Lessons Learned Entry XX

Lesson Info:

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Subject: **Hypergolic Propellant Related Spills and Fires**

Abstract:

The attached report is a compilation of all credible, unintentional hypergolic fluid related spills, fires, and explosions from the Apollo Program, the Space Shuttle Program, Titan Program, and a few other programs. Spill sites include the following government facilities: KSC, JSC, WSTF, VAFB, CCAFS, EAFB, Little Rock AFB, and McConnell AFB.

The root causes and consequences of the incidents contained in this document vary drastically; however, certain "themes" can be deduced and utilized for future hypergolic propellant handling. Some of those common "themes" are summarized below:

- Improper configuration control and complacency can lead to being falsely comfortable with a system
- Communication breakdown can escalate an incident to a level where injuries occur and/or hardware is damaged
- Improper propulsion system and ground support system designs can destine a system for failure
- Improper training of technicians, engineers, and safety personnel can put lives in danger
- Improper PPE, spill protection, and staging of fire extinguishing equipment can result in unnecessary injuries or hardware damage if an incident occurs
- Improper procedural oversight, development, and adherence to the procedure can be detrimental and quickly lead to an undesirable incident
- Improper local cleanliness or compatibility can result in fires or explosions

The items listed above are only a short list of the issues that should be recognized prior to handling of hypergolic fluids or processing of vehicles containing hypergolic propellants. The summary of incidents in this report is intended to cover many more issues than those listed above that have been found during nearly the entire spectrum of hypergolic propellant and/or vehicle processing.

Description of Driving Event:

Hypergolic rocket propellants have proven to be a highly reliable asset in manned and unmanned space flight; however, their maintenance on the ground has proven to be relatively difficult. Do the operational risks from possibly catastrophic incidents, human errors, or hardware failures outweigh the usefulness of hypergols even though they have been used for the last 50 years of manned and unmanned spaceflight? One would have to say no, since hypergols are so widely used in the space industry currently and are being proposed to be used on many vehicles in the future. Therefore, ground operations on hypergol systems have become increasingly scrutinized for possible unknowns and rightfully so. This document is not an example of why we should not be using hypergolic propellants on spacecraft and launch vehicles, but rather what we can and should do to mitigate possible unforeseen ground operation and/or design problems.

Some type of human error can be traced to nearly every incident discussed in this document as a root cause, whether it be an error in the design phase or an error prior to or during operational use of hardware containing hypergols. Humans are most definitely not perfect and even when the most knowledgeable personnel are intimately involved in the design phase (vehicle or GSE) or during an operation, mistakes can be made and items can be overlooked. One can deduce, however, that most incidents happen during some sort of operation, i.e. when the system is not static. Hypergols tend to be very stable in a static configuration (as long as the compatibility characteristics have been well addressed).

Lesson(s) Learned:

Some common lessons learned deduced from the various root causes are shown in the following list. If these items were properly addressed prior to the incidents, prevention may have been possible (in hindsight) or the impact of the incident could have been reduced.

- Improper configuration control and complacency can lead to being falsely comfortable with a system.
  - Vent systems are often neglected and treated as non-hazardous even though they can capture and contain hypergolic liquids (especially in low points).
  - Aging support hardware should be routinely inspected to reduce the risk of a failure during critical operations.
- Communication breakdown can escalate an incident to a level where injuries occur or hardware is damaged.
- Improper training of technicians, engineers, and safety personnel can put lives in danger.
  - Inadequate knowledge of electrostatic discharge while working fuel operations can lead to a fire or explosion.
  - Knowledge of transducer offsets is very important for system oversight.
  - Unknown incompatibilities (from lack of training or research) with propellants can cause surprising failures.
  - **If an incident does occur, the system should immediately be put into a stable configuration; following this, the procedure should be stopped to assess the problem and its possible ramifications.**
  - A heightened amount of situational awareness of technicians and engineers working operations can reduce the risk of an incident and decrease the possibility of injuries or damage if an incident does occur.

- Improper PPE, spill protection, and staging of fire extinguishing equipment can result in unnecessary injuries or hardware damage if an incident occurs.
- Improper procedural oversight, development, and adherence to the procedure can be detrimental and quickly lead to an incident.
    - Improper emergency procedures can increase the risk of injuries or hardware damage.
- Improper local cleanliness (for example: iron oxide or rust) can result in fires or explosions.
- A thorough hypergol system evacuation should be completed (wherever a vacuum is tolerable by the system) prior to the removal or disconnection of any hypergolic propellant fittings.
    - A pulse purge has proven to be inadequate for the removal of residual propellants.

Table 49-1 summarizes the fuel and oxidizer spills and fires presented in the report. Note that if the numbers in the table are totaled, they do not sum to the total amount of fuel and/or oxidizer spills summarized in this document. This is a result of some incidents having injuries and a fire, for example. A larger, more extensive list of the data shown in Table 49-1 can be seen in Appendix C: Detailed Assessment of Incidents (Refer to attached document).

Table 49-1: Hypergol Spill and Fire Summary

Oxidizer Incidents	**Fuel Incidents**
21 Total (Liquid and Vapor)	25 Total
7 Vapor Only	9 Led to a Fire
2 Led to a Fire	2 Led to an Explosion
3 Led to an Explosion	7 Led to Injuries (Minor to Death)
7 Led to Injuries (Minor to Death)	13 Led to Hardware Damage
11 Led to Hardware Damage	

10 Oxidizer/Fuel No Hardware Damage or Injuries

Root Causes:

7 Procedure Adherence/Control (engineer or technician did not follow procedure or protocols were ignored)
9 Improper Personnel Training (engineers or technicians were untrained or too inexperienced)
14 Human Error (technician and/or engineers making a real-time error)
19 Improper GSE/Vehicle Design (improper materials, unknown low points, incompatibilities etc.)
11 Improper Configuration Management (system configuration and upkeep errors that led to an incident)

Incident Occurred During:

17 During Commodity Movement
15 During an R&R Procedure
40 During a Nominal Hypergol Operation
11 During Opened Hyper System
3 In a Static Hyper System

Some lessons learned from the Apollo program related to hypergol loading equipment according to J. Tribe include:

- On-board vehicle instrumentation was limited to that required for flight evaluation; this dictated use of GSE instrumentation to monitor critical vehicle parameters during ground operations – a less than desirable configuration
- Operational visibility from the control room was minimal and there was extensive reliance on technicians (usually in SCAPE) to read gages correctly and position multiple manual valves.
    - This servicing and test disconnects on the command and service module (CSM) were challenging to manually position correctly
    - This inevitably led to a mis-configuration on Apollo 16 that resulted in a CM RCS tank ruptured bladder, roll back of the Saturn V stack and destack of the CSM and lunar module, lack of flight system instrumentation was a direct contributor to this event.
- As design matured, configuration changes increased complexity for ground operations greatly extended servicing timelines.
    - SM RCS changes from individual block 1 "quads" to block 2 to the propellant storage module installation are an example (8 tanks to 16 tanks to 25 tanks)
    - Each "quad" was a stand-alone system until the propellant storage module interconnected them.
- Multiple individual tanks on CSM required multiple access panels and disconnects
    - This multiplicity resulted in a complex ground servicing operation whit an extensive fluid distribution system, valve boxes, bleed units, ullage cylinders, purge panels and the need for weather-protected 360-degree access.
    - Servicing operations required a variety of loading methods – mostly sequential and time-consuming:
        - SPS fill used on-board gauging/totalizer to determine flight loads
        - RCS fill used a combination of evacuated tanks with load by weight and fill to overflow, removal of a specified ullage and manual PV determination to confirm flight loads.
        - Flight loads were accurate but the methods were time-consuming.
    - During the life of the program significant propellant spills (especially during Apollo 7 preps) drove increased need for spill collection and containment.
        - The installation of improved scuppers at vehicle interfaces and facility precautions were complex and time-consuming.
    - Different fuels for different flight systems (A-50 and MMH) double the number of servicing units and fluid distribution systems
    - The Space Shuttle Program corrected many of these deficiencies with:
        - Remotely controlled operations from the LLC
        - Extensive use of software loading programs
        - Remotely operated disconnects and leak checks
        - Gang servicing valve disconnects for OMS and ARCS

Appendix B: Summary of Incidents (Found In Attached Document)

The proceeding table is a summary of all the credible spills and fires included in this report along with their respective dates, locations, a short description, and primary lessons learned.

Incident	Date	Location	Description	Primary Lesson(s) Learned
Apollo 7 SPS N_2O_4 Spill	9/1968	CCAFS LC-34	Inadequate purges resulted in the collection of liquid N_2O_4 in a tubing low point, technician was removing a panel when about 1-2 gallons of liquid N_2O_4 spilled onto the vehicle and surrounding structure, some vehicle damage, no reported injuries	Spill protection is necessary in a hypergolic propellant transfer operation, do not attempt to dilute liquid N_2O_4 with water, and tubing low points should be eliminated from GSE in the design phase.
Apollo-Soyuz Astronaut N2O4 Vapor Exposure	7/24/1975	Apollo-Soyuz Test Project Apollo Command Module Reentry	During reentry the astronauts performed a few tasks out of sequence leading to injection of N_2O_4 (NO_2) vapors into the crew module.	Performing tasks out of planned sequence can lead to unexpected results.
OV-101 APU 1 Cavity Seal N_2H_4 Spill	6/28/1977	During second captive-active test flight of Enterprise	Approximately 5 gallons of N_2H_4 spilled onto the side of the ship and in through the vent doors when a shaft seal failed, some flight hardware damage	Kapton and N_2H_4 are not compatible, some components of the APU system were redesigned.
Titan II Silo Large Scale N_2O_4 Spill	8/24/1978	McConnell AFB Silo 533-7	The worst known N_2O_4 spill in U.S. history where approximately 13,450 gallons of liquid N_2O_4 spilled into a missile silo killing 2 and injuring 25, caused by o-ring seal lodging in AHC poppet, filter was missing from system to catch the o-ring	Proper configuration control of GSE components, in this case the filter, is highly important in the handling of toxic chemicals especially hypergols
Titan II Explosion Following A-50 Spill	9/18/1980	Little Rock AFB Silo 374-7	A technician dropped a large socket 70 feet, it bounced into the Titan II rocket piercing the A-50 propellant tank, spilled about 11,140 gallons of fuel which later ignited causing the N_2O_4 propellant tank to rupture causing a large explosion killing one and injuring 21, the silo and rocket were damaged beyond repair.	All workers should wear a belt with lanyards to attach tools, care should be taken to ensure the exclusive use of explosion proof hardware in a facility that contains hypergolic propellants, sending personnel into an unknown situation is extremely dangerous.

Incident	Date	Location	Description	Primary Lesson(s) Learned
N_2H_4 Spill Following APU Hotfire	Prior to STS-1	KSC OPF 1	N_2H_4 dissolved brass in a sight glass spilling a couple gallons of N_2H_4, no reports of injuries or damage	Unknown incompatibilities can lead to surprising spills during an operation or while in a static configuration
KSC Incorrect Flight Cap N_2O_4 Vapor Release	July 1981	KSC OPF 1	A ¼-inch AHC cap was placed onto a ½-inch AHC causing the poppet to depress and the release N_2O_4 (NO_2) vapors, minor injuries, no hardware damage	An incorrect tag was attached to the flight cap and the number etched on the cap was sanded off in attempt to remove corrosion
MMH Exposure Following Flexhose Removal at Pad Farm	7/14/1981	KSC Pad 39A Fuel Farm	A technician removed a mislabeled flexhose resulting in a MMH spill, minor injuries, no hardware damage	Flexhose was not labeled as hazardous and procedure was not properly scrutinized
STS-2 OV-102 Right Pod MMH Fire	Fall 1981	KSC OPF 1	Small amount of MMH dripped onto gold MLI blanket causing ignition, no injuries, minor flight hardware damage	Ignition properties of MMH, incompatibility of MMH and Gold
STS-2 OV-102 N_2O_4 Spill	9/22/1981	KSC Pad 39A 207-Foot Level	Iron nitrates caused a QD to hang open, spilling approximately 15 to 20 gallons of N_2O_4, no injuries, notable flight hardware damage	Do not use QDs as shut off valves, inadequate spill protection
Pad 39A Fuel Farm MMH Spill and Fire Following Pneumatic Valve R&R	6/29/1982	KSC Pad 39A Fuel Farm	Valve removal led to MMH geyser hitting hot metal cable tray and igniting, no injuries, some GSE hardware damage	Removal of GN_2 control pressure allowed normally open valves to open, manual overrides added later
N_2O_4 Vapor Release from Flange Gasket	2/10/1983	KSC Pad 39A Oxidizer Farm	A GSE valve gasket blew out, venting N_2O_4 (NO_2) vapors to atmosphere, there were no injuries or hardware damage	The technicians and engineers responded correctly
FRCS Ferry Plug Removal MMH Spill	4/18/1983	KSC OPF1	Cold outside temperatures caused thruster MMH valves to leak and collect liquid in the chambers, a technician was exposed to liquid (less than ½ cup) when a ferry plug was removed	Keep thruster heaters on during all ferry flight and post-landing operations to prevent valve leakage

Incident	Date	Location	Description	Primary Lesson(s) Learned
STS-9 OV-102 APU 1 and 2 Explosion	12/8/1983	EAFB Runway 170	Stress corrosion cracking was present in the APU injector stem thus causing an N_2H_4 leak and explosion, no injuries, significant flight hardware damage	Injector stem is now chromized and manufacturing stresses are minimized
N2O4 Vapor Release from Loose Fitting	2/17/1984	KSC OPF2	A small amount of N_2O_4 vapor was released from an improperly torque fitting on the GSE oxidizer vent system, no injuries or hardware damage	Inadequate contractor oversight resulted in many incorrectly torque fittings in the vent system
CCAFS Tanker MMH Fire	5/16/1984	CCAFS Fuel Storage Area 1	MMH being drained from tanker low point sump ignited, technicians received minor burns through SCAPE suits, minor GSE hardware damage	Was either result of electrostatic discharge from something nearby or reaction of MMH with local iron oxide (rust)
Liquid Trap in Purge Adapter Flexhose MMH Spill	5/24/1985	KSC OPF1	Approximately 1 cup of MMH spilled from a thruster purge adapter and onto the body flap, minor injuries, minor flight hardware damage	Proper procedure controls could have prevented this
STS-61C OV-102 SRB HPU Loading N_2H_4 Spill	12/8/1985	KSC Pad 39A MLP Surface	During removal of Leer- Romec QD, HC was spun off internal line leaking approximately 3 gallons of N_2H_4, no injuries or damage	QD anti-rotation devices were implemented for use after RTF from Challenger
Inadvertent Dry Well Removal MMH Spill	1/21/1986	KSC Pad 39A Fuel Farm	A technician erroneously removed a temperature transducer dry well from a 3-inch GSE line causing a 12-foot geyser of MMH, spilling 100 gallons, minor injuries, minor GSE damage	Dry well retainers are now used on all hypergolic dry wells
Relief Valve R&R Oxidizer Farm N_2O_4 Vapor Release	7/29/1986	KSC Pad 39A	During a relief valve R&R, a technician's SCAPE suit tore delaying an operation where the N_2O_4 storage tank was open to atmosphere releasing N_2O_4 (NO_2) vapors, minor injuries, no hardware damage	Engineering had request to modify the hardware which was denied until after this incident
OPF2 Trench N_2H_4 Spill and Fire	9/19/1986	KSC OPF2 Trench	N_2H_4 leaked from a GSE check valve fitting that did not have an o-ring, dripped into trench and reacted with the residual debris in the trench, igniting, no injuries or damage	Care needs to be taken when installing components in hypergolic ground support equipment, also, cleanliness should be scrutinized

Incident	Date	Location	Description	Primary Lesson(s) Learned
N_2O_4 and Insulation Adhesive Small Fire	6/23/1988	KSC Pad 39B Oxidizer Farm	During a sampling operation, liquid N_2O_4 spilled onto some GSE line insulation adhesive and ignited, no injuries, minimal hardware damage	An incompatibility exists between N_2O_4 and the adhesive used, adhesive was not given enough time to properly cure
STS-26R OV-103 N_2O_4 Tubing Leak on Vehicle	7/14/1988	KSC Pad 39B	A scratched LRCS N_2O_4 propellant tank ullage vent dynatube leaked vapors into vehicle at a rate of about 0.23 psi/hour, no injuries or hardware damage	The ingenuity of the launch team resulted in only a short delay of the successful launch of Discovery
WSTF Fuel Waste Flash Fire	2/16/1990	WSTF	Following the gravity draining of a fuel aspirator into a treatment tank, the residual vapors ignited, no injuries, minor hardware damage	Care needs to be taken in an environment that contains high concentrations of fuel vapors, they are highly susceptible to ignition
Aspiration of N_2O_4 into MMH Aspirator System	3/26/1990	WSTF TS 401	A MMH aspiration flexhose was mistakenly connected to the N_2O_4 GSE manifold service valve instead of the fuel manifold service valve, evidence of internal ignition, no injuries, minor hardware damage	Improper identification was the direct cause of this incident
HMF Screens Test Drum MMH Spill	12/7/1990	KSC HMF M7-961 East Test Cell	The hard-line hose from a SCAPE suit caught on a GSE manual valve handle and opened it, filling a 55 gallon drum and subsequently spilling MMH out the drum's relief valve, no injuries or damage	It was not wise to design the system in which a manual valve handle protruded beyond the edge of the panel allowing items to become caught on it
STS-42 OV-103 Ferry Plug Removal MMH Spill	2/12/1992	KSC OPF3	Similar to the incident 4/18/1983, less than a cup of MMH spill from thruster when ferry plug was removed, no injuries or hardware damage	Cold temperatures during a SCA stopover resulted in RCS thruster MMH valve to leak since vehicle remained unpowered and the thruster heaters were off
WSTF Incorrect Flight Cap N_2O_4 Exposure	11/4/1992	WSTF OMS Ground Test Article	A ¼-inch AHC cap was placed onto a ½-inch AHC causing the poppet to depress and spill liquid N_2O_4, minor injuries, no hardware damage	Proper training of technicians would have decreased the possibility of this occurrence, similar to event on 7/14/1981

Incident	Date	Location	Description	Primary Lesson(s) Learned
Thermochemical Test Area N_2O_4 Vapor Release	4/21/1994	JSC TTA	Approximately 16 gallons of liquid N_2O_4 vaporized and exited a burner stack as a result of a leaky solenoid valve and inadequately prepared test team, some minor injuries, no hardware damage	The test team failed to notice anomalous system performance and to take appropriate action
Titan IV A K-9 N_2O_4 Spill	8/20/1994	CCAFS SLC-41	N_2O_4 liquid release of approximately 350-400 gallons following thermal expansion causing a line to rupture at a weld seam while static shortly after sunrise	Schedule pressure can result in leaving a system in an undesirable configuration, proper utilization of relief valves or ullage volumes should be mandatory
STS-69 OV-105 Left Pod MMH Fire	12/9/1994	KSC OPF1	Decomposition reaction of MMH in open thruster flexhose caused ignition, no injuries, minimal flight hardware damage	Proper training needs to take place for all parties including the engineers relating to emergency response, hypergol fire identification, and communication
STS-69 OV-105 Right Pod MMH Fire	5/4/1995	KSC OPF1	MMH was present in a manifold that was having a dynatube disconnected, fire ignited possibly from an electrostatic discharge or decomposition reaction, no injuries, some flight hardware damage	A transducer offset was not accounted for thus hiding an increase in the manifold pressure, proper care was not taken with respect to electrostatic discharge and fire extinguishing equipment
ORSU Open Manual Valve N_2O_4 Spill	3/1/1996	WSTF 400-Area N2O4 Storage Area	Liquid N_2O_4 (approximately 90 gallons) poured from the vent stack of the storage tank, no injuries or hardware damage	Improper configuration management (manual valve left slightly open) existed in the 400 area vent system
OPF2 GSE MMH Spill	2/17/1997	KSC OPF2	Approximately a pint of MMH spilled from a line when the cap was removed, injuring three technicians, no hardware damage	An unrecognized low point in the line allowed the MMH liquid to collect
HMF Sample Valve MMH Spill	3/26/1997	KSC HMF M7-1212 West Test Cell	Approximately six ounces of MMH spilled from a sample valve port, MMH collected in flexhose low point, minor injuries, no hardware damage	MMH was not saturated with Helium which aids the draining procedure

Incident	Date	Location	Description	Primary Lesson(s) Learned
VAFB Titan IV K-18 N_2O_4 Spill	7/16/1997	VAFB SLC-4E	Three of four Titan IV SRM TVC FCVs failed during system pressurization spilling about 244 gallons of liquid N_2O_4 onto the vehicle SRM aft skirts and ground, no injuries, minor flight hardware damage	Incompatable cleaning agents caused a seal in the FCV to rapidly expand within the valve when the Bio T-200A cleaning agent reacted with liquid N_2O_4, proper scrutiny of material compatibility was not completed on a newly design component
Pad 39B Slope N_2O_4 Spill	11/6/1997	KSC Pad 39B Slope	An undersized flange gasket and improper mounting brackets enabled a water hammer effect to spill 25-50 gallons of liquid N_2O_4 on the pad B slope, an electrical fire ensued when the liquid N_2O_4 contacted some nearby live cabling, no injuries, minor GSE hardware damage	Improper configuration management by improper drawing specifications, drawings were not updated to require the installation of the proper gaskets as the pad A drawings were, cross-over valve complex was removed and replaced with hard-line tubing
STS-109 OV-102 APU N_2H_4 Spill	8/20/1999	KSC OPF3	Liquid N_2H_4 ran down a flexhose from the high point bleed QD and dripped on the orbiter elevon, no injuries, minimal flight hardware damage	New GSE was designed and installed to prevent this in the future
WSTF Pathfinder Axial Engine Valve Failure	8/7/2000	WSTF TS 401	During a decontamination procedure following an engine hotfire test, an axial engine valve and N_2O_4 tubing failed (exploded) causing extensive damage to surrounding hardware, no injuries	Working steps out of sequence and several days later than required along with performing the procedure with a temporary procedure rather than a permanent procedure were likely contributors to this event
WSTF Pathfinder Small MMH Fire	8/12/2000	WSTF TS 401	Small amount of MMH dripped from a disconnected feedline and ignited, minimal hardware damage and no injuries	This event was likely the result of several issues compounding
WSTF Pressure Transducer Explosion	3/25/2003	WSTF TS 831	A pressure transducer diaphragm failed causing N_2O_4 to leak into a volume filled with silicon oil leading to an explosion and a vapor release of approximately 3 quarts, no injuries, some hardware damage	The pressure transducer manufacturer did not make the user aware that the transducer contained silicon oil

Incident	Date	Location	Description	Primary Lesson(s) Learned
Titan IV N_2O_4 Pump Explosion	8/12/2003	CCAFS LC-40	A clogged filter in the recirculation loop of the pump resulted in an increase in N_2O_4 (NO_2) vapors and a decrease in the lubrication of the stator allowing N_2O_4 to leak into the copper windings and exploding, no injuries, major GSE hardware damage	Improper maintenance of the pumps and possible design flaws led to the explosion
HMF RP01 N_2O_4 Spill	6/5/2004	KSC HMF M7-961 East Test Cell	A flight cap was removed while, unknowingly, the AHC poppet was stuck slightly in the open state leaking roughly 1.4 gallons of N_2O_4, minor injuries and no hardware damage	The most probable causes include improper and/or inadequate bleed procedures, degradation of process and/or system knowledge over time, or nitrate buildup on the flight cap bleed port
WSTF N_2H_4 Spill Following Manual Valve Failure	9/30/2005	WSTF TC 844B	A manual valve bonnet (handle) failed in a IAPU GSE setup spilling approximately 74 gallons of liquid N_2H_4, no injuries, some GSE hardware damage	The valve soft seals failed thus leaking liquid N_2H_4 into an internal area where an aluminum bronze fitting was located, over time the fitting corroded and later failed spilling the N_2H_4
STS-121 FRC3 N_2O_4 Spill	1/9/2006	KSC HMF M7-1212 West Test Cell	Approximately 2.9 gallons of N_2O_4 spilled following removal of AHC MD122 poppet, no injuries, some flight hardware damage	Closer scrutiny of procedures and spill protection could have reduced the likelihood of this spill

Documents Related To Lesson:

- Hypergol Spills and Fires Rev A.pdf

Mission Directorate(s):

- Aeronautics Research
- Exploration Systems
- Space Operations

Additional Info:

- **Project:** Hypergolic Propellant Systems

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