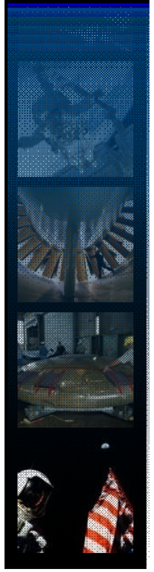
National Aeronautics and Space Administration

Recurring Themes from Human Spaceflight Mishaps During Flight Tests and Early Operations



"Safety First; Safety for All"

8th IAASS Conference

May 18-20, 2016

Team Members:

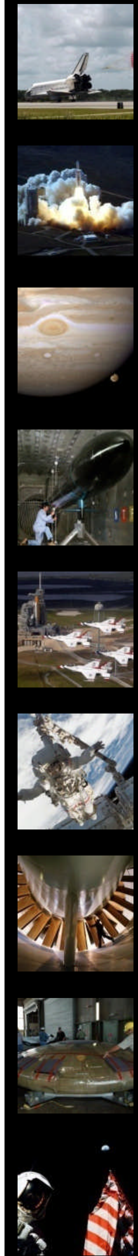
Tim Barth
KSC/NASA Engineering and Safety Center

Donna Blankmann-Alexander
KSC/Abacus Technology Corporation

Barbara Kanki
Ames/Human Factors

Steve Lilley
Glenn/NASA Safety Center

Blake Parker
KSC/ASRC Aerospace

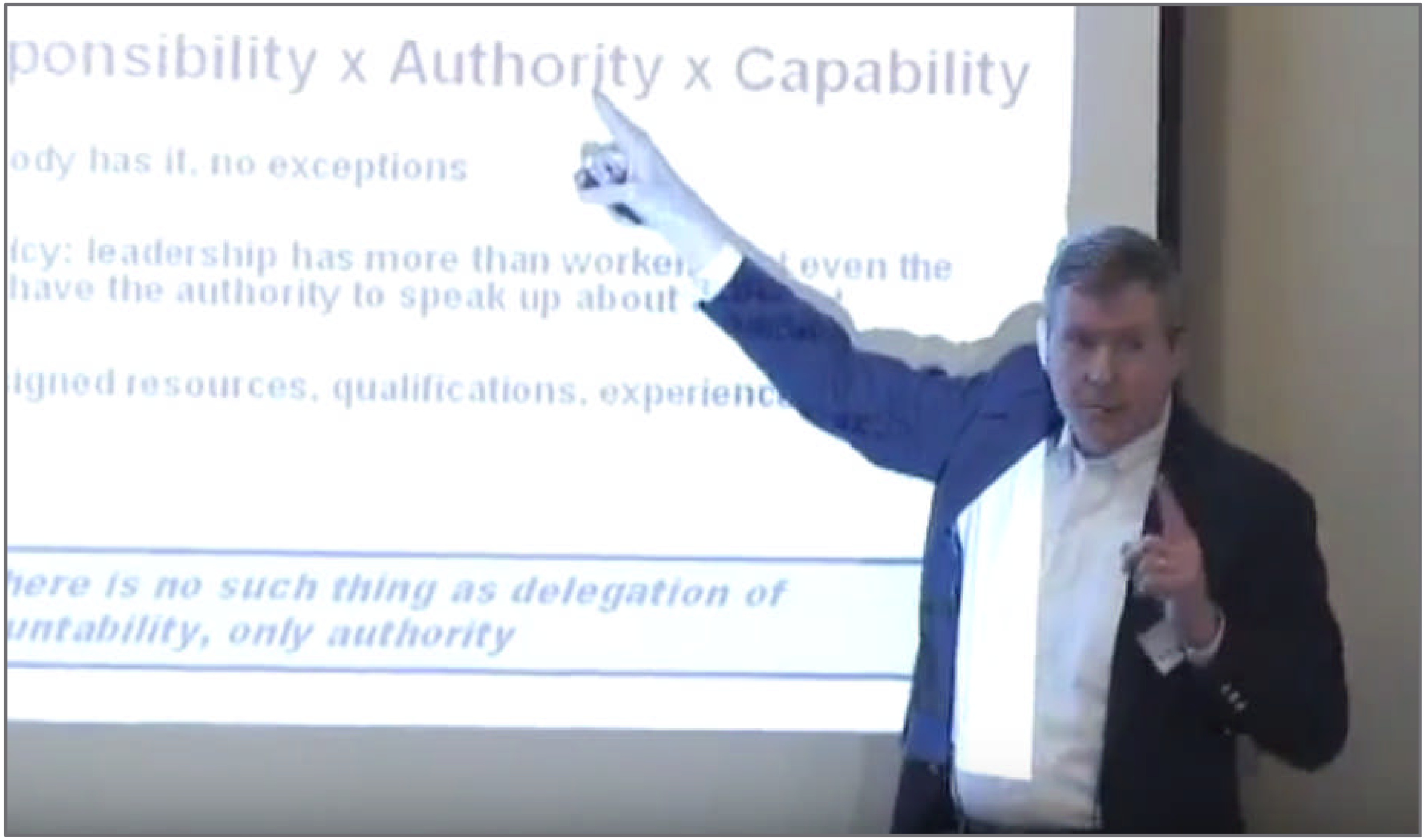


Background

- **Study goal: using selected flight test/early operations mishap investigations, identify recurring factor patterns and provide results to current human spaceflight programs to inform and stimulate their mishap risk management efforts.**
  - **“The NESC gains insight into the technical activities of programs/projects through…systems engineering reviews and independent trend or pattern analyses of program/project technical problems, technical issues, mishaps, and close calls within and across programs/projects.” (NESC Management Plan)**
  - **"The NSC will conduct …special studies…at the request of Centers, programs and projects to provide trends within Centers, programs, projects, or facility activities.“ (NSC Implementation Plan)**

- **“Safety through engineering and technical excellence”**
  - **Everybody is responsible for safety, but is everybody accountable for safety?**
  - **Accountability = Responsibility x Authority x Capability (Bryan O’Connor)**

Safety Accountability vs. Responsibility



https://www.youtube.com/watch?v=t-jlwW7ppvA

Background (continued)

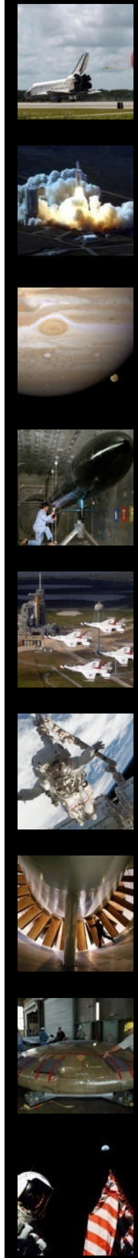
- **Study evolution:**
  - **Shuttle Human Factors Team and Model (1990's - early 2000's)**
  - **Columbia – systemic/recurring factor analysis methodology development (2003-2006)**
  - **Shuttle Ground Processing Mishap Study – post Columbia; focus on safe fly-out for flight and ground crews (2006-2011)**
  - **Shuttle Workforce Message from Bob Crippen (2010)**
  - **"Tough Transitions" STS-1 System Failure Case Study (2011)**
  - **Mars Science Laboratory (MSL) Ground Test and Checkout – recurring factor review of significant close calls (2012)**

MSL Ground Processing Close Calls

- ***Inadvertent crane "up" command after lifting and connecting the MSL Descent Stage Simulator (DSS) to the flight backshell interface***
- ***Shipping GSE not removed before drill percussion test***
- ***Cable installed in reversed position on flight fluid pump***
- ***Flight Drill Bit Assembly (DBA) second alignment not performed***

Shuttle Workforce Message from Bob Crippen

www.youtube.com/watch?v=5vfyZtVPvfs



Excerpt from the STS-1 System Failure Case Study

"Tragedy has marred the start of every human spaceflight program since three American astronauts were lost in the 1967 Apollo-1 fire: a Russian cosmonaut died when his spacecraft, Soyuz 1, plummeted to Earth after a parachute deployment failure; NASA's Space Shuttle Program endured an inauspicious beginning when three technicians were asphyxiated in the aft compartment while preparing STS-1 for launch; and the first commercial spaceflight suffered a setback when three Scaled Composites employees perished while performing a cold flow nitrous oxide test. In addition, the first orbiting space station, Skylab, was nearly lost during Skylab-1, and a ground crew fatality was narrowly avoided during preparations for the Ares 1-X test flight in the Parachute Refurbishment Facility at KSC."

National Aeronautics and Space Administration

SYSTEM FAILURE CASE STUDIES

OCTOBER 2011 VOLUME 5 ISSUE 9

Tough Transitions

March 1981: Twelve years had passed since astronauts first landed on the moon, six years had passed since the legendary Apollo program had come to a close, and a new chapter in human spaceflight was about to begin. Space Shuttle Columbia, the first reusable launch system and orbital spacecraft, would soon embark upon its maiden voyage. The Space Shuttle had been in development since the early 1970's, and its initial test flight, STS-1, was over two years behind schedule. As ground crews worked diligently to prepare for the launch, a group of technicians collapsed inside Columbia's nitrogen-filled aft compartment after a countdown demonstration test on March 19. STS-1 Pilot Bob Crippen recalled that day: "About a month before the first flight, John (Young) and I were at the Kennedy Space Center doing a Terminal Countdown Demonstration Test, which is pretty much a dry run of what actually goes on when you go launch a Shuttle. The test went great. John and I climbed out of the cockpit, went back to the crew quarters at the O&C Building, and we were patting each other on the back and said 'Hey, we're getting pretty close to flight.' That was when we got the bad news. There had been an accident at the Pad." Nitrogen exposure would claim three of the technicians' lives.

Figure 1: Space Shuttle Columbia prior to the STS-1 launch.

BACKGROUND

Space Shuttle Program

NASA had been developing early designs for the space shuttle years before Apollo's first lunar landing in 1969. When President Richard Nixon authorized the development of reusable space exploration vehicles three years later, those designs became a springboard from which NASA launched the project known officially as the Space Transportation System (STS) and unofficially as the Space Shuttle Program. The Space Shuttle grew into a significantly more complex system than earlier human spaceflight programs. The vehicle's intricate launch and reentry configurations challenged flight crew safety considerations, and the decision to fly astronauts on the first (or any) launch rested upon successful test and quality control processes.

In June 1974, Rockwell International (now owned by The Boeing Company) began work on the first orbiter, which NASA named Enterprise in response to a massive write-in campaign by *Star Trek* fans. Enterprise never left the atmosphere, but flew approach and landing tests to help verify the reliability and redundancy of the Space Shuttle's design.

STS-1 Mission Objectives

The first operational orbiter, Columbia, arrived at Kennedy Space Center (KSC) atop a modified 747 in March 1979. On STS-1, its first mission, Columbia would carry a Development Flight Instrumentation package as its only payload. This package contained sensors and measuring devices that would record orbiter performance and log stresses encountered during each stage of the flight profile. The flight's primary mission objectives were to safely ascend into orbit, check all systems, and return to Earth landing as an unpowered glider.

Three Technicians Die Before Space Shuttle Columbia's Inaugural Launch

Proximate Cause:

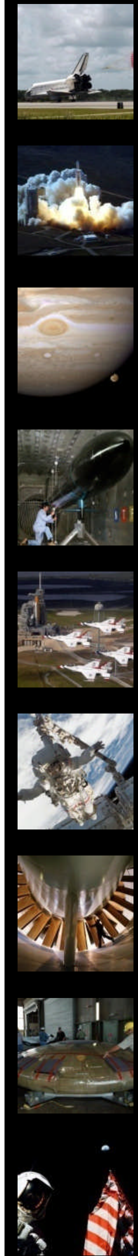
- Oxygen-deficient environment in aft compartment renders workers unconscious and hampers rescue efforts.

Underlying Issues:

- Unclear and Incomplete Procedures
- Communications Breakdown
- Inadequate Controls and Recovery Systems
- Competing Operations Philosophies
- Failure to address recurring causes of earlier mishaps

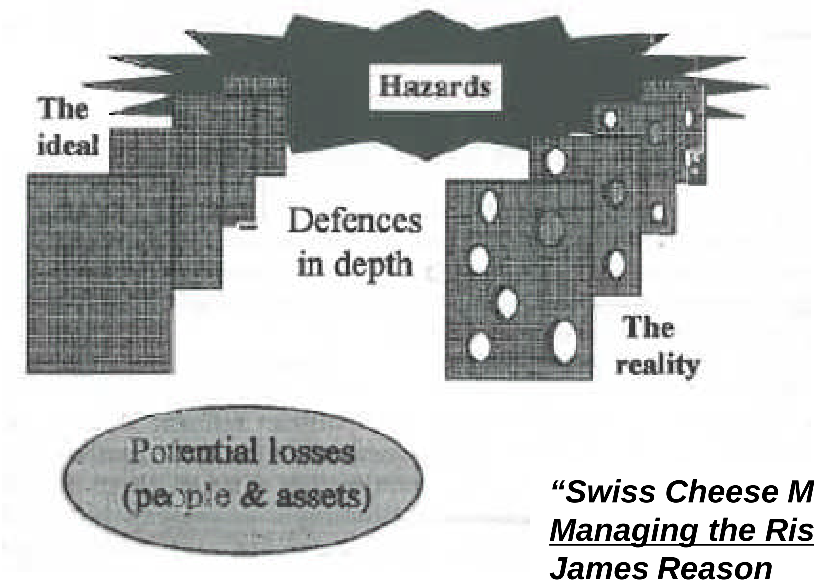
"No one wants to learn by mistakes, but we cannot learn enough from successes to go beyond the state of the art."
Henry Petrosky, <u>To Engineer is Human</u>

http://nsc.nasa.gov/SFCS/



Major Insights from Shuttle and MSL Mishap Risk Reduction Efforts

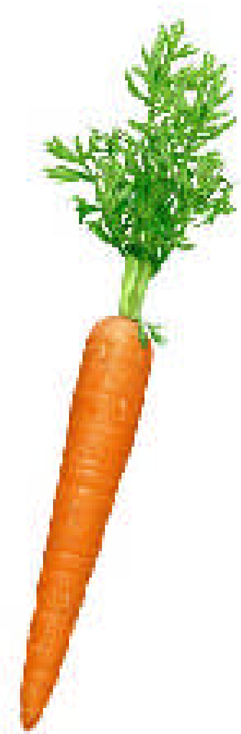
- **Need an appropriate systems model as the basis for the analysis**



"Swiss Cheese Model of Organizational Defenses"
<u>Managing the Risks of Organizational Accidents</u>, James Reason

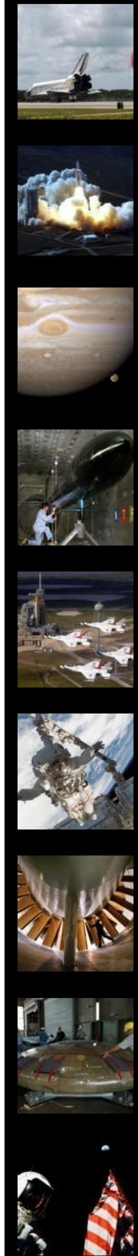
- **Organizational system-level issues recur because they are hard to fix**
  - **No silver bullets; requires sustained, data-driven effort**
- **Need to evaluate all contributing factors and causes**
  - **Because a contributing factor can be a cause in a different situation or on another day, and vice-versa**

Carrots and Crabgrass
(Different Types of Roots)



"I would hasten to add there isn't a root cause. It's a bad term. There are many causes and contributing factors, and to say that there's just one, I would doubt you could ever show an event that there was just one cause. There might be one principal cause, but there are many that, you know, contribute to in sum total end up with a bad event. And you have to look at the myriad of things that contribute to a bad event."

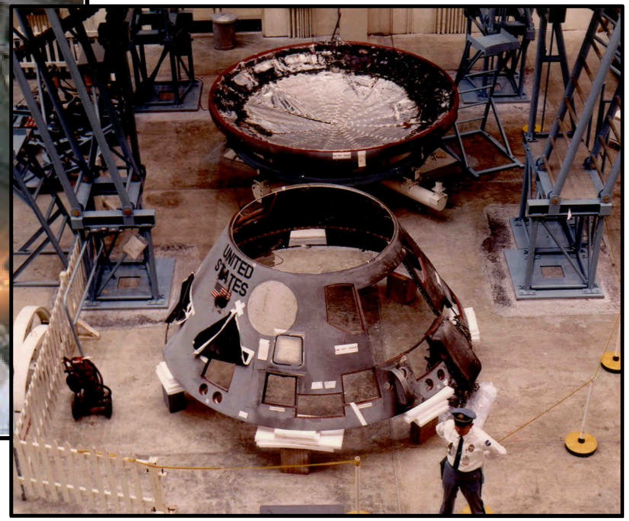
Dr. James Bagian during an 8/9/10 NPR panel discussion on "What Can be Done to Avoid Man-Made Disasters"



Human Spaceflight (HSF)-1 Mishaps

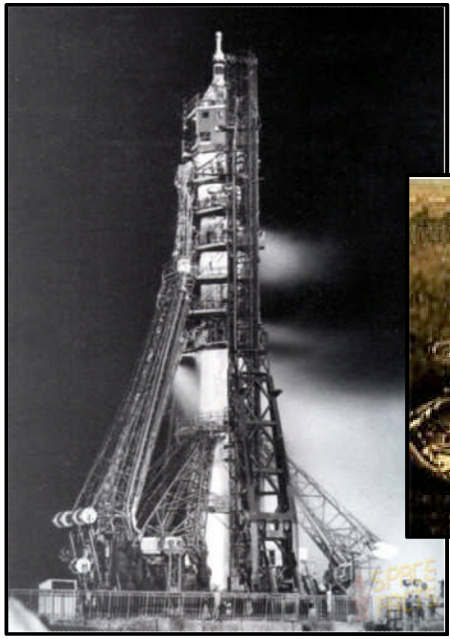
Apollo-1 Crew Module Fire at Launch Complex 34

January 27, 1967
Loss of Flight Crew (3)



Soyuz-1 Main and Reserve Parachute Failures During Reentry

April 24, 1967
Loss of Flight Crew (1)



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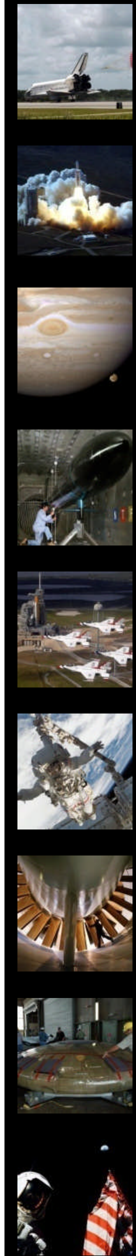


HSF-1 Mishaps (continued)

Skylab-1 Loss of Meteoroid Shield During Launch Ascent

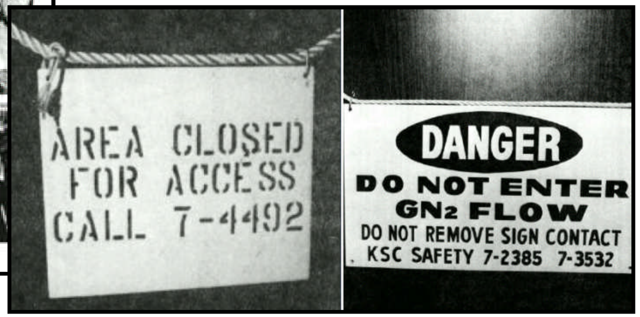
May 14, 1973

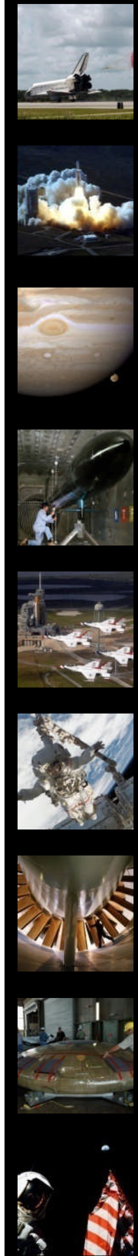
Rescue Mission Needed to Save the Orbital Workshop

STS-1 Oxygen Deficiency in Aft Compartment at Launch Complex 39A

March 19, 1981

Loss of Ground Crew (3)





HSF-1 Mishaps (continued)

Scaled Composites Ground Explosion During Cold Flow N2O Test

July 26, 2007

Loss of Ground Crew (3) and Ground Crew Injuries (3)

SpaceShipTwo Test Flight

October 31, 2014

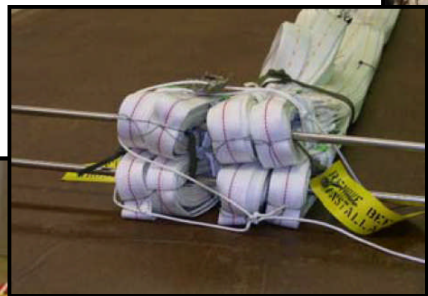
Loss of Flight Crew (1)

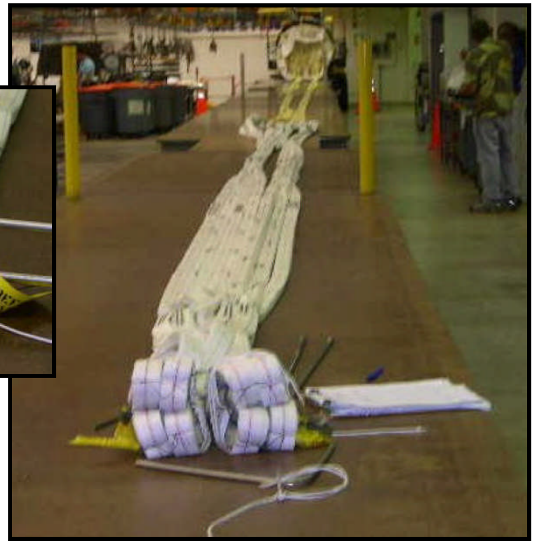
and Flight Crew Injury (*1)*

Ares-1X Steel Rod Mishap During Static Strip Test at KSC Parachute Refurbishment Facility

September 5, 2007

Ground Crew Injury (1)





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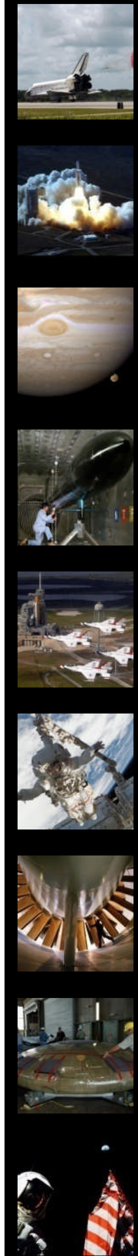
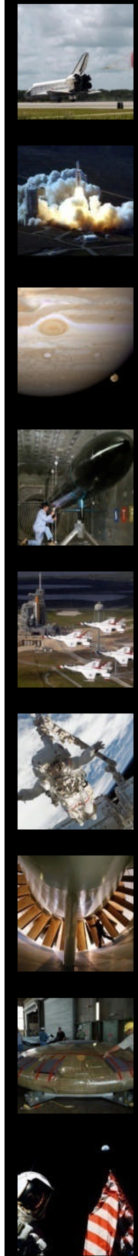


Study Inputs and References

- **Detailed (micro) analysis of 6 HSF-1 mishaps**
  - **142 factors/causes in 6 HSF-1 mishaps where mishap investigation reports were available**
- **High-level (macro) analysis of Aerospace Safety Advisory Panel (ASAP) recommendations**
  - **513 recommendations from 1972-2012**
- **Historical independent assessment reports**
  - **Early Apollo Operations: Manned Space Programs Accident/Incident Summaries (1970), Cranston Research, Inc.**
  - **Early Shuttle Operations: Space Shuttle Productivity and Error Prevention (1981), Anacapa Sciences**
- **Other special studies**
  - **Readiness for First Crewed Flight (2011), NESC**
  - **Technical Risk Identification at Program Inception (2014), Aerospace Corporation**
- **Human Spaceflight SME inputs**



Human Spaceflight SME's

<u>JSC</u>:
- Bo Bejmuk
- Wayne Hale
- Gary Johnson
- Steve Lilley*

<u>MSFC</u>:
- Jim Blair
- Bob Ryan
- Don Hull*

<u>WebEx</u>:
- Mike Blythe
- Nancy Currie
- TK Mattingly

<u>KSC</u>:
- Jay Honeycutt
- Bob Lang
- Charlie Mars
- Gerry Schumann
- Bob Sieck
- Tip Talone
- John Tribe
- Donna Blankmann-Alexander*
- Barbara Kanki*
- Tim Barth*

***Facilitators**

Reminders from the independent review team:
- *Mishaps depend on a specific situation and set of circumstances where the various events, factors, and causes line up and lead to a bad day. In different situations, it is possible that Challenger or Columbia-type tragedies could have occurred on STS-1.*
- *In human spaceflight, every mission should be treated as an inaugural mission.*

Taxonomy of Mishap Causes and Contributing Factors

Control System Factors →

- SL; Senior Leadership (8)
  - SL1; Organizational Culture LTA
  - SL2; Resource ($ & staff) Allocation LTA
  - SL3; High Level Policy-Guidance LTA
  - SL4; High Level Org Perf Msmt LTA
  - SL5; Customer-Stakeholder Relat Mgmt LTA
  - SL6; Supplier-Subcont-Reg Relat Mgmt LTA
  - SL7; Internal Relationship Mgmt LTA
  - SL8; Strategic-Succession Planning LTA
- ES; Enabling Systems (8)
  - ES1; Adminstrative Controls LTA
  - ES2; Budget Controls LTA
  - ES3; Schedule Controls LTA
  - ES4; Tech Ctrls-Proc Chng Ctrls-Risk Mgmt LTA
  - ES5; Human Resource Systems LTA
  - ES6; Procuremt-Logistics-Matl Ctrl Systems LTA
  - ES7; Int Cont Imp & Org Learning Systems LTA
  - ES8; Cust-Stakeholder Feedback Systems LTA
- DS; Design & Development Systems (7)
  - DS1; Support Equip-Tool Des & Dev LTA
  - DS2; System-Part Des & Dev LTA
  - DS3; Task Des & Dev LTA
  - DS4; Wkspace-Work Env Des & Dev LTA
  - DS5; Procedure Des & Dev LTA
  - DS6; Training Course Des & Dev LTA
  - DS7; Organizational Des & Dev LTA
- TS; Training Systems (5)
  - TS1; System Training LTA
  - TS2; Task Technical Training LTA
  - TS3; Emerg-Contingency Trng LTA
  - TS4; Safety-HF Awarens Trng LTA
  - TS5; Leader-Team Skills Trng LTA

Dual Role Factors →

- SV; Supervision (4)
  - SV1; Supv Task Preparation LTA
  - SV2; Supervision During Task LTA
  - SV3; Poor Supv Example-Excess Risk Taking
  - SV4; Supv-Employee Relationship Mgmt LTA
- QC; Quality Control (5)
  - QC1; Insp-Surv-Audit Reqmts LTA
  - QC2; Insp-Surv-Audit Instructions LTA
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Local Resource Factors →

- SI; Support Information (5)
  - SI1; Written Support Info LTA
  - SI2; Verbal Support Info LTA
  - SI3; Support Equip-Tool Feedback LTA
  - SI4; System-Part Feedback LTA
  - SI5; Worker-Work Env Sensory Signals LTA
- MW; Matl Resources & Work Env (7)
  - MW1; Supt Equip-Tool Reliability-Usability LTA
  - MW2; Supt Equip-Tool Unavail-Uncertified
  - MW3; System-Part Reliability-Usability LTA
  - MW4; System-Part Unavail-Uncertified
  - MW5; Infrequent-Unique Task
  - MW6; Workspace-Facility Work Env LTA
  - MW7; External Work Env LTA
- IN; Individuals (7)
  - IN1; Physical Factors
  - IN2; Cognitive Factors
  - IN3; Emotional Factors
  - IN4; Indiv Exp & Skills LTA
  - IN5; Accepted Indiv Work Practices LTA
  - IN6; Indiv Assertiveness LTA
  - IN7; Values-Attit-Disc LTA, Willful Viol, Disruptive Behavior

Typical Schedule Controls Influence Chain: Taxonomy View

Control System Factors →

- SL; Senior Leadership (8)
  - SL1; Organizational Culture LTA
  - SL2; Resource ($ & staff) Allocation LTA
  - SL3; High Level Policy-Guidance LTA
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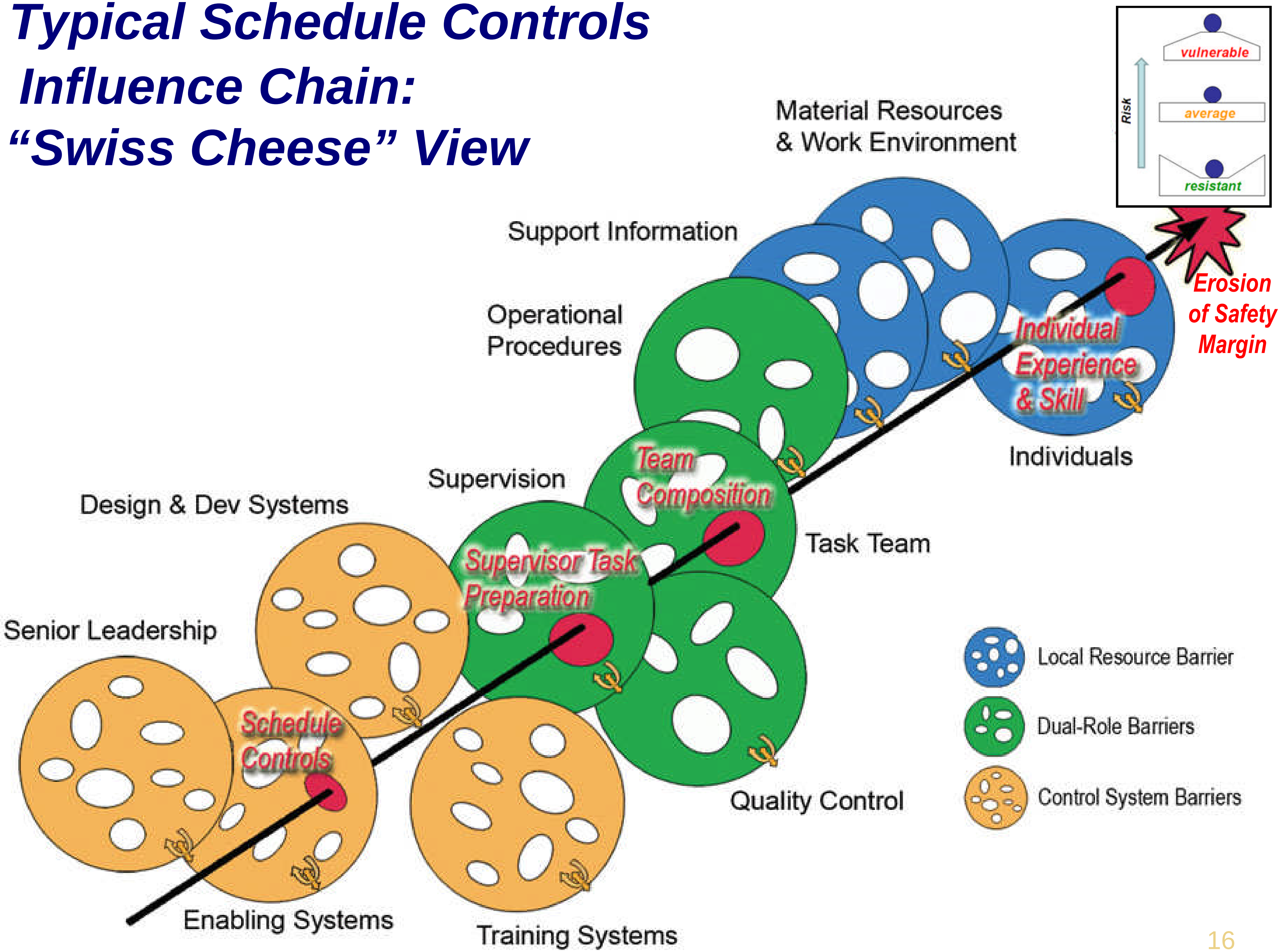
Typical Schedule Controls Influence Chain: "Swiss Cheese" View



STS-1 Orbiter Aft Compartment Mishap: Causes and Factors

Control System Factors →

- SL; Senior Leadership (8)
  - [redacted]
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  - SL3; High Level Policy-Guidance LTA
  - SL4; High Level Org Perf Msmt LTA
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  - [redacted]
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  - IN6; Indiv Assertiveness LTA
  - IN7; Values-Attit-Disc LTA, Willful Viol, Disruptive Behavior

Study Results – Recurring Themes (1 of 5)

- **Insufficient technical controls or risk management practices**
  - **Inadequate safety hazard/risk analysis, FMEA's, technical reviews**

- ***HSF-1 examples:***
  - ***Soyuz-1: The failure mode of the primary parachute's malfunction (jammed in its container), which caused backup chute failure as well, was not accounted for in the design.***
  - ***Ares-1X: Even though the parachute riser lines were approximately 4 times longer than the riser lines on the Shuttle's drag chute, there was no requirement for engineering to perform a first-time GSE DE loads analysis of the test set-up or a readiness review for the initial Area-1X parachute static strip test.***
  - ***Skylab-1: "Despite six years of progressive reviews and certifications, two major hazards eluded discovery until actual flight: aerodynamic load effects on the meteoroid shield and aeroelastic interactions between the shield and its external pressure environment during launch escaped otherwise rigorous design, research and test engineers working under experienced and competent leadership."***

Study Results – Recurring Themes (2 of 5)

- **Flight and ground system design/development issues**
  - **Inadequate testing and verification of system interfaces**
    - **"Test as you fly, fly as you test"**
  - **Inadequate trade-off analyses**

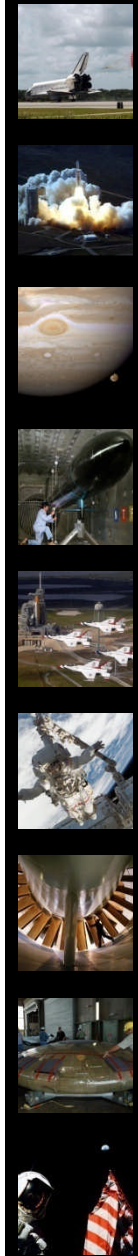
- ***HSF-1 examples:***
  - ***Apollo-1: Teflon wire coating was chosen for superior insulation, chemical inertness and fire resistance. However, the soft, unprotected, thick-wall Teflon was susceptible to creep, cold-flow deformation and abrasion. Teflon coating wore away during installation and training. Exposed electrical wiring cracked and contributed to unending command module technical problems during tests. Five days before the fire, a frustrated Grissom hung a lemon from his yard on the simulator.***

  - ***Soyuz-1: "In retrospect, the Soyuz-1 flight should not have been carried out at that time. The spacecraft was insufficiently tested in space conditions, and it was certainly not ready for the ambitious first mission it was scheduled to accomplish."***
  - ***Scaled Composites: N2O tank design included several materials incompatible with N2O. The tank lacked a burst disc to protect against rapid over-pressurization.***

"We were too gung ho about the schedule and we locked out all of the problems we saw each day in our work...Not one of us stood up and said, 'Dammit, stop!"

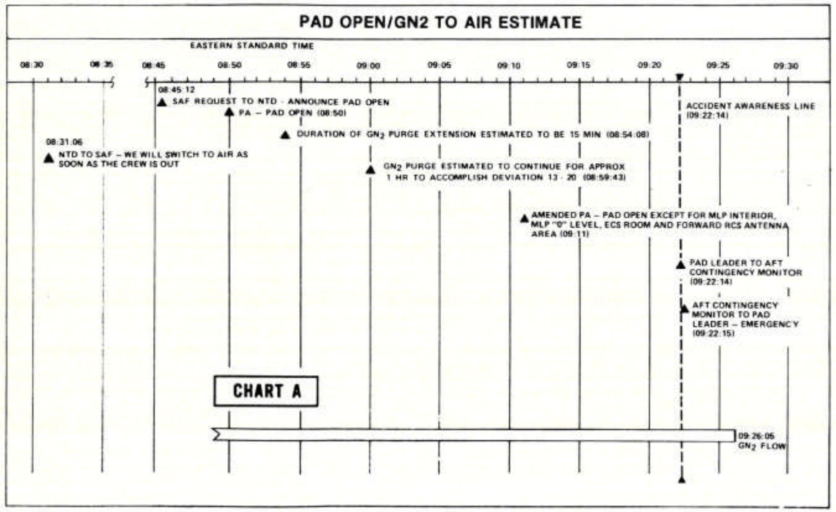
Gene Kranz to his team on the Monday morning following the Apollo-1 fire

Study Results – Recurring Themes (3 of 5)

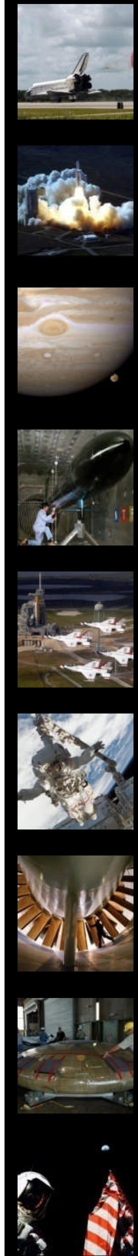


- **Inadequate secondary verification methods**
  - **Inadequate inspection requirements and methods for known materials, safety, and contamination issues**
  - **Secondary verifications, not necessarily more inspections**
    - **System feedback**
    - **Engineering evaluations**

- ***HSF-1 examples:***
  - ***Apollo-1: Given the fragile nature of the Teflon coated wiring, inadequate attention was given to the inspection of the wire bundles to detect abrasion or deformation.***
  - ***Soyuz-1: There was no requirement to inspect the parachute container for contamination.***
  - ***Skylab-1: There was no system feedback (such as a visual cue) to the technicians, quality inspectors, and engineers that a "tight fit" had not been achieved during rigging. Inadequate quality inspections.***
  - ***STS-1: Applicable safety documents did not have sufficient requirements for atmosphere checks or verification of an air purge before aft re-entry. No oxygen deficiency monitoring system in the aft.***



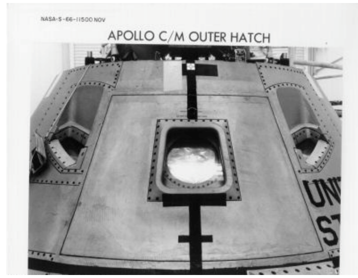
STS-1 mishap report timeline of GN2 purge continuing after pad was re-opened for work.



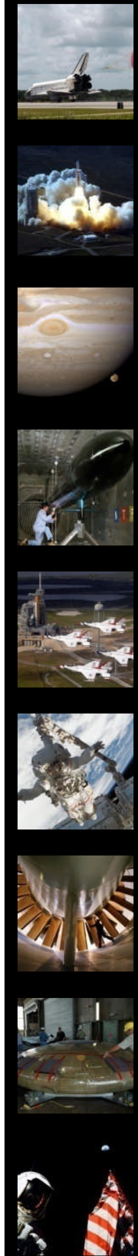
Study Results - Recurring Themes (4 of 5)

- **Ground processing task analysis and design issues**
  - **Inadequate use of task analysis tools and standards during task design and initial procedure development (human factors checklists, process-FMEA's)**
  - **Incomplete or unclear procedures**
  - **Inadequate design of emergency/contingency/troubleshooting/nonstandard tasks**
    - **Require AT LEAST same level of rigor in procedures, training, and system design for contingency/off-nominal ops as planned/nominal ops**

- ***HSF-1 examples:***
  - ***Apollo-1: The astronauts requested the emergency egress simulation be added to the end of the plug-out test because they were 3 weeks from launch and had not yet practiced an emergency escape yet. The plug out test did not require all the hatches be closed and locked.***



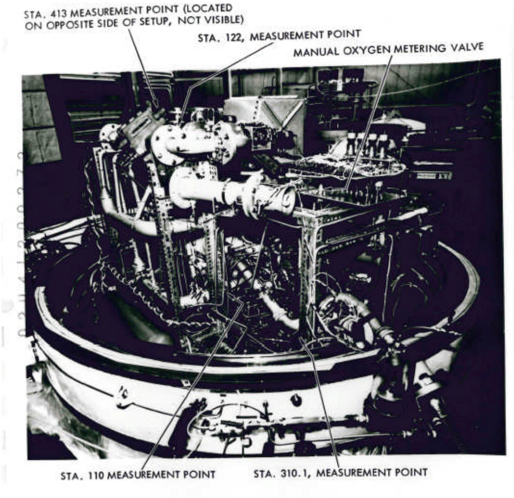
  - ***Skylab-1: Stowing and rigging the large, lightweight micrometeoroid shield to the Orbital Work Shop (OWS) proved extremely difficult, requiring the coordinated action of a large group of technicians. Despite considerable adjustments to the assembly of the various panels, a snug fit between the shield and the OWS wall could not be made.***
  - ***Ares-1X: The initial Ares I-X strip test set-up combined components (forklift, a capstan winch, nylon break ties, and a nylon towline) in an untested combination. The nylon towline used to extract the parachute released a dangerous amount of stored energy upon failure.***



Study Results – Recurring Themes (5 of 5)

- **Inadequate organizational learning**
  - **Failures to learn from previous incidents or issues within the organization (similar mishaps, close-calls, or other precursor events) as well as failures to learn from previous, well-documented incidents outside the organization.**

- ***HSF-1 examples:***
  - ***Apollo-1: There was an electrical fire of an Apollo Command Module ECS test rig in a vacuum chamber in 1966, well before the Apollo-1 fire. The test was conducted under a lower atmospheric pressure (only 5 psi to simulate cabin pressure in space) but a 100% O2 environment. The test incident report was classified.***



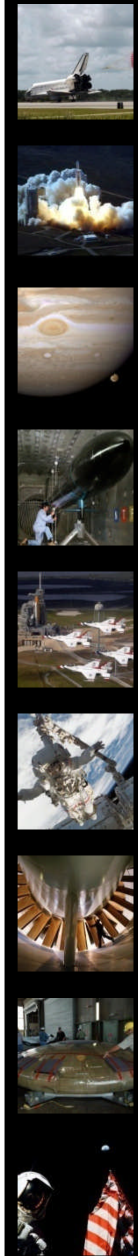
Command Module ECS test rig

  - ***STS-1: Apollo-1 Congressional hearings uncovered a problem at KSC with timely submittals of operational checkout procedures to Safety for review in 1967. STS-1 procedures had the same problem.***

  - ***Scaled Composites: Multiple OSHA citations were issued before the mishap regarding lack of engineering controls to abate well-documented N2O storage and handling hazards.***

"There's no shortage of lessons, but learning is the issue"

T.K. Mattingly



Anomaly Investigation

- **Examples of little-known but significant HSF events**
  - **Apollo Mission A-003 Little Joe II Launch Abort (Gary Johnson)***
  - **Apollo Mission A-201 Command Module Reaction Control System Loss (Gary Johnson)***
  - **Apollo 7 Mission AC electrical bus short (Gary Johnson)**
  - **Apollo 10 Inadvertent LM Abort and Fuel Cell Failure (Gary Johnson)**
  - **Apollo 14 Docking Problem (Gary Johnson)**
  - **Apollo 15 Service Propulsion System Engine and Main Chute Failure (Gary Johnson)**
  - **Apollo 16 SPS Secondary Yaw Gimbal Actuator Oscillations (Gary Johnson)**
  - **Apollo 16 Lunar Rover Anomalies (Gary Johnson)**
  - **Skylab 2 Hard Dock Problem (Gary Johnson)**
  - **Skylab 3 Propellant Leak on Service Module (Gary Johnson)**
  - **Skylab 4 Command Module loss of Pitch/Yaw RCS Control (Gary Johnson)**
  - **Apollo-Soyuz Mission Command Module crew exposure to N2O4 (Gary Johnson)**
  - **STS-1 Negative margins in Orbiter wing during ascent (Bo Bejmuk)**
  - **STS-51F Abort Request Command near miss** (Wayne Hale)**
  - **STS-55 Experiment Valve near miss** (Wayne Hale)**
  - **STS-53 Approach near miss** (Wayne Hale)**
  - **STS-114 Debris strike (Wayne Hale)**
  - **STS-41C Dynamic Standby Computer failure near miss (Wayne Hale blog)**
  - **STS-93 Launch scrub (Wayne Hale blogs)**
  - **STS-93 SSME injector anomaly (Wayne Hale blogs)**

***** A NASA report exists, but is not easily available to need-to-know engineers.***

***** ”near miss” term used where no record of a NASA close call investigation was found in NMIS going back to 1985***

- **Potential enhancements to prevent missed learning opportunities**
  - **Mishap Investigation NPR 8621.1.F; change criteria for “high visibility” close call**
  - **New OCE requirement for “significant” Engineering Anomaly Investigation Report**

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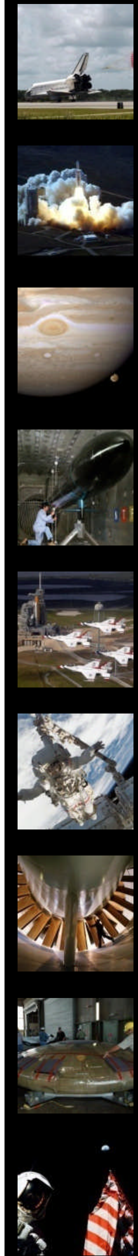
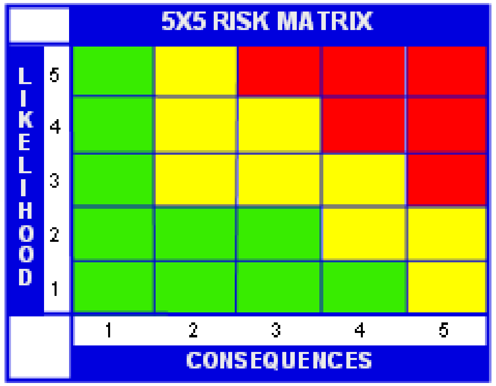
Sample Questions for HSF Programs



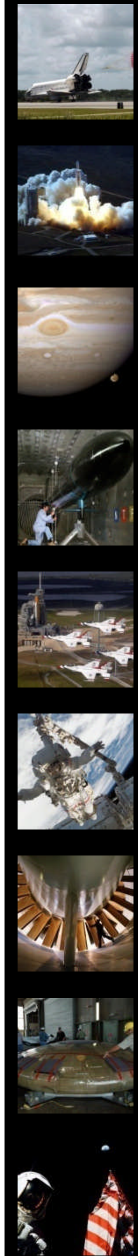
- **Are any of the recurring themes identified in the study applicable?**
  - **If so, have they been recognized? Are they being adequately addressed? What current efforts are addressing them? Should new proactive risk reduction efforts be initiated?**
- **Are there any emerging or unique safety and technical risks associated with test and early operations phases that should be considered?**
- **Are hazards and risks being openly and candidly communicated up and down the management chain?**



- **What can we do to reverse the HSF-1 mishap trend?**

"Risks identified are rarely realized, risks realized were rarely identified."

Aerospace Corporation Study, "Technical Risk Identification at Program Inception," U.S. Space Program Mission Assurance Workshop, May 8, 2014



"Turning Badness Into Goodness"

- **January 27, 1967: Apollo-1 fire**
  - **July 16, 1969: Apollo 11 launch**
- **April 24, 1967: Soyuz-1 parachute failures**
  - **October 25, 1968: Soyuz-2 launch**
- **May 14, 1973: Skylab-1 loss of meteoroid shield during ascent**
  - **May 25, 1973: Skylab-2 launch**
- **March 19, 1981: STS-1 aft compartment mishap**
  - **April 12, 1981: STS-1 launch**
- **September 5, 2007: Ares-1X static strip test mishap**
  - **October 28, 2009: Ares-1X launch**

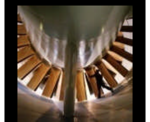
"We must challenge our assumptions, recognize our risks, and address each difficulty directly and openly so that we can operate more safely and more successfully than we did yesterday, or last month, or last year. We must always strive to be better, and to do better."

Chris Scolese, Day of Remembrance Memo, January 29, 2009









Available Resources

- **OSMA/NASA Safety Center**
  http://www.nasa.gov/offices/nsc/home/
  - **System Failure Case Studies**
  - **NSC Cases of Interest**
  - **NASA Mishap Investigation Board Reports**
  - **Risk Management Handbook**
  - **SMA Technical Excellence Program (STEP)**
  - **Quality Audit, Assessment, and Review (QAAR)**
  - **OSMA News and Safety Messages**
  - **IV&V Services**

- **OCE/NASA Engineering and Safety Center**
  http://www.nasa.gov/offices/nesc/home/
  - **Independent Assessment Reports**
  - **Technical Bulletins**
  - **On-line NESC Academy Courses**
  - **APPEL Courses and Case Studies**
  - **NASA Knowledge Map**
  - **Lessons Learned Information System**
  - **DDT&E Best Practices Report**
  - **Readiness for Crewed Flight Report**