H/W due to compressed schedules; config.rqmts for each not communicated; lack of task coordination	Practice config control, communicate among parallel tasks (e.g., status tags); coordinate concurrent ops
	Apollo-1 [30]	Loss of capsule and crew to fire on pad during plugs-out test	Test considered routine and safe, conducted w/ hazardous cabin conditions; poor S/C workmanship; "failure of imagination"	Tasks that seem routine and safe still demand due diligence and task discipline
	Magellen [22]	Fire and damage to flight H/W and GSE	Battery shorted during blind mate; standard policy did not allow moving MLI to facilitate access to connector	Allow policy flexibility when technical rqmts dictate
	Skylab [106]	Micrometeorite shield lost during ascent, debris inhibited solar array deployment	Design deficiency not recognized; unsound engineering judgement regarding shield system and ascent venting	Attention to rigor and detail should not overemphasize formulism and documentation at the expense of intuitive thought
	IUS (Magellan) [6]	Engine nozzle damaged during I&T, replacement req'd	Tech tripped on lab coat and impacted nozzle	Practice safe walking, wear right-sized garments
	HST [6]	LGA damaged during rotation for inspection of secondary mirror	Inspection not performed during mirror integration a decade earlier; improper handling of flight H/W during rotation	Complete tasks before higher level of integration; handle flight hardware w/ care

Acronyms and Abbreviations
(For I&T Lessons Table)

AC	Alternating Current
Assy	Assembly
ATLAS	Advanced Topographic Laser Altimeter System
AVHRR	Advanced Very High Resolution Radiometer
BAT	Burst Alert Telescope
BOB	Break-Out Box
CAPL	CApillary Pumped Loop
CM	Configuration Management
Comm	Communicate, Communication
Config	Configure, Configuration
Contam	Contamination
DC	Direct Current, Douglas Commercial
Doc	Document, Documentation
DS	Deep Space
E2E	End-to-end (test)
EED	Electro-Explosive Device
EFE	Environmental Control and Life Support System Flight Experiment
EM	Engineering Model
EMI	Electromagnetic Interference
EMOS	Environmental Monitors on Station
EPP	Exploration Payloads Project
ESD	Electrostatic Discharge
Esp	Especially
Ext	External, Exterior
FOD	Foreign Object Debris
FOT	Flight Operations Team
FREESTAR	Fast-Reaction Experiments Enabling Science, Technology, And Research
FSW	Flight Software
g	Gravity
GCP	Glo-Cryo Payload
GEDI	Global Ecosystems Dynamics Investigation
GP-B	Gravity Probe B
GPM	Global Precipitation Measurement
Grd	Ground
GSE	Ground Support Equipment
HESSI	High-Energy Solar Spectroscopic Imager
HGA	High-Gain Antenna
HGAS	High-Gain Antenna System
HST	Hubble Space Telescope
HUT	Hopkins Ultraviolet Telescope
H/W	Hardware
I&T	Integration and Test
ICD	Interface Control Document
IEH	International Extreme-ultraviolet Hitchhiker
Incl	Include, Including
Info	Information
Instr	Instrument
IPA	Isopropyl Alcohol
IRAS	InfraRed Astronomical Satellite
ISS	International Space Station

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IT	Information Technology
IUS	Inertial Upper Stage
IVT	Interface Verification Test
JSC	Johnson Space Center
KICS	Kennedy Integrated Control Schedule
KSC	Kennedy Space Center
LADEE	Lunar Atmosphere Dust Environment Explorer
LC	Launch Complex
LCC	Launch Control Center
LDCM	LandSat Data Continuity Mission
LGA	Low-Gain Antenna
LiOH	Lithium Hydroxide
LPS	Launch Processing System
LRO	Lunar Reconnaissance Orbiter
MCO	Mars Climate Orbiter
MER	Mars Exploration Rover
MGA	Medium-Gain Antenna
Mgmt	Management
Mgr	Manager
MGS	Mars Global Surveyor
MGSE	Mechanical Ground Support Equipment
MLI	MultiLayer Insulation
Mod	Modification
MPL	Mars Polar Lander
MSL	Mars Science Laboratory
MST	Mission Sequence Test
MT	Mobile Transporter
N/A	Not Applicable
Navcam	Navigation Camera
NICER	Neutron star Interior Composition Explorer
NOAA	National Oceanic and Atmospheric Adminstration
OCO	Orbiting Carbon Observatory
ODERACS	Orbital DEbris RAdar Calibration Spheres
Op	Operation, Operational
OPF	Orbiter Processing Facility
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, and Security Regolith Explorer
OT	Overtime
OV	Orbiter Vehicle
PCR	Payload Changeout Room
P/L	Payload
Prep	Prepare, Preparation
Proc	Procedure, Procedural
P/S	Power Supply
Pyro	Pyrotechnic
QA	Quality Assurance
Qual	Qualification
Req'd	Required
RTLS	Return-To-Launch-Site (Abort)
S&A	Safe and Arm
SAD	Solar Array Drive
SAGE	Stratospheric Aerosol and Gas Experiment
SAM	Sample Analysis at Mars

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SAMPEX	Solar Anomalous Magnetospheric Particle Explorer
S/C	Spacecraft
SE	Systems Engineer, Systems Engineering
SEH	Solar Extreme-ultraviolet Hitchhiker
SIRTF	Space Infrared Telescope Facility
SRA	Search and Rescue Antenna
SRM	Solid Rocket Motor
S/S	Subsystem
SSME	Space Shuttle Main Engine
ST	Space Technology
STM	Safe-To-Mate (Procedure)
STS	Space Transportation System
S/W	Software
TAS	Technology, Applications, and Science
TC	Test Conductor
Tech	Technician
Temp	Temperature
TIRS	Transverse Impulse Rocket System
TLS	Tunable Laser Spectrometer
TOC	Turn-Over Cart
TOPEX	TOPography EXperiment for ocean circulation
TRR	Test Readiness Review
T'vac	Thermal-Vacuum (test)
UPS	Uninterruptable Power Supply
USML	United States Microgravity Laboratory
UVSTAR	Ultraviolet Spectrograph Telescope for Astronomical Research
V	Volt, Voltage
Verif	Verification
Vibe	Vibration
W/	With
WIRE	Wide-Field Infrared Explorer
Wrt	With respect to, With regard to
XARM	X-ray Astronomy Recovery Mission