MIT January Operational Internship Experience

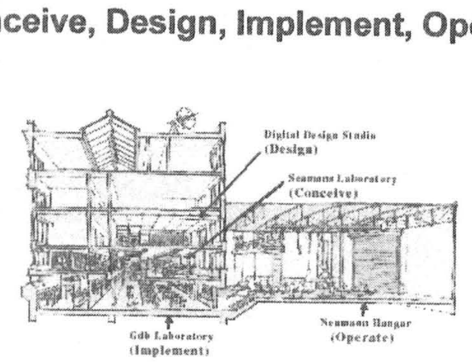
January 29, 2010

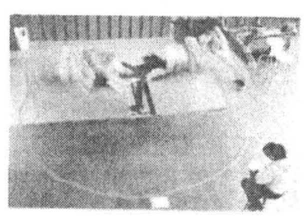
Natasha Bosanac
Charlie De Vivero
Jillian James
Carla Perez-Martinez

Wendy Pino
Andrew Wang
Ezekiel Willett
Kwami Williams

January Operational Internship Experience (JOIE)

- Introduce engineering students to the operational aspects of space flight.
- Explore the relationship between design and operations.
- Core component of MIT's Aeronautics and Astronautics CDIO curriculum (Conceive, Design, Implement, Operate).

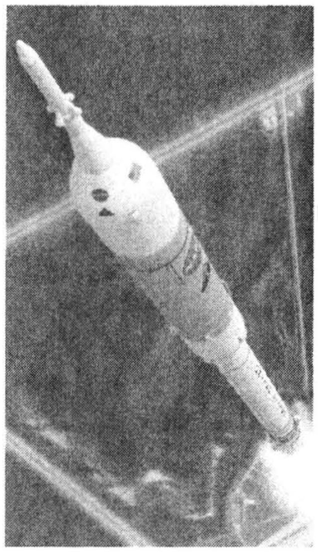


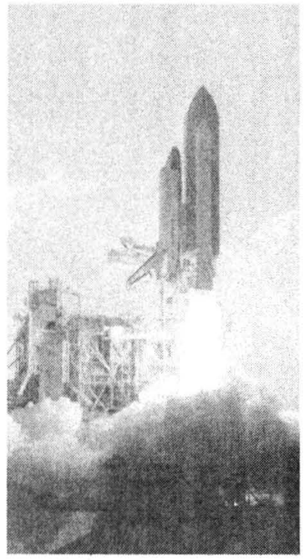


Images taken from http://web.mit.edu/aeroastro/academics/cdio.html

Topics

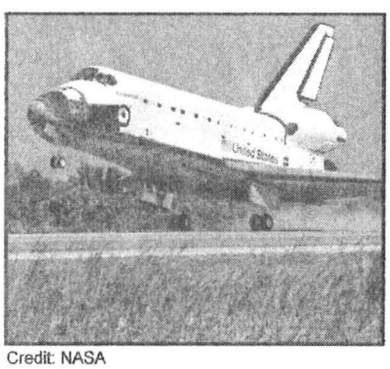
- Landing & Recovery
- Transportation
- Shuttle Processing
- Constellation Processing
- External Tank
- Launch Pad
- Ground Operations
- Hypergolic Propellants
- Environmental
- Logistics
- Six Sigma
- Systems Engineering
- Human Factors



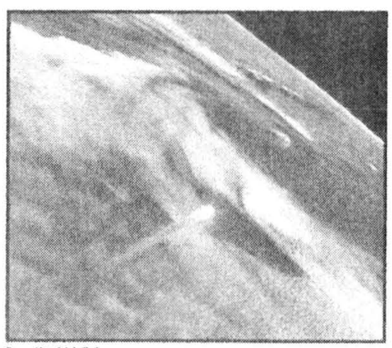


Images taken from http://www.nasa.gov

Landing & Recovery



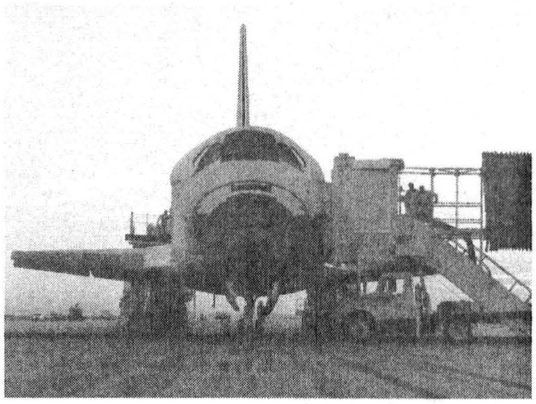
Credit: NASA



Credit: NASA

Shuttle Landing & Recovery

- **Landing capabilities are necessary any time the space shuttle leaves the launch pad**
- **Landing at Kennedy Space Center imposes the least operational burden as opposed to alternate landing sites**
  - Deservicing of hypergolic propellant on site
  - Venting of poisonous hydrazine fumes (APU & RCS) on runway
  - No mating/demating to 747 required
- **Once the shuttle lands at KSC recovery operations can begin in preparation for next mission**



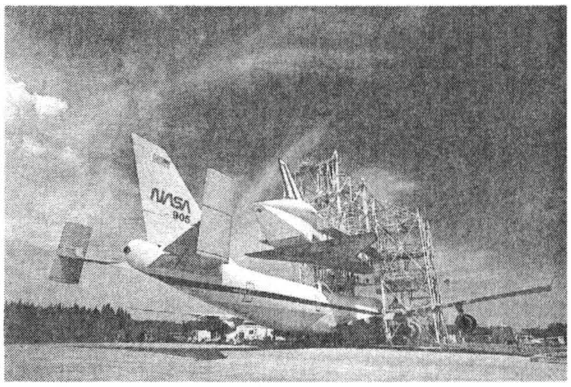
Credit: NASA

Shuttle Abort: A Necessary Contingency

- **If safe landing is not an option...**
- **Abort Scenarios**
  - RSLS, RTLS, TAL, AOA, ATO
- **Shuttle has no abort option from T-0 to SRB burnout at 126 seconds after liftoff**
- **Crew has no means to separate from the vehicle in an abort**
- **Most desirable TAL sites are in Western Europe**
  - Zaragosa Air Base, Spain
  - Moron Air Base, Spain
  - Istres Air Base, France
- **However, unlike the landing facility at KSC, the TAL sites are not equipped with the ideal logistics to process the shuttle**

Why Are Aborts A Challenge?

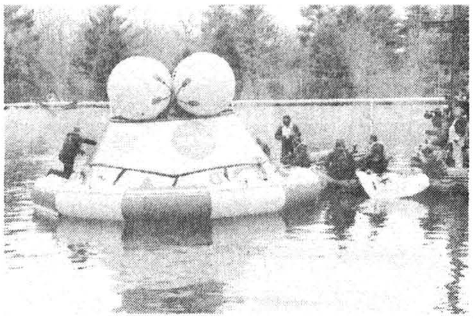
- **TAL sites must be equipped with the necessary means to support shuttle recovery**
  - Security (now provided by military)
  - Deservicing equipment and power
  - TRACAN or GPS
  - MSLBS
  - Xenon lighting
  - Communications
  - Weather Equipment
  - Mate/Demate device

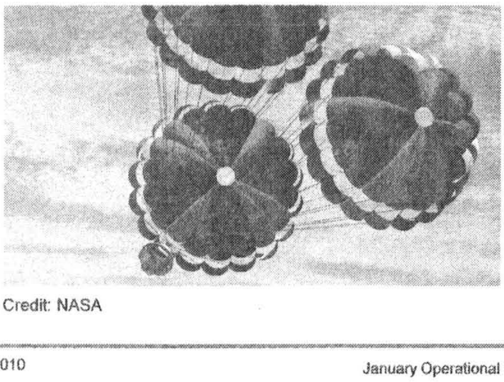


Credit: NASA

Servicing commodities at each TAL site add to the immense cost required to transport the shuttle back to KSC, but they are a cheap insurance policy for the life of the crew.

Orion Landing & Recovery


Credit: NASA

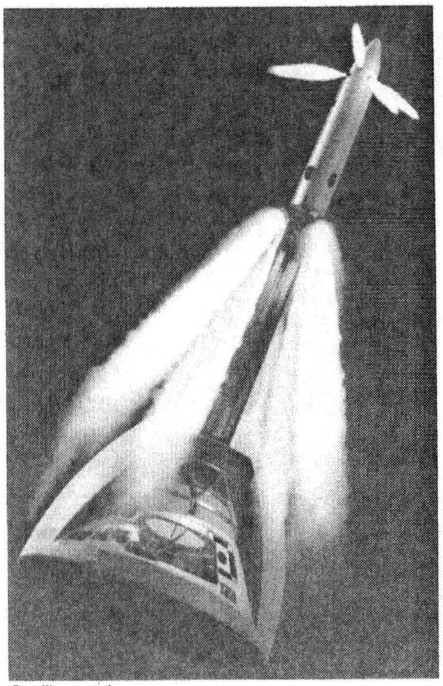

Credit: NASA

- **Design of Ares I calls for a water landing for Orion crew module**
  - Landing off the coast of Southern California
  - Service module must be jettisoned over the ocean
- **Crew module will have at least 24 hour human sustainability**
- **CM will be towed from the ocean onto ship**
  - Orion crew will remain in the CM until it is onboard recovery ship

Orion LAS & Abort Scenarios

- **Orion LAS can be utilized until 120 seconds into flight**
  - Also includes SRB burn
- **For aborts after LAS separation, the CM and SM would both jettison from the Ares stack**
  - Landing in Western Europe
  - Pacific Ocean or landing at Edwards or White Sands (AOA)
  - ATO

Ability for crew to escape Ares stack during SRB burn is substantial safety improvement from shuttle program.



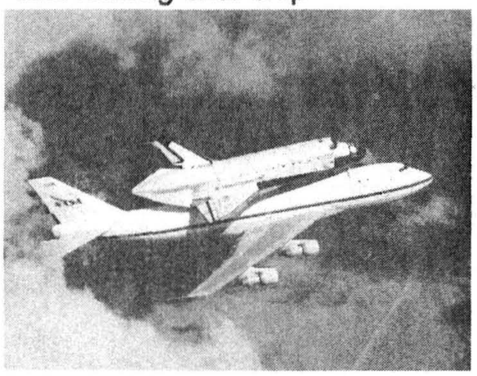
Credit: popsci.com

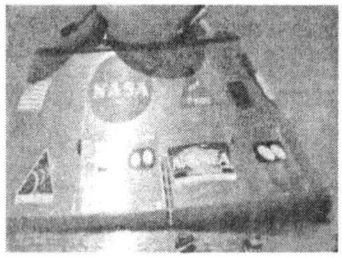
Transportation

Credits: nasa.gov

Transportation Infrastructure

- **Shuttle is a large and reusable vehicle**
  - Complicates remote landing and recovery
  - Configuration with 747 requires ideal flying conditions, short durations
  - Overseas landing requires towing and loading onto ship



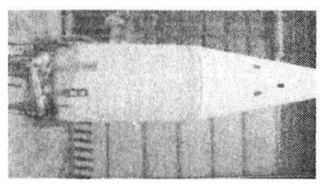


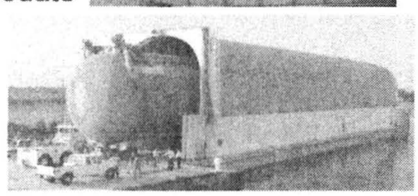
- **Crew module is lighter with salvageable parts**
  - Recovery by swimmers and ship
  - Ground transportation to JSC and KSC
- **Reusable SRBs – similar recovery**

Credits: slate.com,interspacenews.com

Transportation Infrastructure

- **Solid Rocket Boosters**
  - Manufactured in Utah, heavy propellant
    → modify railcars to have extra wheels
  - Entire length too long for tracks to accommodate
    → assembly waits until RPSF and VAB
- **External Tank**
  - Manufactured in Alabama in one piece
    → float on a barge
  - Meticulous rotation can only occur in the VAB
- **Hypergolics**
  - Must drain hypergolics before transporting vehicles
  - Special procedures for transporting hypergolics to HMFs
- **Mobile Launch Pad Crawlers**
  - Immense weight requires special rock tracks and maintenance

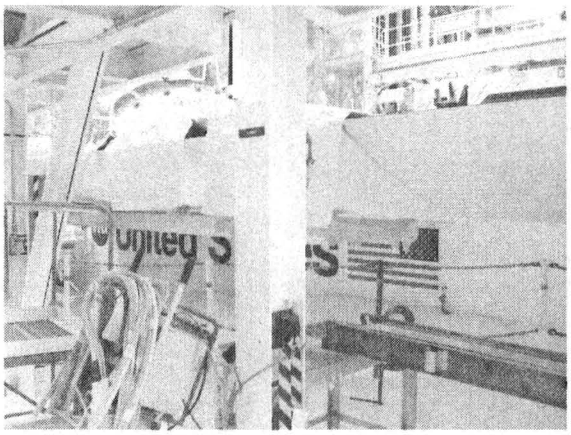




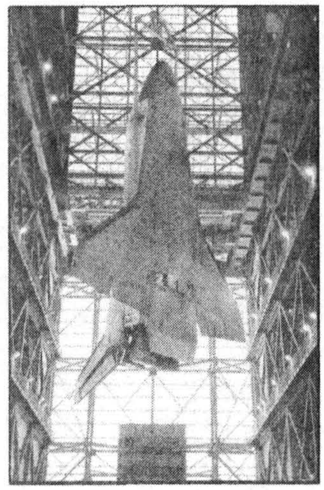
Vehicle component design determines transport mode, which in turn affects facility usage.

Credits: al.com

Shuttle Processing



Space Shuttle Atlantis



Credit: funonthenet.in

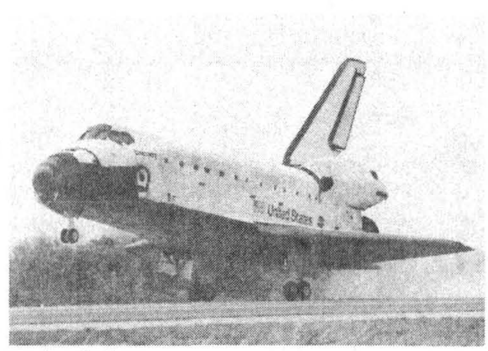
It All Starts At Landing

Life of Shuttle at KSC

Runway → OPF → VAB → Launch Pad

3..2..1..Liftoff

- **Runway**
  - Shuttle processing begins at touch down
  - Nose gear failure on early missions due to inability to steer
  - Corrected with hydraulic actuator placed on nose gear

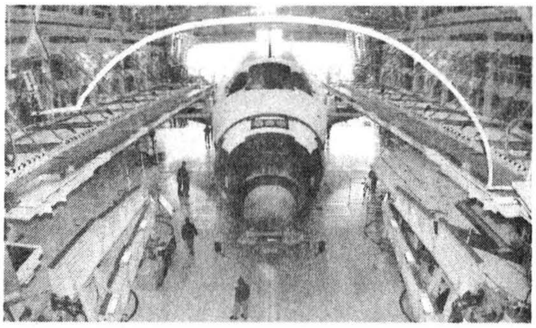


Credit: scibuff.net

Designs that are less expensive in the beginning can become more costly in the lifecycle of the program

On To The OPF

- **Orbital Processing Facility (OPF)**
  - Large scale maintenance on the shuttle
  - After being rolled in, orbiter is raised on hydraulic jacks
    - Jacks must level orbiter for servicing
  - Payload bay doors must be opened
    - Strongbacks maintain structural integrity



Credit: NASA

- Tiles
  - Damaged tiles replaced and entire system waterproofed

NASA underestimated the scale of shuttle processing which led to later modifications at the OPF. i.e. service platforms

Integration in VAB

- **After OPF, shuttle goes to VAB for stacking with SRBs and ET**
- **Wait…the vertical stabilizer does not fit**
  - Notch in VAB door was cut to allow easy access for the shuttle
- **Transition to Constellation**
  - Modification of platforms to allow processing of Ares rockets
- **KSC was able to use the VAB for three completely separate programs**

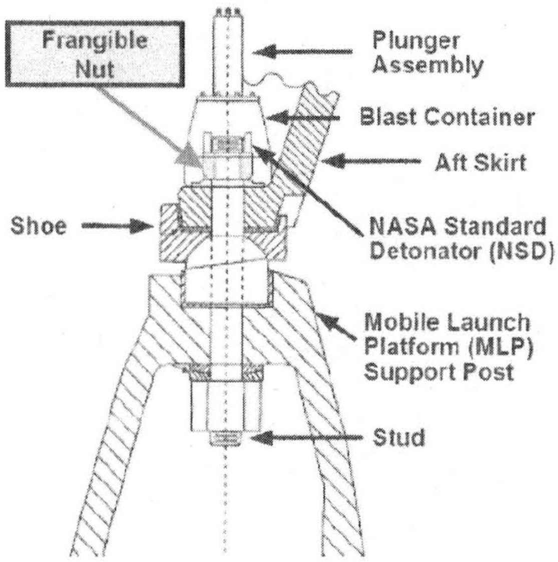
Credit: NASA

Design modifications in operations are sometimes necessary for the smooth transition of programs

At the Launch Pad

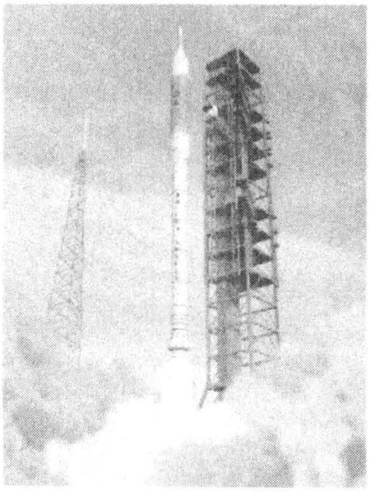
- **Once on the pad the shuttle waits for approximately 30 days until launch**
- **It was observed that the frangible nuts were breaking free of their torque over time**
  - Engineers preloaded the nuts with more torque to allow them to loosen once the shuttle reached the pad

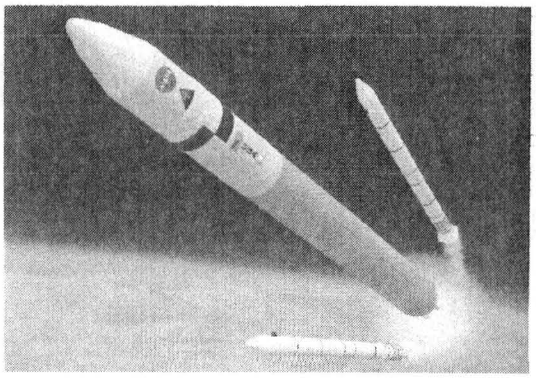
Because components are designed to exceed operational loads, fixes such as this are possible



Credit: NASA

Constellation Processing





Heritage Equipment and Hardware Reuse

Reused Between Flights

Command Module

Solid Rocket Booster

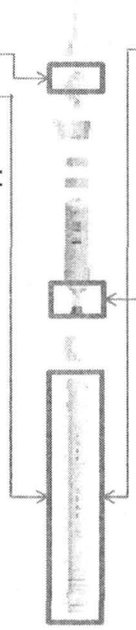
Less reuse of components means:

- Less maintenance between flights
- Decreased ground turnaround time
- Fewer limitations on design

Reuse of SRB limits Orion design space

Limited supply of Aft Skirts

Images taken from www.nasa.gov



Ares I

Heritage Equipment

Solid Rocket Booster

Cheaper than developing new technologies

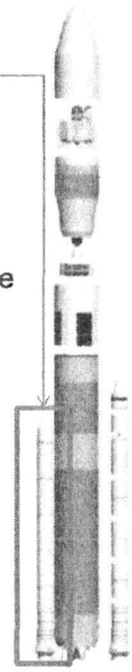
J-2X Upper Stage Engine

Derivative of Saturn V J-2 Engine

Preferred over SSME due to proven success of start-up in space

Use of heritage equipment means:

- Increased reliability
- Existing knowledge base for processing
- Existing facilities
- Decreased burden on schedule

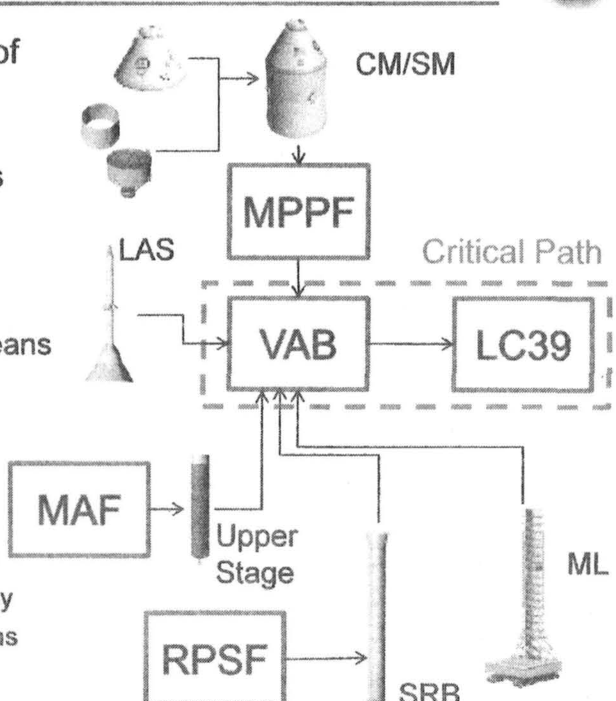


Ares V

Reorganization of Workflow at KSC

Compared with Shuttle, processing of Constellation benefits from:

- **Reduction of spare components**
  - Off-site production of parts
    - Less burden on KSC facilities
    - Reduces logistics footprint
  - Independent production off-site means spares automatically available
- **Reduction of critical path**
  - Increased parallelization of AI&P
    - Decreased ground turnaround time
    - Decrease probability of launch delay
    - Reduces need for VAB modifications
  - Examples:
    - 1-piece Ogive
    - Fueling of SM prior to stacking



Individual images taken from "Orion Production Overview", John Weeks.

Simultaneous Processing of Ares I / Ares V

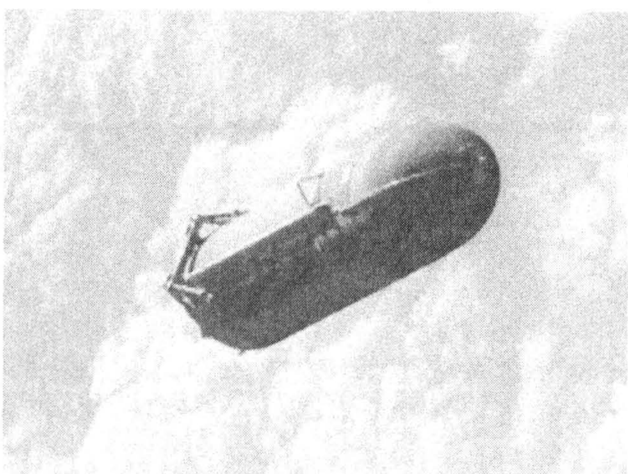
- **Limited buffer time between Ares I and Ares V launch**
  - Must simultaneously process both launch vehicles
  - Allocation of human resources may be difficult
  - Implications for Ground Systems

Constellation is easing the burden to its facilities through:

- **Customization of critical path facilities**
  - Customized High Bays in VAB, and ML's for Ares I or Ares V
  - Eases implementation of launch vehicle-dependent operations
  - Decreases human confusion

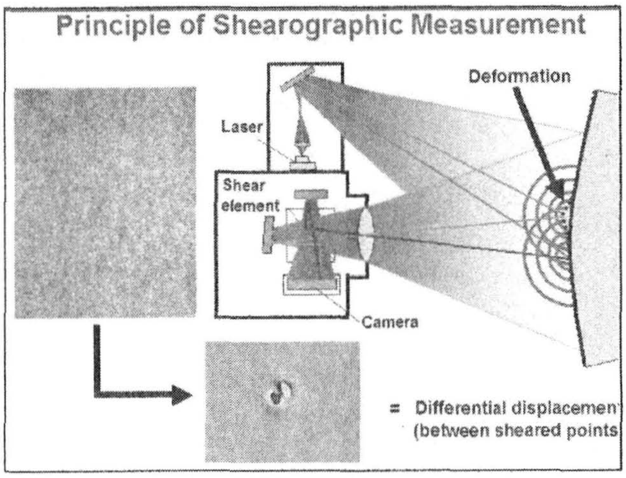
- **Flexibility of platforms in VAB**
  - Evolution of design accommodated through +/- 3 feet adjustment to platform height
    - Only possible once upon installation
  - 18in gap between Ares and platforms bridged with adjustable extensions

External Tank

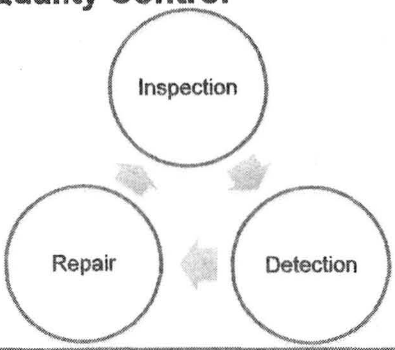


External Tank: Factors in Operability

- **Assembly Characteristics Related to Performance**
  - Foam spray pattern
    - Size of foam sprayer
    - *Orientation of bolts*
  - Friction stir welding
  - Paint



- **Quality Control**

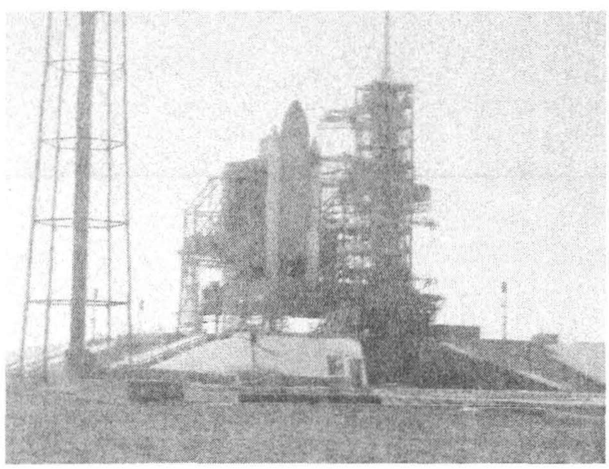


Design with the next step in mind!

Credits: www.fcsolution.co.kr

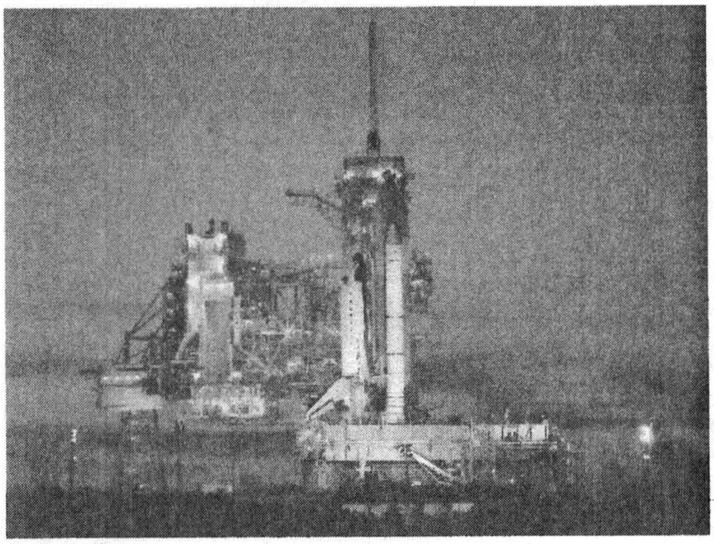
External Tank: Factors in Operability

- **On the Launch Pad**
  - ET and fuel feed lines have different rates of expansion
    ⇨ implementation of the boomerang joint
  - Cryogenics pumping leads to foam loss
    ⇨ visual inspection aided by video surveillance to monitor foam condition



Processing methodologies learned from ET operations can be applied to other space flight components.

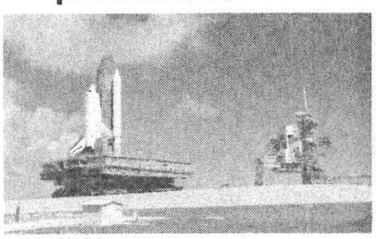
Launch Pad



Credit: NASA.gov

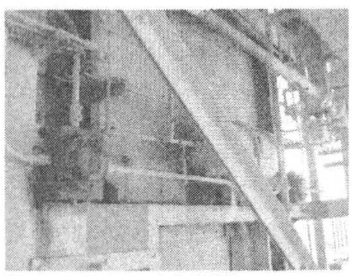
Structural Design and Maintenance Issues

- Effect of launch pad design on roll-out and operational procedures

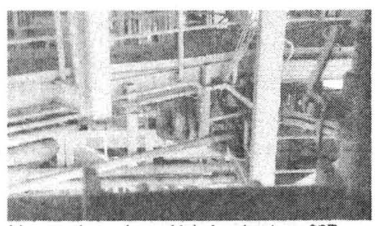


Credit: NASA.gov

- Tubular vs. I-beam/channel designs

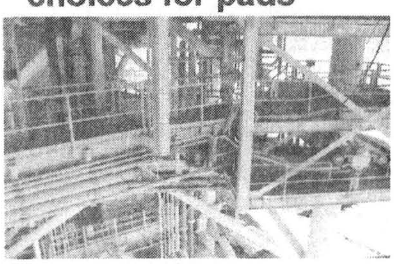


Work panel at Launch Pad 39B



I-beam, channels, and tubular structure; 39B

- Ramifications of material choices for pads

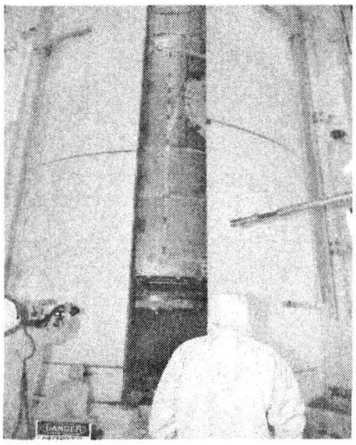


Salt water and blast debris damage

Design decisions can help curtail lifetime operational costs and decrease the functional requirements of hardware.

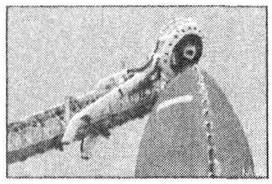
Processing Challenges at the Pad

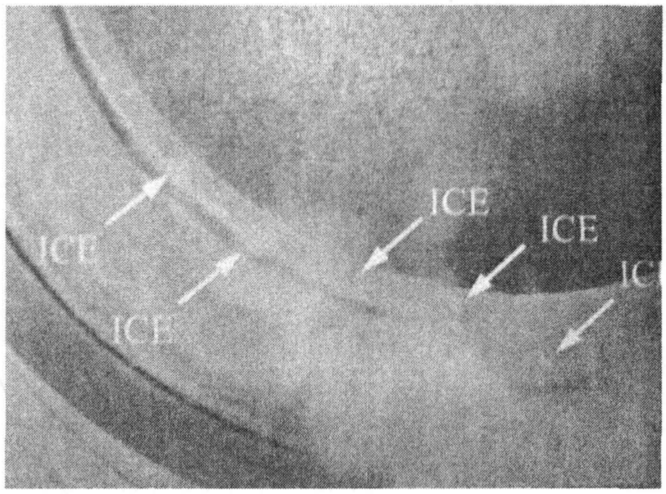
- **Vertical payload loading**
  - Clean room requirements
    - Payload Changeout Room
    - Clean-air purges and work platforms
  - Necessitates PGHM



Credit: NASA.gov

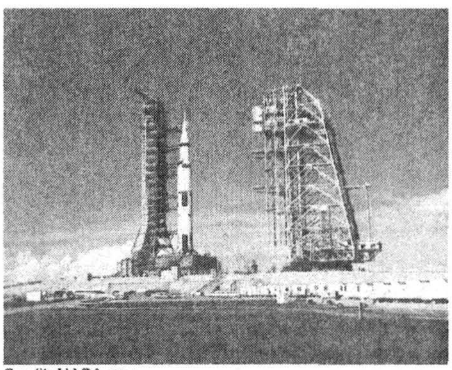
- **Dealing with cryogenic propellant loading**
  - Design evolution of GOX Vent Duct System





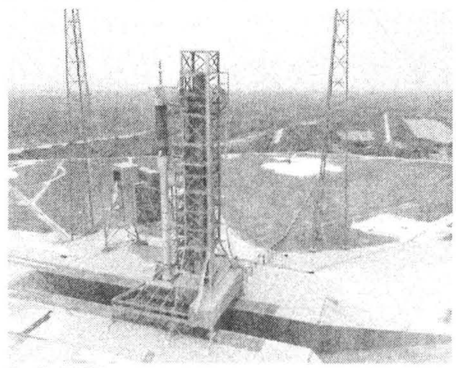
Credit: NASA.gov

Pad Innovations



Credit: NASA.gov

- **Return to a clean pad**
  - **Utilizing Apollo operational architecture**
  - **Employing Mobile Launcher design expertise**



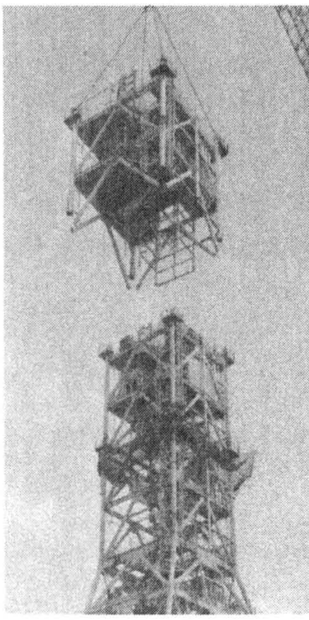
Credit: NASA.gov

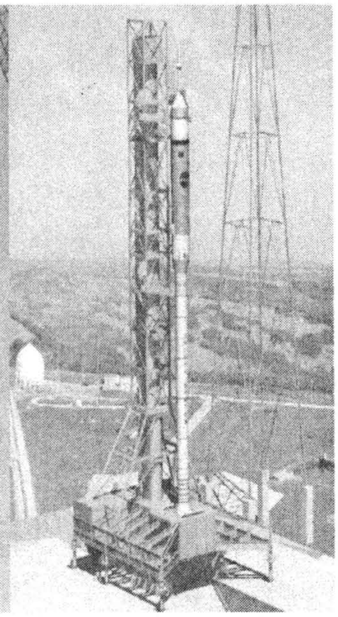
- **Implementation of Faraday cage**
  - Additional taller lightning masts
- **Emergency egress improvement**
  - Egress design changes

Drawing on knowledge and expertise from the past as well as everyday experiences can help improve design decisions and reduce LCC.

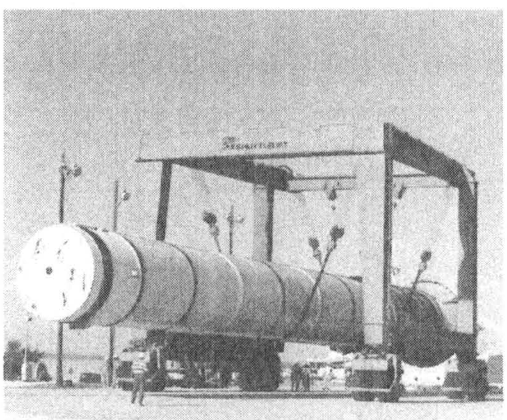
MLP operation lessons drive ML design

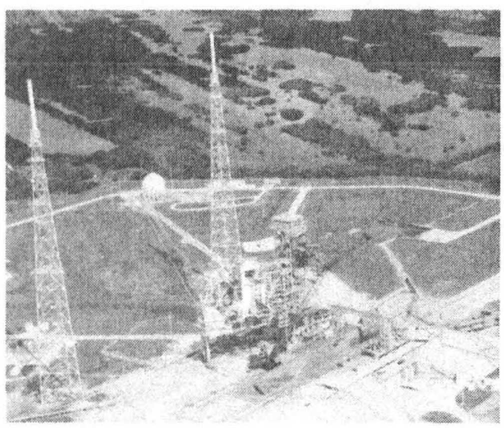
- **Material science improvements**
  - Anti-corrosion, anti-abrasion
  - Use stainless steel despite cost
- **Modular structure**
  - Easily adaptable tower
- **Increase safety**
  - Abandoning ordnances for hold down system
- **Benefits of Simplicity**
  - Swing arm vs. Tilt-up umbilical
    - Weather factors
    - Maintenance factors
    - Reliance on mechanical systems





Ground Operations





Images taken from http://www.nasa.gov

Ground Operations

- **Design features of the vehicle directly affect what facilities and commodities are required.**

- **Constellation requirements are being developed with input from ground operations experts.**
  - Idea is to reduce long-term logistics footprint and life cycle costs.

- **Examples from the Shuttle:**

Design Feature	Commodities & Facilities
LOX/LH2 engines	Cryogenic storage
Hypergolic thrusters	HMF; SCAPE suits
Solid Rocket Boosters	Special railroads; RPSF
Thermal tiles	TPSF

Design influences operability & supportability

Ground Operations

Ground Ops considerations in Constellation:

- **One-piece ogive assembly on Ares I rocket**
  - Reduces time spent in the VAB
  - Eliminates complications with assembly

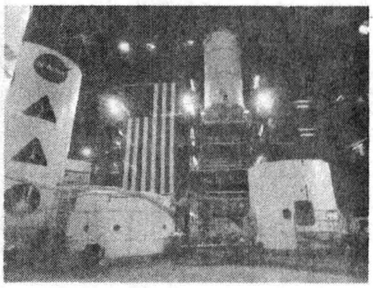
- **Mobile launch tower solution, instead of permanent structures built on the launch pad**
  - Reduces environmental wear on launch structures
  - Reduces time spent on the pad; the "ship-and-shoot" method
  - Mitigates complications on the critical path

- **Less maintenance of flight hardware, since most of the rocket is not reusable**
  - Eliminates the need for large warehouse storage of spare parts
  - Less refurbishing operations required

Image taken from http://www.nasa.gov

Ground Operations

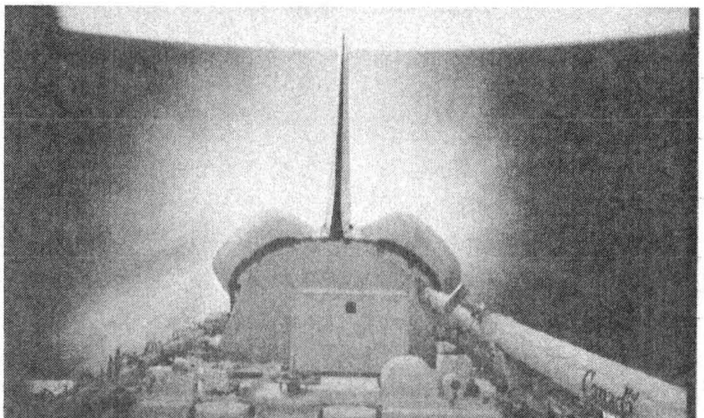
- **Ares V design pushes the capacity limits of current facilities**
  - Crawler Transport will be unable to carry the current Ares V design
  - Ares V pushes the operational limits of cranes in the VAB
  - Fully constructed Ares V may not fit inside of the VAB
- **LOX & LH2 tanks at launch pad are insufficient for Ares V**
  - One solution: truck in fuel constantly
  - Alternative: build larger fuel tanks at the pad



Efficient use of GSE is a factor in reducing life cycle costs and logistics footprint

Images taken from http://www.nasa.gov

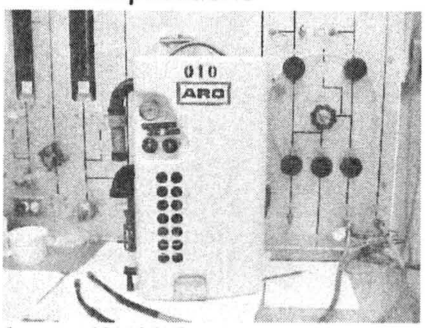
Hypergolic Propellants



Credit: NASA.gov

Complications with Hypergolic Propellants

- **Favorable Performance characteristics**
  - Negates need for ignition source
  - Storability
- **Operational complications**
  - Increase structural amenities
  - SCAPE and purge operations complications



Category 1 SCAPE-PHE
Credit: NASA.gov

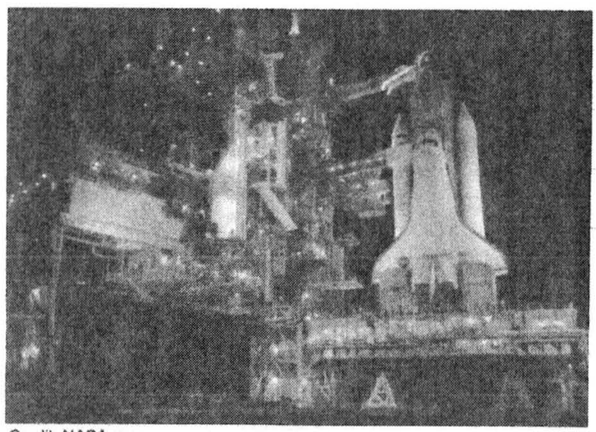
- **Health Hazards**
  - High toxicity
  - Corrosive characteristics

Category IV SCAPE-PHE
Credit: NASA.gov

Performance requirements may lead to unavoidable operational costs.

Life Cycle Challenges

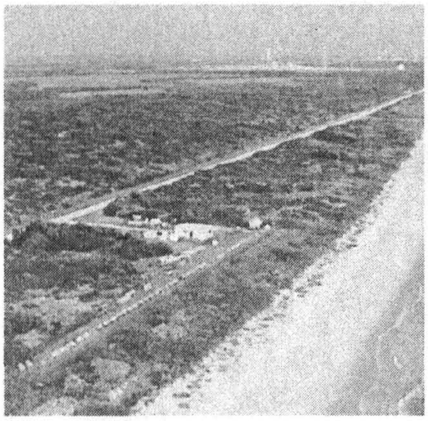
- **Facility and processing demands**
  - Hypergolic shelf-life
    - Limitation of pressurized tanks
  - Outfit facility with hazard mitigation equipment
    - Quick Disconnect
    - Egress paths
    - Purge and ventilation systems
  - Rotating Service Structure
    - Hypergolic Umbilical System
    - Effect of moisture on OMS/RCS
  - Using Multi-purpose Processing Facility for Constellation
    - Save time at launch pad
    - Operations cost savings



Credit: NASA.gov

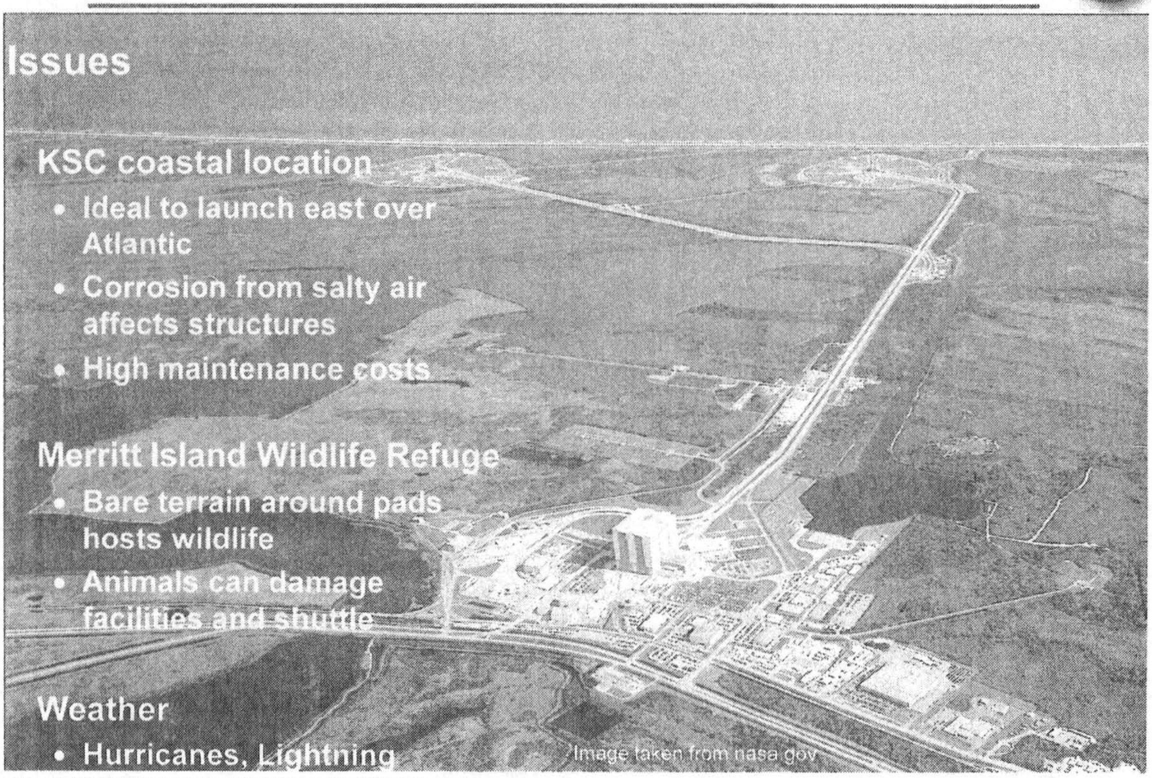
Hypergolic propellant facilities were not expected to handle as much maintenance as they do now.

Environmental Factors



Images taken from nasa.gov

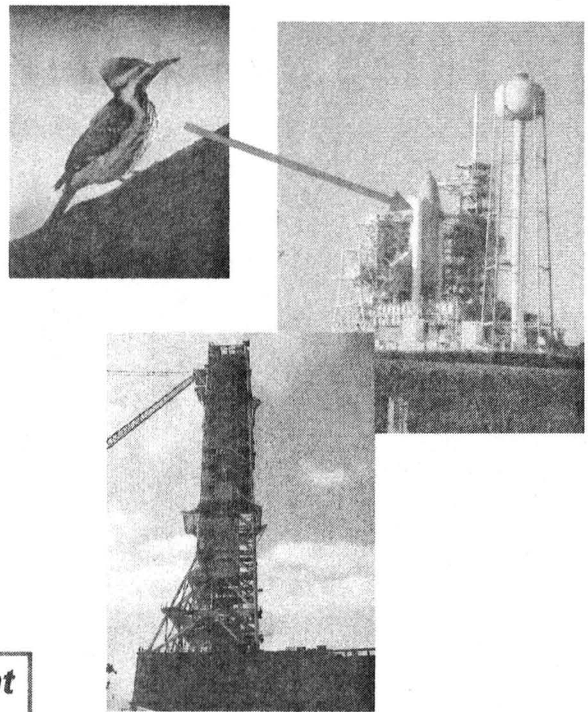
Environmental Factors in Operations



Environmental Factors in Operations

Solutions

- **Mobile Launch Pad for Constellation**
- **Wildlife control**
  - Birdstrike
    - Radar monitoring
    - Decoy owls at pad
  - Carrion removal program
- **Lightning towers, rollback**
- **Other considerations**
  - Decreasing environmental impact
    - Freon use in ET manufacturing
  - Disposal of hazardous substances
    - Hypergolic fuels
  - Storage of materials



Consider operational environment during the design phase

Logistics

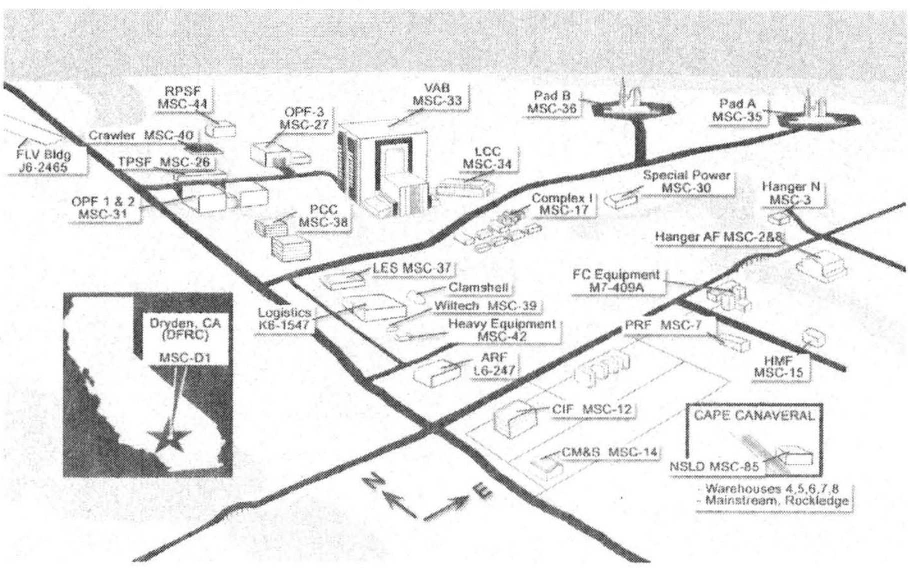


Image taken from PH Logistics Division Training Module 2

Logistics
Main Responsibilities

- **On-time delivery of spares.**
- **Currently handle 200K+ repair parts for shuttle and GSE.**

- **Spare sources:**

	Shuttle	Constellation
Vendors	✓	✓
Heritage	✓	✓
Cannibalization	✓	✗

- **Forecasting necessary spares and timely delivery, within budget**
  - Likelihood of failure
    - Delphi method, trade studies
  - Criticality of part
  - Transportation and storage needs
  - Tradeoff between risk and cost

Forecasting is necessary to successfully provide support while minimizing costs.

Logistics
Shuttle Processing Support

Vendor | KSC Facilities | NSLD (USA)

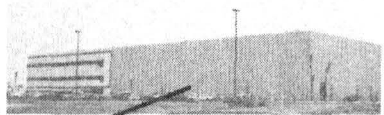
Image taken from nasa.gov

- **Vendor Maintenance**
  - Expensive
    - Hughes: $6M a year for KU bands
  - Technician and Product Certification
    - Flight Readiness
  - Proprietary claims
  - Vendor holds on to old technology

KSC and NSLD images from PH Logistics Division Training Module 2

Logistics
Storage, Fabrication, Repair

Vendor | KSC Facilities | NSLD (USA)



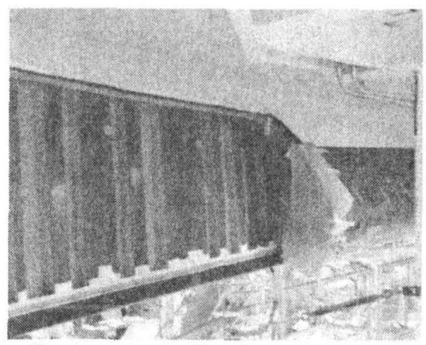
- **Ability to retrieve pieces quickly**
  - Warehouse
    - Highly automated and efficient
    - Part segregation avoids confusion, reduces risk on inventory
  - Custom, on-need construction of tiles
  - NSLD: parts and repair without contract, no vendor
- **Challenge: tracking part changes**
  - COTS items
  - Obsoleteness
  - Certification vs. continuity

Design must foresee change of available components during operations

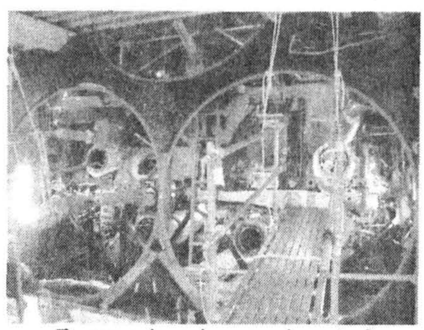
Logistical Challenges - Shuttle

- **Access to components requiring maintenance**
  - Avionics box located in front of filter
    - Difficulty in filter replacement
  - Access to wing interior
    - Required for replacement of RCC panels
    - Can cause damage to wing struts
  - Engine nozzles
    - Following each flight, must be cleaned and checked

Amend by:
- Considering criticality of hardware and failure rate
- Incorporating logistics into design early



Replacement of leading edge panel



Removed engine nozzles at aft

- **Failure analysis of Avionics**
  - Difficult to replicate failures
  - "Unexplained anomalies" do not solve the problem

Base failure analysis on criticality of component

Transition From Shuttle to Constellation

Primary improvement in Constellation relies on:

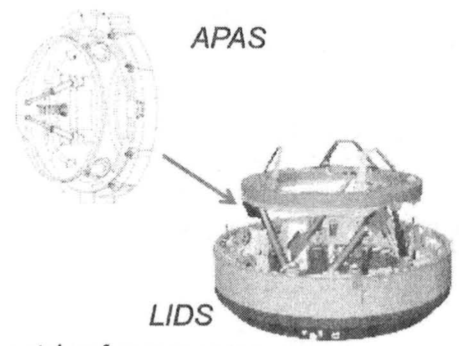
Reduction of Logistics Footprint

Goals

- Lower life cycle cost
- Establish flexible and reliable logistics and maintenance infrastructure

Implementation

- Reduction of spares stored at KSC
- Use of "just-in-time" replacements
- Consolidation of facilities, e.g Depot
- Designing ground systems with Ares I and Ares V in mind



Images taken from www.nasa.gov

Reducing life cycle cost by considering operations, maintenance, support and disposal during design phase will:

- Decrease operations and maintenance cost
- Increase efficiency of logistics
- Minimize supportability implications

Logistical Challenges - Constellation

- **Facility for encapsulation of Altair**
  - Should be completed outside of VAB
    - Installation of clean room would be costly
    - Off-line processing favorable
  - Option of NRO shared use
    - Transportation implications
    - Sharing may impose unexpected cost, schedule delays and additional risk

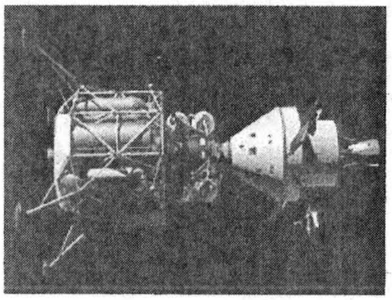
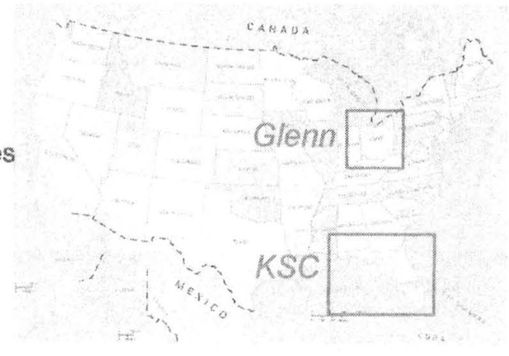


Image taken from www.nasa.gov

Extensive trade studies of facilities will help to minimize logistics footprint

- **Thermal Vacuum Testing of Orion**
  - Glenn Research Center
    - Orion dimensions impose limitation on facilities
    - Large distance from KSC

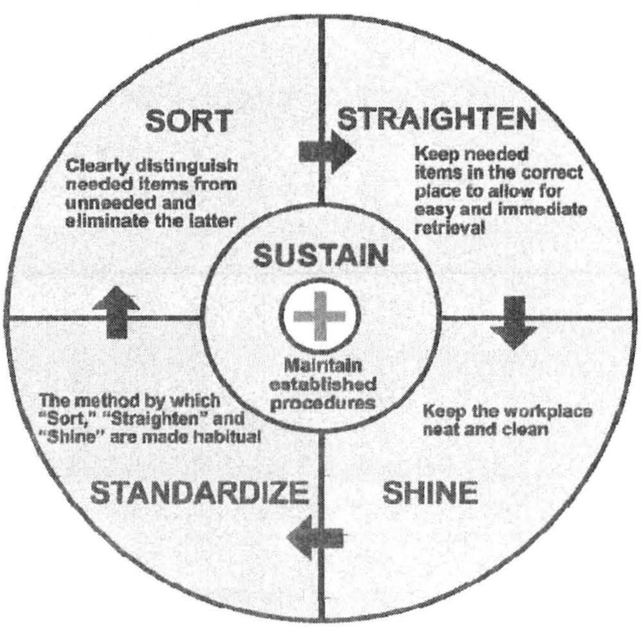


Parallelization of assembly processes may alleviate negative effect of additional testing on schedule

Lean Six Sigma

6σ

Lean Six Sigma Strategies

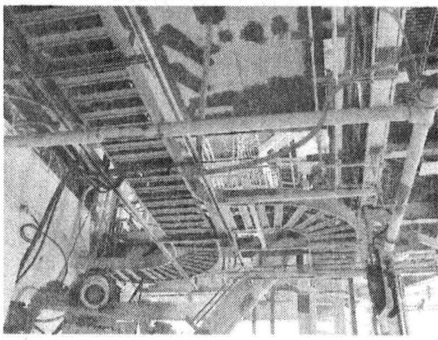


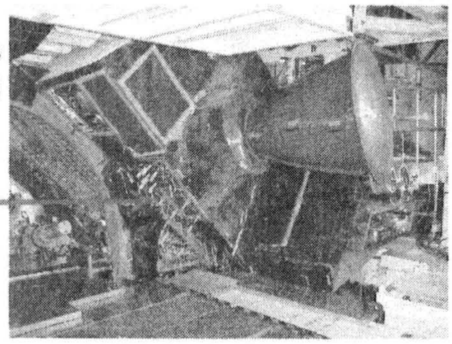
- **Organization**
  - Warehouse layout
  - Consolidating facilities
  - Automated storage
  - Arranged workspaces

Organization methods lead to efficiency.

Credits: Enterprise Lean

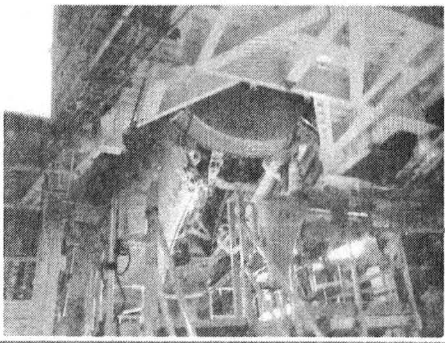
Lean Six Sigma Strategies

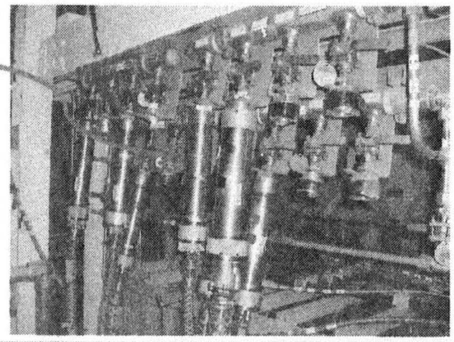




Cable Railcars at Launch Pad

Tile Labels



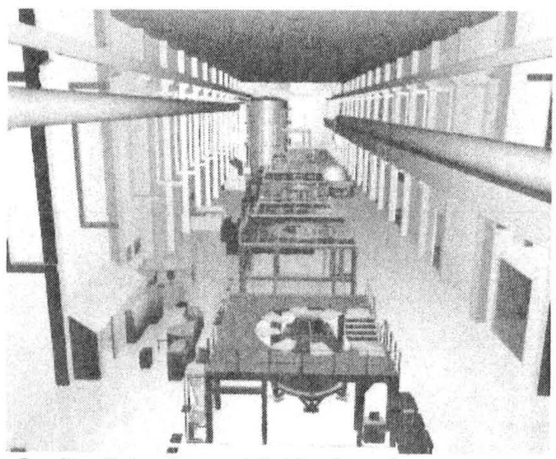


HMF Oxidizer & Fuel Labels

FOD Basket In the OPF

Lean Six Sigma Strategies

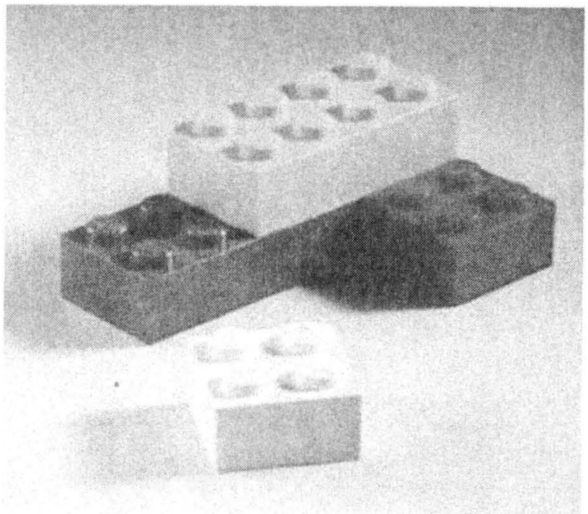
- **Reduce Processing Time**
  - Support connections made inside facilities
  - Physical data interface on MLP
  - Conscious of logistics and lifecycle costs
  - Information transparency
- **Reusing Established Resources**
  - Distributing work
  - Combining expertise from ELVs and Shuttle
  - Modifying existing facilities



Credits: Orion General Public Overview by John Weeks

Consolidating facilities and resources simplifies operations.

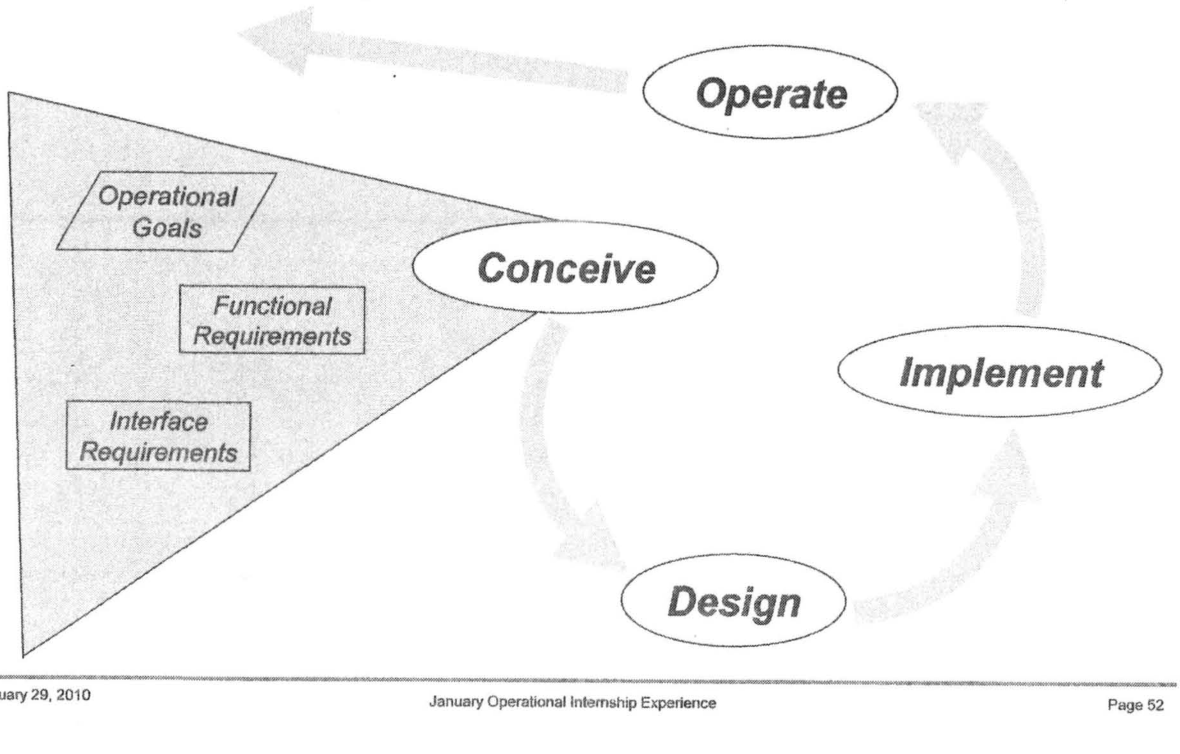
Systems Engineering



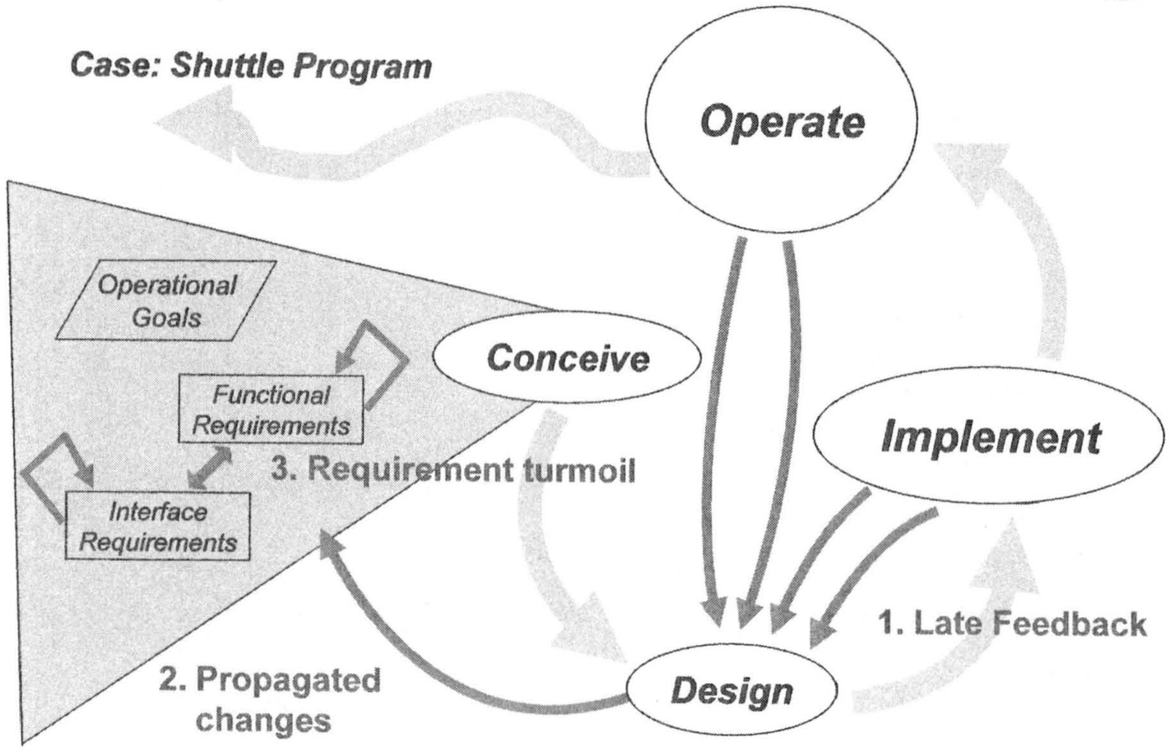
Credits: babble.com

Requirements Interacting with Design

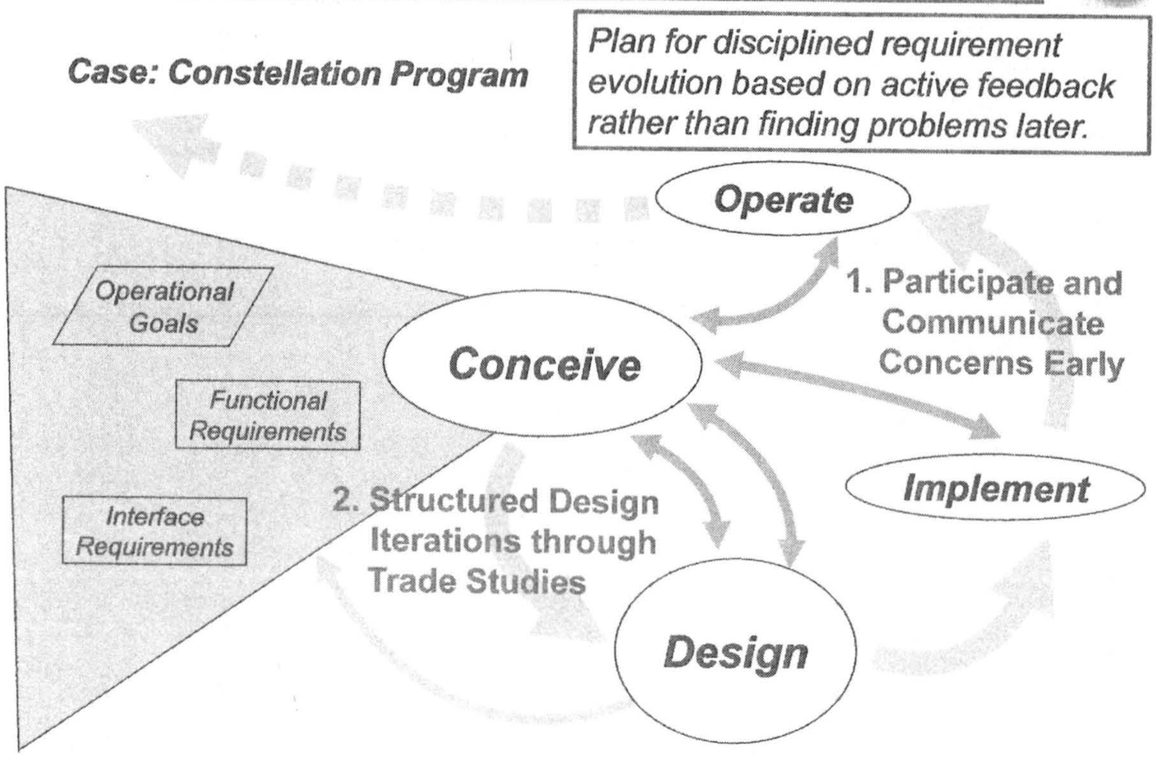
Case: Theoretically...



Requirements Interacting with Design

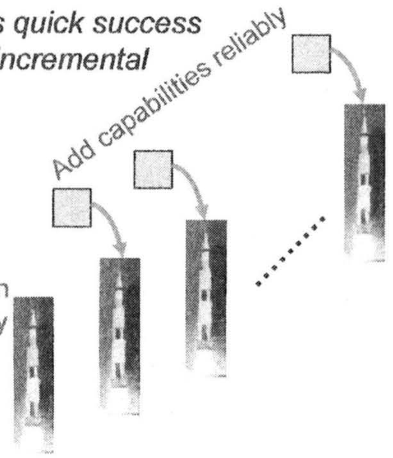


Requirements Interacting with Design



Testing Incrementally

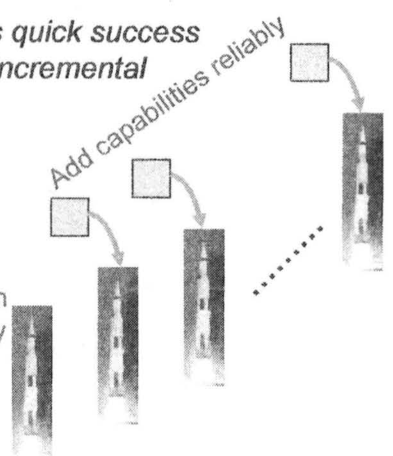
Apollo's quick success due to incremental testing



Start with near-proven functionality

Testing Incrementally

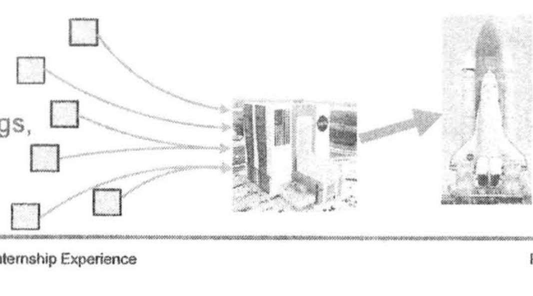
Apollo's quick success due to incremental testing



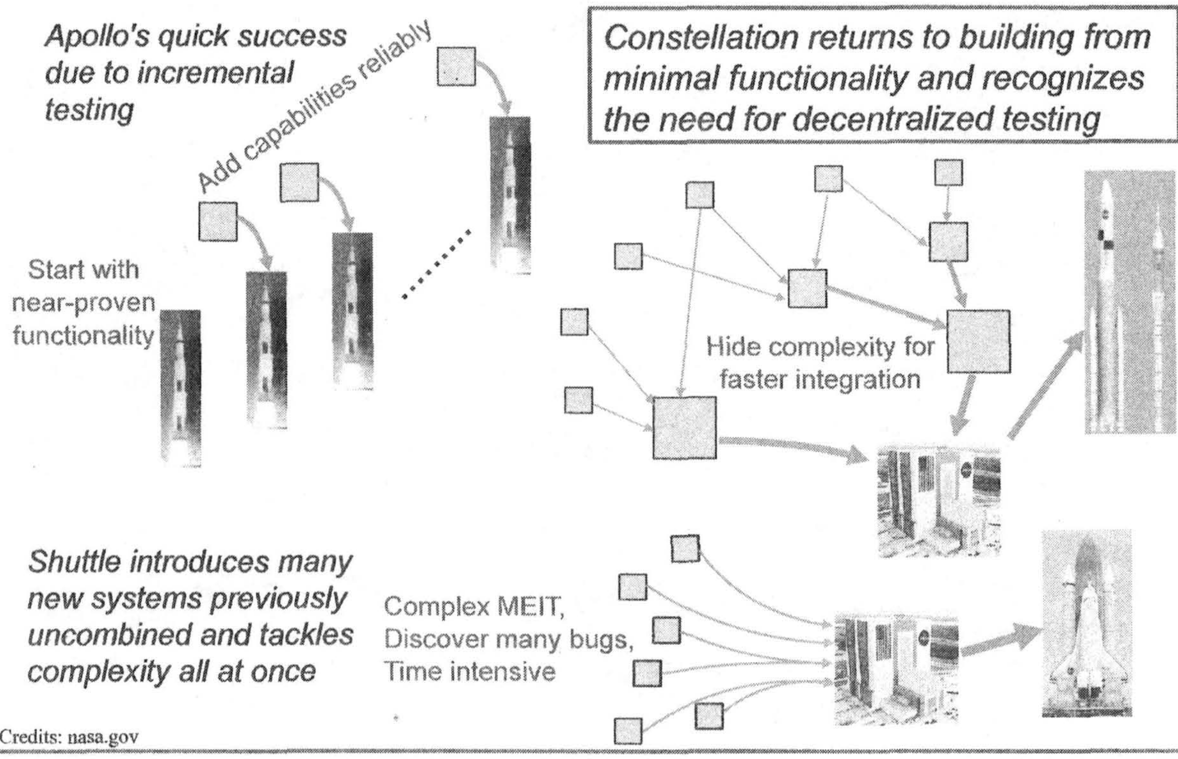
Start with near-proven functionality

Shuttle introduces many new systems previously uncombined and tackles complexity all at once

Complex MEIT,
Discover many bugs,
Time intensive



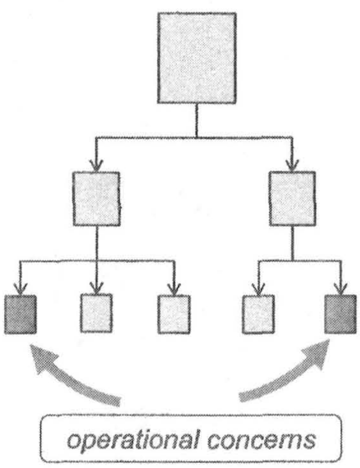
Testing Incrementally



Credits: nasa.gov

Upgrading Information Technology

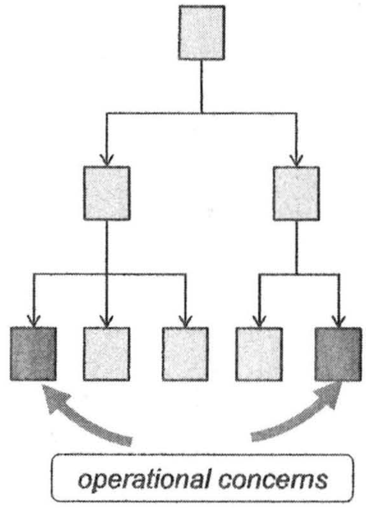
Design | Manage | Test



Enforcing a strict "flow-down" requirement hierarchy inhibits and delays communication of operational concerns

Upgrading Information Technology

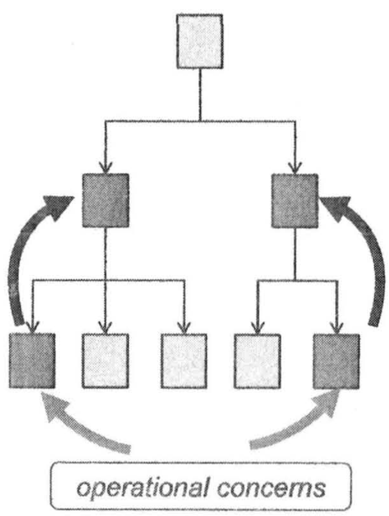
Design | Manage | Test



An efficient IT system is needed for enabling concerns to flow up the requirement hierarchy

Upgrading Information Technology

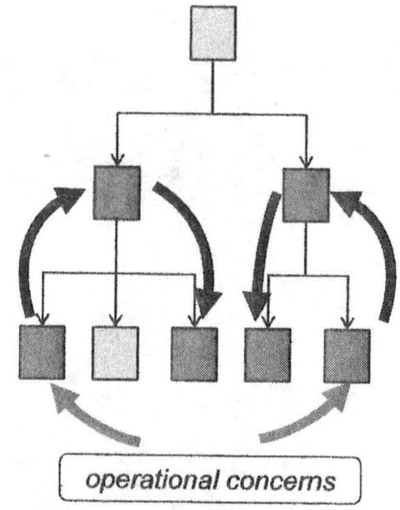
Design | Manage | Test



An efficient IT system is needed for enabling concerns to flow up the requirement hierarchy

Upgrading Information Technology

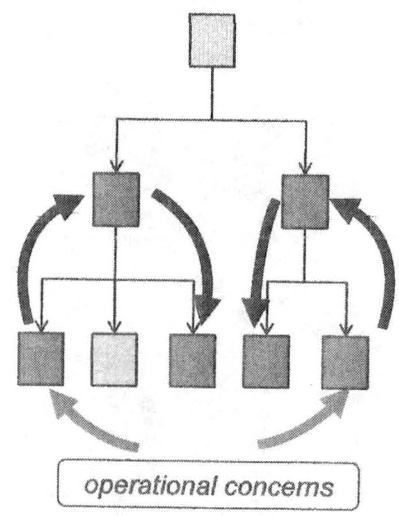
Design	Manage	Test



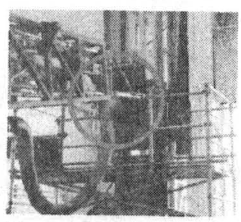
An efficient IT system is needed for enabling concerns to flow up the requirement hierarchy

Upgrading Information Technology

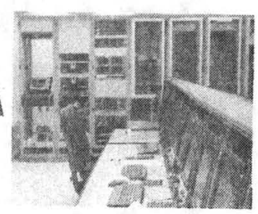
Design	Manage	Test



An efficient IT system is needed for enabling concerns to flow up the requirement hierarchy



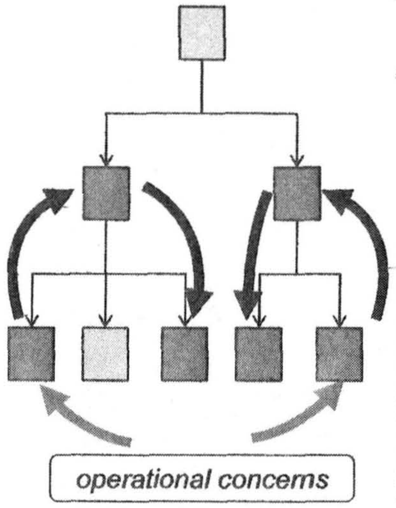
New technology and upgraded integrative tests deliver more sensor data



Modern test control room manages data and unifies interfaces

Upgrading Information Technology

Design



An efficient IT system is needed for enabling concerns to flow up the requirement hierarchy

Manage

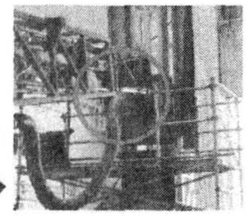
SME Probabilistic Inputs

Discrete Event Simulation

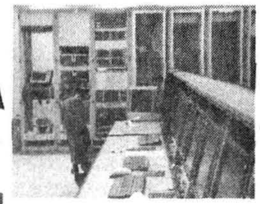
Probabilistic Schedule & Costs

Decentralization requires more IT infrastructure to streamline processes

Test

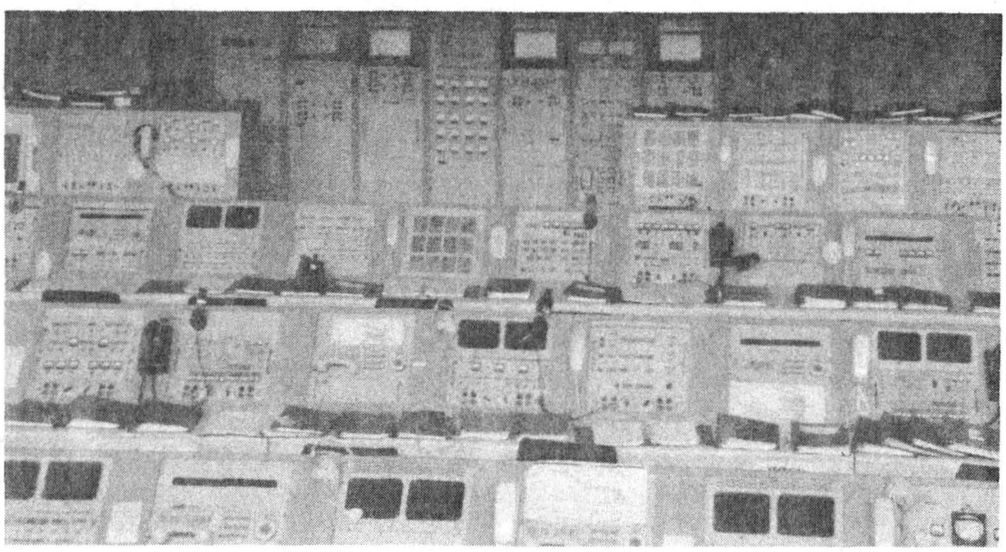


New technology and upgraded integrative tests deliver more sensor data



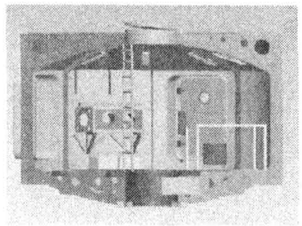
Modern test control room manages data and unifies interfaces

Human Factors



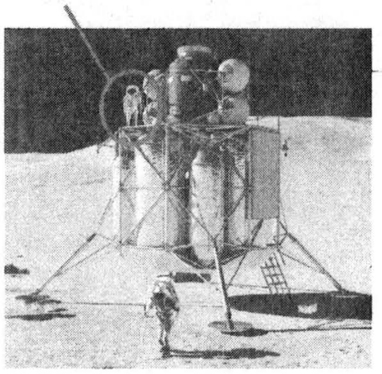
Human Factors in Design Concepts

Considerations:
- ♦ **Ergonomics**
- ♦ **Anthropometrics**
- ♦ **Intuitive operation**



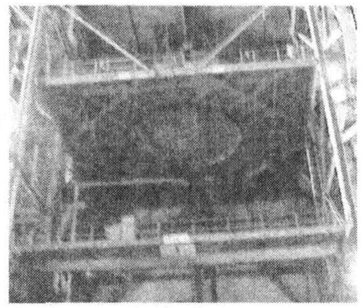
HDU (Habitat Demonstration Unit)

Astronaut



Altair Lunar Lander

Assembly Facilities:
- ♦ **Platform height**
- ♦ **Adjustability**



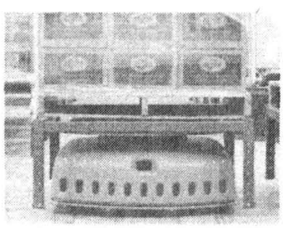
Ares 1-X Platform

> ***Human strengths and limitations must be considered in design***

Images taken from www.nasa.gov

Human Input and Automation

- ♦ **Survey SME (subject matter experts) using Delphi Method**
  - Anonymity
  - Non-leading questions
  - Task duration estimates for median, 95%, and minimum



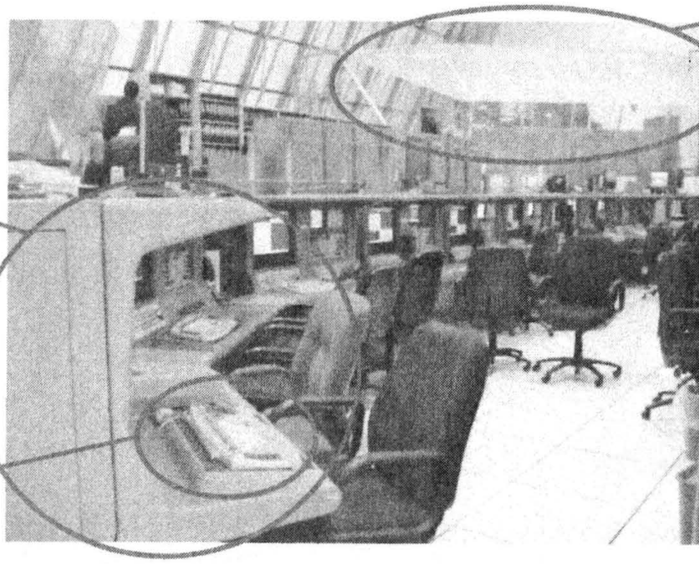
Automation in warehouses
- ♦ **Shelf Robot**
  - Fast & accurate retrieval and delivery of items
- ♦ **Trackless Transport Robots**
  - Great for high-traffic, low-priority item transportation
  - Critical-path space components can be delayed

Training
- ♦ **Operators of equipment must practice operations procedures**

> ***Maintain human involvement in monitoring autonomous operations and develop feedback loop***

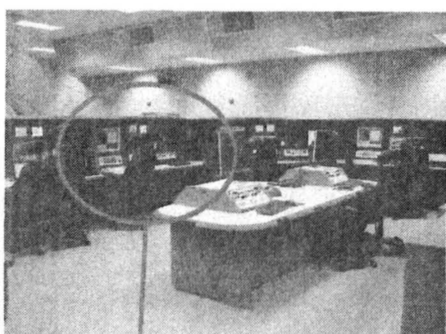
Image taken from www.spectrum.com

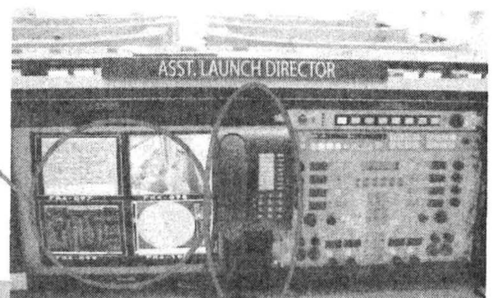
Shuttle Firing Control Room



Reduce costs by adapting old technologies and by customizing COTS equipment

New Shuttle Firing Control Room



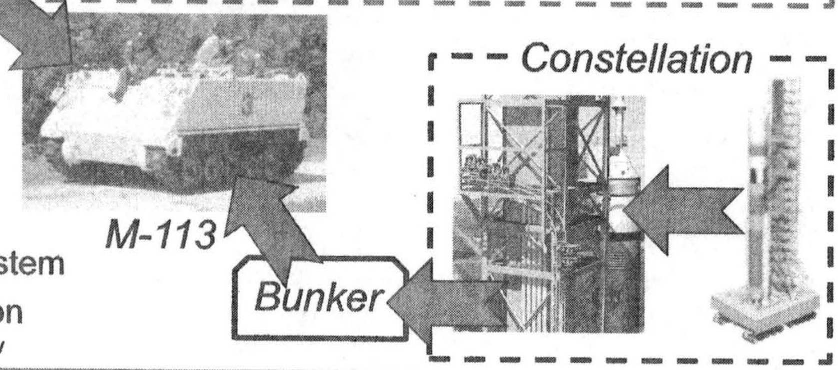


Intuitive design of displays allows for smooth operation

Emergency Egress Systems

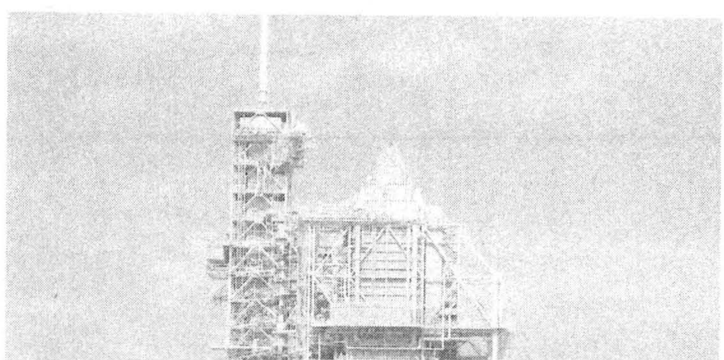
Considerations:

- Medical condition of astronauts
- Reliability
- Speed of exit
- Maintenance of system
- Safety of destination



Images taken from www.nasa.gov

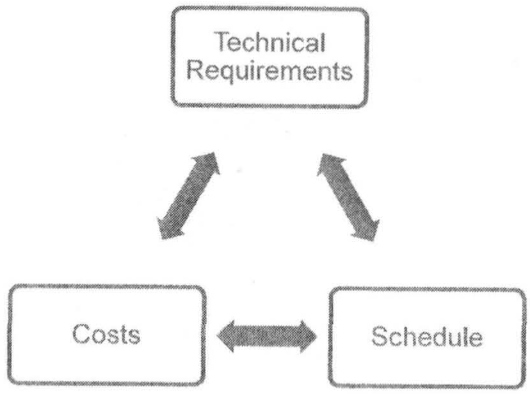
Summary



Design Lessons Learned

- **Learn from the experts (SME)**
- **Design with flexibility in mind**
- **Consider human factors**
  - Accessibility of replaceable and high failure rate components
- **Incorporate redundancies and abort systems to reduce risk**
- **Implications of logistic capacities & facilities (i.e. factor logistics into design trades)**
- **Compatibility, re-usability & disposability**
- **Standardization & commonality**
- **Consideration of environment and use of hazardous materials**

Design Tradeoffs



Operational Lessons from the Experts

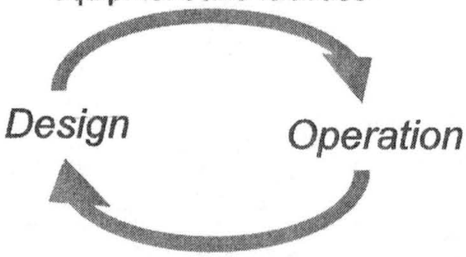
- **Hardware fit check**
- **Inclusion of test equipment in operational planning**
- **Track parts while limiting overwhelming documentation**
- **Benefits of DES trade studies**
- **Lean Eng. (Six Sigma & 5S)**
  - Efficiency of manufacture, assembly and maintenance
  - Just-in-time delivery
  - Optimize online/offline pathways

Image taken from "Lunar DES MIT," Tracy Gill

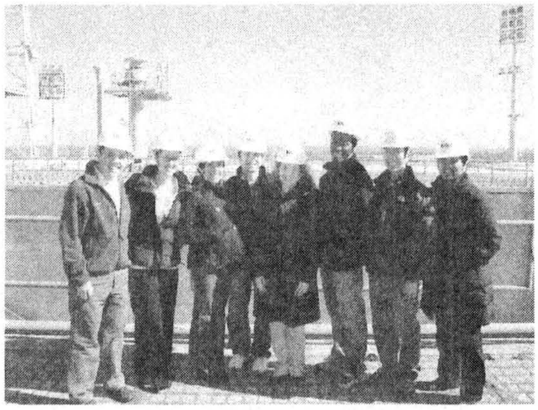
Operations & Design

As future engineers, we will remember how design and operations are interrelated

Responsible for maintenance costs
Dictates necessary support equipment and facilities



Minimize lifecycle costs
Ensure feasibility



Operations should be considered throughout the design process

Acknowledgements

- **Massachusetts Space Grant for its generous support**
- **Ms. Raji Patel & Dr. Jeffrey Hoffman**
- **Thank you to all these personnel and more:**
  - Wanda Petty, Elizabeth Kline, Robert Holl, Michelle Dailey, Andrew Knutson, Sarah Schilling, Michael Turner, Michael Hartnett, Jeffrey Skaja, Ahmad Declase, Alicia Mendoza, Kevin Panik, Kelly Corridan, Seth Berkowitz, Robert Libbey, Jim Thomas, Lamar Russell, Troy Heron, Janet Parker, Terry Kenney, Anne Gavarosac, Frank Ochoa-Gonzales, John Weeks, Michael Vinje, Steve Clarke, Debra Kral, Dave Shelton, Kirk Logsdon, Tim Honeycutt, Tammy, Stephanie Sowards, Scott Colloredo, Tracy Gill, Norm Tokarz, Charles Shelton, Sasha Sims, Jessica Parsons, Paul Mogan, Ronnie Rodriquez, Linda Trocine, Prentice Washington, John Moss, Joe Madden, Mike Stelzer, Jeremy Parsons, Cliff, Gregory Clements, Pat Simpkins, Robert Mueller, Alfredo Menendez, Ralonda Farrant, Curtis Williams, Timothy McKelvey, Albert Folensbee, Rolando Nieves, Jeffrey Crowder, Karen Mendoza, Roger Mathews, Patricia, Julie Peacock, Harold Turner, Jim Shaver...
- **Special thanks to Ms. Helen Kane**

Questions?